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Evaluating and Optimizing Recycled Concrete Fines in PCC Mixtures Containing Supplementary Cementitious Materials

by

Elyse M. Hanson
Undergraduate Research Assistant

Nicholas J. Connolly
Undergraduate Research Assistant

Donald J. Janssen
Associate Professor

Department of Civil and Environmental Engineering
University of Washington
Seattle, WA 98195

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ABSTRACT

Portland cement concrete (PCC) is used throughout transportation infrastructure, for roads as well as bridges and other structures. One of the most effective ways of making PCC more "green" is to replace a portion of the portland cement (the portion of a PCC mixture with the greatest carbon footprint) with a supplementary cementitious material such as flash or ground granulated blast furnace slag (GGBFS). Since these supplementary cementitious are waste byproducts, they can significantly reduce the carbon footprint of PCC. A consequence of using these materials, however, is that they can reduce the rate of early PCC strength gain. This reduced rate of strength gain can cause problems, especially in urban areas where user costs from delayed construction must be considered when evaluating a project's overall cost.

Previous work (Janssen, et al., 2006) demonstrated that the use of recycled concrete fines could offset some or all of the delayed strength-gain effects from cement-GGBFS blends. Current work appears to indicate that the use of such fines could allow for increased cement replacement with no additional reduction in early strength gain. Unfortunately, recycled concrete fines can be quite variable from batch to batch. To effectively utilize recycled concrete fines to offset delayed strength gains associated with the use of supplementary cementitious materials, a procedure must be developed that: 1) evaluates the effectiveness of a specific recycled concrete fines source, and 2) determines PCC mixture proportions that utilize the recycled concrete fines to offset reduced strength-gain effects associated with the use of supplementary cementitious materials as cement replacement. This procedure must be rapid and inexpensive so that ready-mix concrete producers could easily perform the procedure whenever a new recycled concrete fines source is obtained.

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1.0 Introduction

Portland cement is a versatile construction material that is essential for modern transportation infrastructure including bridges and pavements. The production of portland cement requires considerable energy (0.2 to 0.35 kwh/kg cement). Advances in technology have reduced the energy consumption associated with cement production and continued technological advances promise to continue this trend. Even with technological advances, cement production is still an energy intensive process.

Energy consumption, however, is not the only concern with portland cement production. Limestone is one of the primary raw materials used in portland cement production, and the conversion of limestone from calcium carbonate to calcium oxide releases considerable carbon dioxide. This carbon dioxide release, combined with the carbon dioxide released by the energy production for portland cement manufacturing results in the total release of up to a kg of carbon dioxide for every kg of cement produced. [Bentur, 2002] Cement production worldwide is estimated to account for approximately 5-8 percent of the total carbon dioxide emissions. [Nixon, 2002]

The increased consciousness within the construction industry of the importance of incorporating "green" building materials and practices into structures has resulted in an increased use of supplementary cementitious materials as a replacement for portland cement in concrete. Principal among these materials are flyash and ground granulated blast furnace slag (GGBFS). Flyash is a byproduct of coal-burning power plants, and GGBFS is a byproduct of iron refining. GGBFS is somewhat cementitious on its own, and requires both water and either sodium hydroxide or calcium hydroxide to hydrate. Since portland cement produces excess calcium hydroxide, a blend of portland cement and GGBFS can be an effective cementitious material even at cement replacements of 40% and higher.

Unfortunately, many applications for portland cement concrete require rapid reaction rates during the first few days after the concrete is placed. This is primarily important in order to avoid delaying the construction process. Contractors often want to remove formwork within two or three days after concrete has been placed in order to proceed with another part of the structure. The concrete must have adequate strength to support its own weight during the form-removal process. Other construction processes, such as stressing post-tensioning cables, also require strengths at early ages. Portland cement concrete pavements also must gain strength at a reasonable rate so that they can be driven on by construction vehicles with minimal delay. Most portland cement concrete mixtures having high cement replacement levels tend to react significantly more slowly than mixtures containing portland cement alone. Therefore, some cost-effective method must be found to accelerate the rate of early strength gain to make high levels of portland cement replacement acceptable for most infrastructure construction.

1.1 Background

The use of recycled concrete fines has the potential to offset the undesirable effect of the above-mentioned delayed strength gain due to its accelerating effect on portland cement concrete. It has long been known that finely-ground particles of hydrated portland cement can have a significant accelerating affect on the hydration rate of portland cement concrete. [Mindess, et al., 2002] This effect is believed to be primarily due to the hydrated cement particles acting as nucleation sites, making it easier for the hydration reaction to take place. Minor accelerating affects may also be due to calcium hydroxide and/or alkalis in the hydrated portland cement. Hydrated portland cement is present in a number of recycled concrete fines sources, and the incorporation of these materials into portland cement concrete mixtures needs further investigation.

1.1.1 Wash-Out Fines

One source of recycled concrete fines is the material that is obtained when concrete trucks (and other concrete handling equipment such as mixers) are washed out.

The aggregates can be screened out of the wash-out material for re-use, but the wash-out fines (WOF) that are collected in settling ponds or other extraction methods are generally waste materials. These WOF contain hydrated cement particles, and the actual amount of hydrated cement particles depends upon the concrete being used. These WOF can also contain unhydrated cement particles as well as dissolved ions such as calcium and hydroxyl ions. [Shogren, et al, 2009] Unfortunately, the presence of these suspended as well as dissolved materials causes the WOF to be classified as a waste material. The Clean Water Act, authorized in 1972, states that "…the National Pollutant Discharge Elimination System (NPDES) permit program controls water pollution by regulating point sources that discharge pollutants into waters of the United States". [EPA, 2008] This means that concrete plants *must* do something with their washout water other than discharging it into local streams/rivers.

1.1.2 Grinding Fines

Diamond grinding of concrete pavements, often done to restore ride quality or to improve surface friction, also produces a waste material containing hydrated cement particles. This material is also considered a waste material which must be properly disposed of. These grinding fines (GF) probably contain a smaller proportion of hydrated cement particles than our WOF, and the actual amount would also depend on the concrete in the original pavement.

1.1.3 Recycled Concrete Dust

A third material source of hydrated cement paste is the dust produced during recycling of portland cement concrete by crushing. Crushing portland cement concrete produces a considerable amount of fine material (referred to as recycled concrete dust, or RCD), including particles of hydrated cement paste. The actual amount of hydrated cement paste in the RCD depends upon both the original concrete and the crushing process. RCD is generally considered to be less of a waste disposal problem than either WOF or GF, since some fine material is permitted by gradation specifications for base course materials (which is the most common use for recycled concrete).

1.2 Problem Statement

Preliminary results [Janssen, et al, 2006] clearly indicate that at least some of these waste materials can improve the performance of concrete mixtures containing significant amounts of supplementary cementitious materials. The widespread adoption of the use of recycled concrete fines within the concrete industry requires that there first be a way to categorize different types of existing recycled fines as well as how to optimize their use in concrete. To identify a way to quantitatively measure recycled concrete fines to then predict strength gain for a concrete mixture.

1.3 Research Objectives

This research looks to identify which types of fines work best as a supplementary cementitious material as well as a way to evaluate each recycled concrete fine's effectiveness. Secondly, these studies work to develop a procedure to optimize the amount of recycled concrete fines to use in a concrete mixture, and how to simplify this procedure to make it easily adoptable by ready-mix concrete plants. Upon the successful completion of these objectives, it is expected that a material that is now a waste product will become a widely used recycled material. Furthermore, it will make portland cement concrete with supplementary cementitious materials a more attractive product for use by the construction industry because of the reduced negative side effects.

2.0 Method of Analysis

The laboratory testing for this research was divided into three major tasks: Recycled Fines Acquisition, Testing of Fines and Fines Characterization.

2.1 Recycled Fines Acquisition

Recycled concrete fines were acquired with the aid of Dr. Robert Shogren of LaFarge North America. The fines that have been collected are:

Fine Type A – Concrete Plant A, washout fines

Fine Type B – Diamond Grinding Project A

Fine Type C – Concrete Plant B, washout fines

Fine Type D – Concrete Plant C, washout fines

Fine Type E - Diamond Grinding Project B

Fine Type F – Diamond Grinding Project B (taken a week after Fine Type E)

Fine Type G – Concrete Plant B washout water (sampled approximately four months after Fine Type C, and obtained directly from the recirculation system without settling)

Fine Type H – Concrete Plant B washout fines (same as Fine Type G, but dried before using, as were all fines types except for Fine Type G, see below)

All of these except for the Fine Type G were dried at 40°C to permit easier handling in the lab. The Fine Type G was tested at "full strength" (approximately 15% solids by total weight of solution) as well as diluted to match the fines concentrations used for the majority of the mixtures described below.

2.2 Materials

In addition to the recycled fines described above, all concrete mixtures for the laboratory testing used the following materials:

- Type I-II portland cement from LaFarge North America
- Deionized water at room temperature
- Fine aggregate: Silica Sand,
    - Maximum size: Number 80 Sieve
    - Minimum size: Number 30 Sieve
    - Effective size: .35 mm
- Ground granulated blast furnace slag

2.3 Recycled Fines Testing

Prior to the introduction of the recycled fines into the concrete mixtures, baseline mortar mixtures were made. The mortar mixtures were mixed following ASTM C305-06 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. The initial control mixture began with a water-cementitious ratio of

0.42 and material proportions of 930 grams of Type I-II portland cement, 1,947 grams of fine aggregate, and 393 grams of water. The initial control mixture was modified through the addition of water and cement until a flow value of 20 was reached. The final control mixture proportions that were used throughout the laboratory testing were 1,225 grams o cement, 1,947 grams of fine aggregate and 518.2 grams of water. The water-cementitious ratio remained at 0.42.

The final control mixture was used with slag replacement levels of 25, 37.5 and 50 percent, while maintaining the water-cementitious ratio of 0.42. Flow values for mixtures having cement replacement were slightly higher, but not significantly different than the established baseline flow. Compressive strengths were measured at 3 and 28 days to quantify early and long-term strength performance.

2.3.1 Fines Characterization

The process for testing the recycled concrete fines began with the fines characterization testing. The purpose of this segment of testing was to determine a quick and easy method to characterize the fines. The characterization of the fines would allow for eventual predications as to the benefits of each source of recycled fines. Measurements of index of refraction (IR), conductivity and pH were chosen for testing. Conductivity is measured in units of millisiemens (mS). IR is sensitive to both suspended solids and dissolved ions. Conductivity is sensitive to dissolved ions (but not most dissolved molecules such as many organics), and pH is sensitive to hydroxyl ions. All three of these factors (suspended solids, dissolved ions and pH) can affect reactivity, so correlations between these measurements and the strength-effects of the various recycled fines should be possible.

The procedure for the fines characterization testing began with the mixing of the recycled fines and water for the desired mortar mixture. Each sample of recycled fines and water was mixed using a milkshake-type mixer such as is typically used in a soils lab. Mixing was conducted for a total of four minutes with breaks in the mixing at 3 minutes and 3.5 minutes to test the conductivity. This mixing process was used to determine the duration of the mixing of the recycled fines and water that guaranteed stable measurements for conductivity, index of refraction and pH. The conductivity was chosen as the measurement to take at multiple intervals due to its ease and speed of results. Once the duration of mixing was determined, it was decided that this mixing procedure should continue in order to maintain consistency throughout all laboratory tests. At the end of the 4 minutes, measurements of the conductivity, IR and pH were taken. Once the fines characterization testing was complete, the concrete mixing process began.

2.3.2 Mixing

The recycled fines mixtures were modeled after the baseline mixtures discussed previously. Mixtures were prepared at slag levels of 25, 37.5 and 50 percent by mass of cement plus slag. Recycled fines were used as cementitious replacement at levels of 2.5, 5.0 and 7.5 percent of total cementitious material. Using the fines as cementitious replacement was the chosen approach as it has minimal effect on water demand (flow). A control mixture of 0 percent fines was made along with the 2.5, 5 and 7.5 percent fines replacement levels for each type of recycled fines.

Each concrete mixture was made using the recycled fines/water mixture from the fines characterization testing described above following the procedure detailed in ASTM C305-06. The flow of each mixture was tested once the mortar mixture was complete according to ASTM C1437. The final step of mixing was to cast six 2" x 2" cubes of each sample for compression testing.

2.3.3 Testing

Specimens were demolded and labeled after one day and then cured in a moisture room at 23˚C and 100% humidity until the time of compression testing. Three cubes from each sample were tested at both 3-day and 28-day curing periods to determine the effects of the recycled fines percentages for both early and long-term strength gain. The compressive strength testing was performed following ASTM C109 Compressive Strength of Hydraulic Cements Mortars.

3.0 Results

3.1 Fines Characterization

The data collected from the fines characterization testing was used to begin analyzing the fines content versus conductivity, IR and pH respectively. The conductivity measurements proved to have the most reliability, providing consistent measurements and clear trends in the analysis. For all fine types, the conductivity increased approximately linearly with an increase in fines content. Fines content will be defined as grams of fines per liter of mixing water. Figure 1 below shows an example of this approximately linear trend. The conductivity values for all the fine types ranged from 0.32 mS to 6.1 mS, yet most values were focused between 0.32 mS and 2 mS.

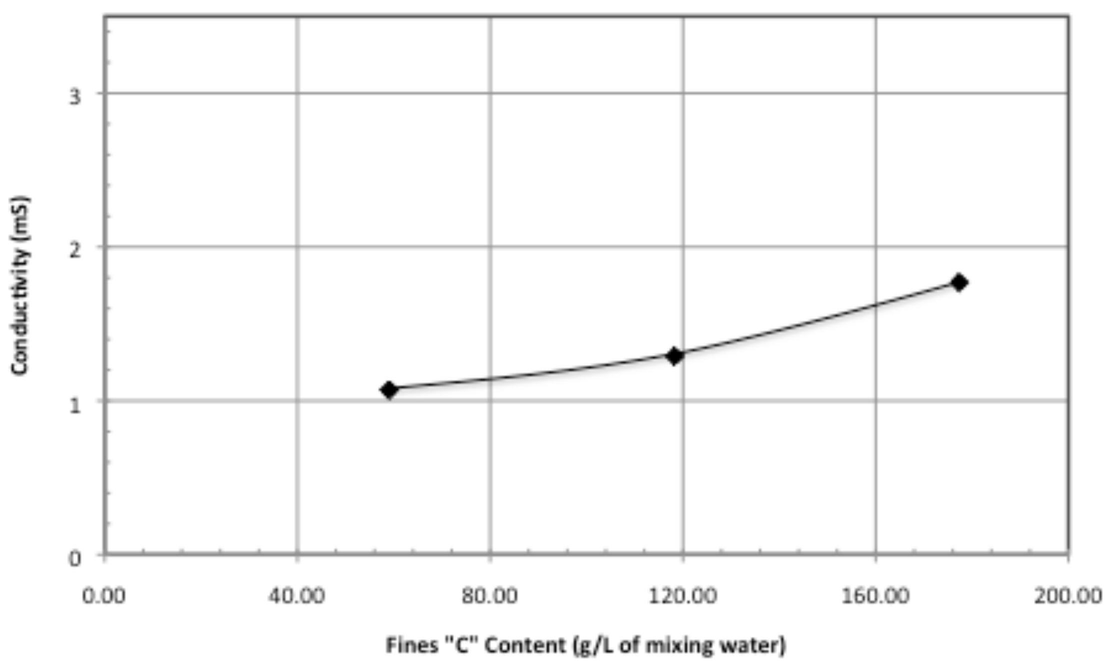

Figure 1. Conductivity vs. Fines "C" Content

Measurements for the Index of Refraction were taken as Brix (B) readings, which can then be converted to IR by the equation:

$$IR = 1.33302 + 0.001427193*B + 0.000005791157*B*B$$

The range of IR values throughout the fine types were between 1.33316 and 1.33597. For most of the fine types, the index of refraction values increased as the fines content increased but there were a few fines that displayed a slight decrease in IR as the fines content increased. Figure 2 displays the typical increasing trend of Fine Type "C".

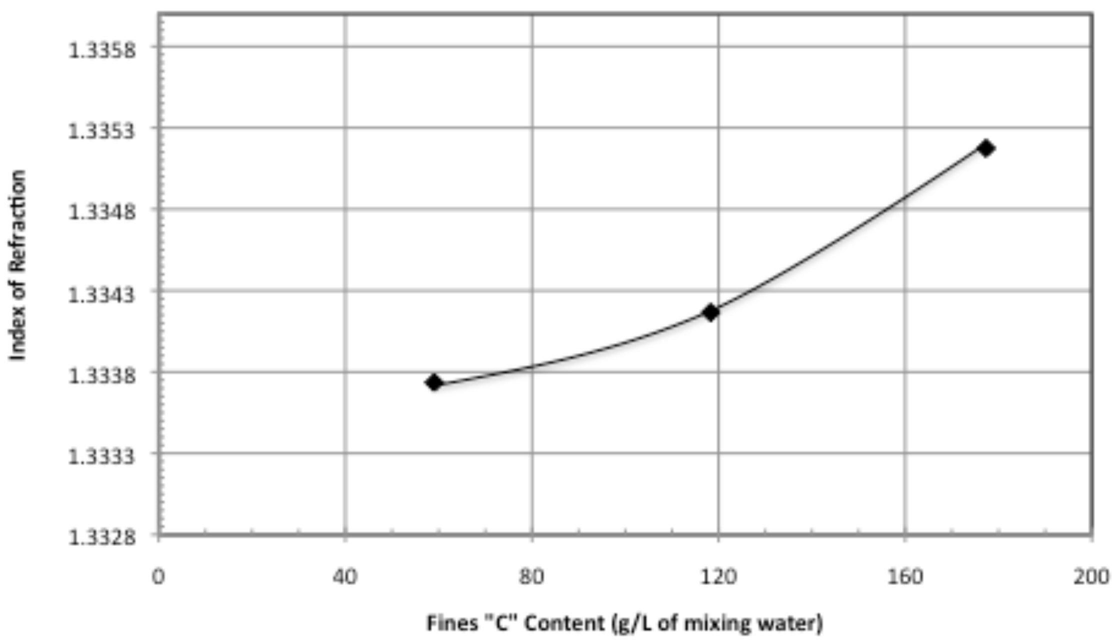

Figure 2. Index of Refraction vs. Fines "C" Content

The last measurement for fines characterization testing was pH. The pH analysis did not display a consistent trend initially, which was determined to be due to a miscalibrated pH meter. Towards the end of the fines characterization testing, a new pH meter was procured to provide more accurate pH readings. Each fines type was tested with the new pH meter, which provided much stronger trends for the pH analysis. Overall, the pH values ranged between 9.3 and 12.8 for all the fine types. There normally was not much change in pH over the range of fines content tested, and the pH frequently appeared to be approximately constant for at least part of the range. This trend can be seen in Figure 3 below. Different fines types, however, tended to have different typical pH values, ranging from valued near 9.5 for fines type F to 12.7 for fines type H.

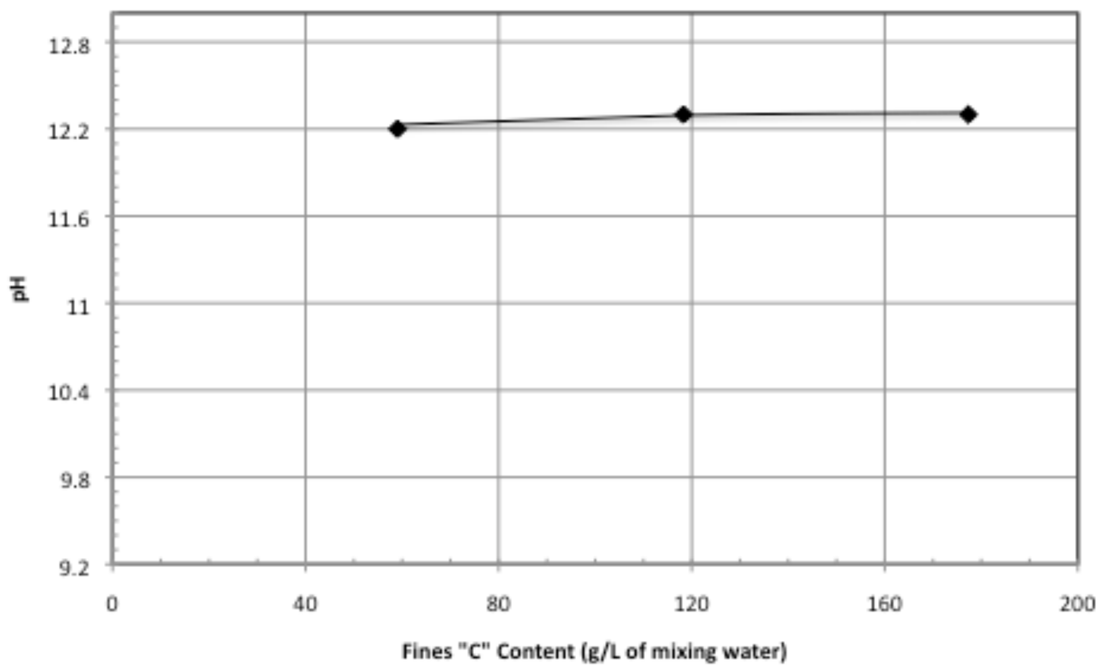

Figure 3. pH vs. Fines "C" Content

3.2 Strength Analysis

Once the compressive strength testing for 3-day and 28-day specimens was completed, the average strength values for each type of recycled fines were plotted on individual graphs of compressive strength versus percent fines content. All of the fines types produced 3-day strength values that were higher than the control mixtures with no recycled concrete fines. There were only a few 28-day strengths that were below the control mixture strengths and the largest decrease in strength was only 8 percent. These graphs were used to determine the fines percentage that produced the highest 3-day strength while also maintaining a strong 28-day strength. This fines percentage was designated as the optimal fines percentage. The optimal fines percentage was determined for each fines types and slag level that was tested. Figure 4 shows compressive strength versus recycled fines content for Fine Type A. This figure shows that a fines content of about 5 percent is the optimal fines percentage based on the peaks in the curves for both 3-day and 28-day strength.

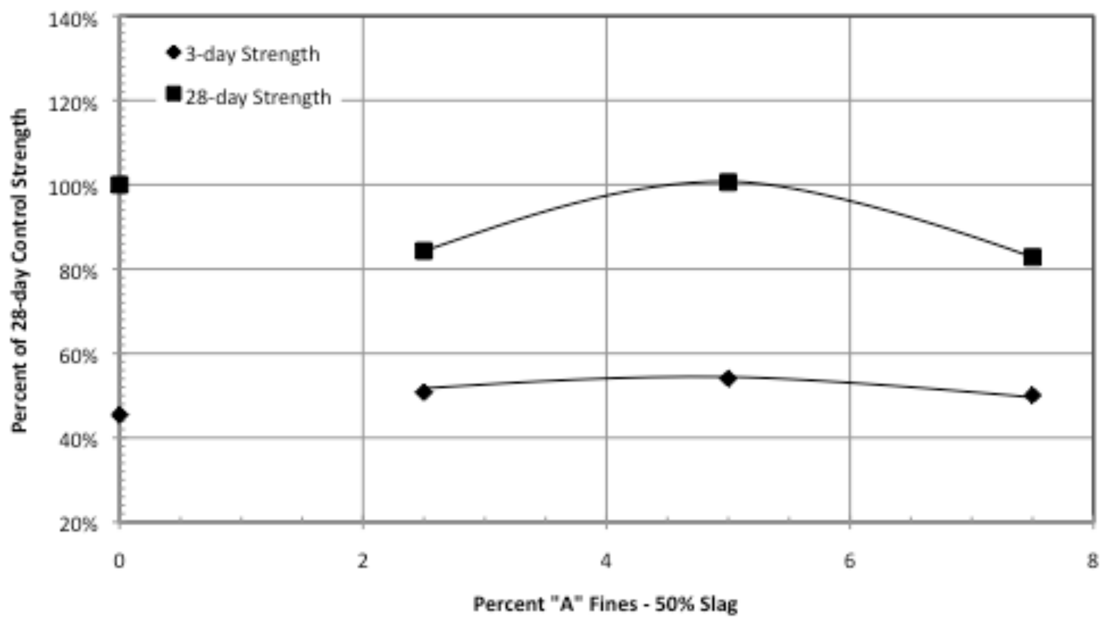

Figure 4. Compresive Strength vs. Percent "A" Fines – 50% Slag

Several of the recycled fines had optimal fines percentages on the upper or lower bounds of the percentages tested. When this was the case, further laboratory testing was performed in order to ensure the appropriate optimal fines percentage was determined. The recycled fines percentage boundaries were extended to 1.25 percent as the lower bound and 10 percent as the upper bound. During initial testing, Fine Type C displayed an optimum fines percentage of 2.5 percent; therefore additional testing at a level of 1.25 percent was performed. The compressive strength values for each fine percentage for Fine Type C are displayed in Figure 5 below. It can be seen from this figure that from the additional laboratory testing at

1.25 percent showed a decrease in strength at this percentage and therefore confirmed the optimum fines percentage as 2.5 percent.

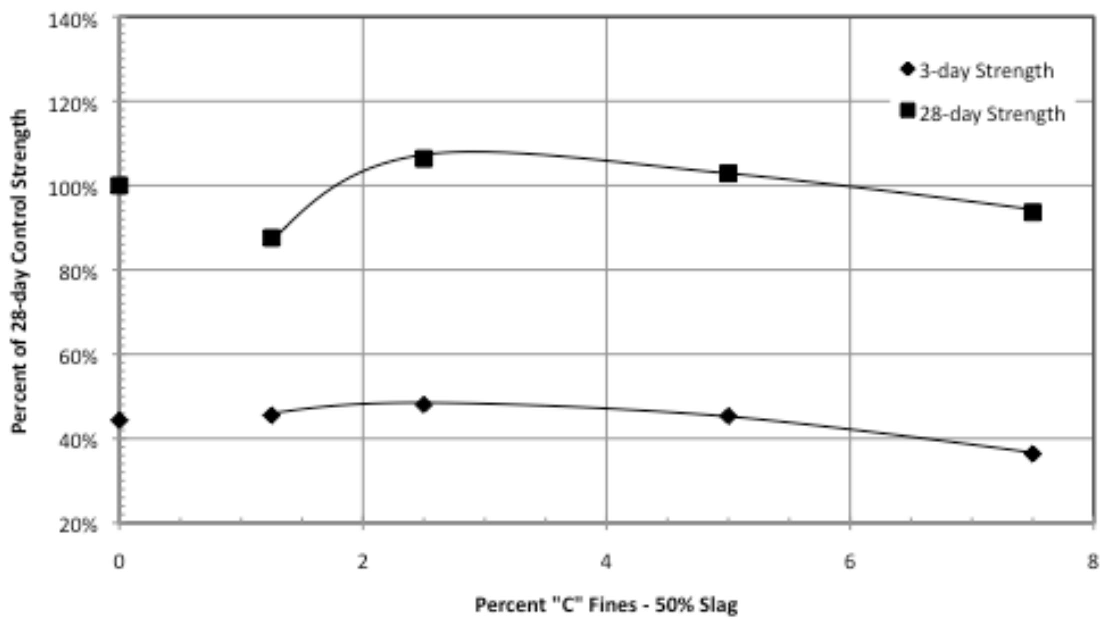

Figure 5. Compressive Strength vs. Percent "C" Fines – 50% Slag

The optimal fines contents for all fine types and slag levels are summarized in tables 1, 2 and 3. Fine type G, which is the fines source in liquid (un-dried) form, was only tested at the 50% slag level because of the difficulty in handling of the fines. There could also be some variability in the optimal fines content for fine type G due to possible settlement of larger solid particles during laboratory testing. Therefore, fine type G is not included in the regression analysis described in Section 3.

Table 1. Optimal Recycled Fines Contents, 50% Slag

Fines Type	50% Slag Optimum Fines %	Percent Increase in Strength versus Control (3-day)	Percent Increase in Strength versus Control (28-day)
A	5.0%	19%	1%
B	7.5%	19%	11%
C	2.5%	8%	6%
D	2.5%	10%	3%
E	2.5%	6%	8%
F	2.5%	8%	0%
G	7.5%	11%	-2%
H	5.0%	8%	-2%

Table 2. Optimal Recycled Fines Contents, 37.5% Slag

Fines Type	37.5% Slag Optimum Fines %	Percent Increase in Strength versus Control (3-day)	Percent Increase in Strength versus Control (28-day)
A	5.0%	5%	9%
B	7.5%	2%	4%
C	2.5%	12%	-6%
D	2.5%	4%	6%
E	5.0%	24%	28%
F	2.5%	19%	21%
G			
H	5.0%	14%	21%

Table 3. Optimal Recycled Fines Contents, 25% Slag

Fines Type	25% Slag Optimum Fines %	Percent Increase in Strength versus Control (3-day)	Percent Increase in Strength versus Control (28-day)
A	5.0%	0%	4%
B	2.5%	18%	16%
C	1.3%	57%	18%
D	5.0%	12%	21%
E	5.0%	6%	-8%
F	5.0%	8%	9%
G			
H	7.5%	4%	16%

3.3 Regression Analysis

The ability to correctly predict how a certain type of fines was affecting strength gain was an integral part of the research. Initially, measurements of the IR and conductivity were taken to quantify the amount of reactive material (both dissolved and undissolved ions). These values would then be used to perform single and multi-variable regressions to determine if these measurements were correctly predicting strength gain. After several laboratory tests, it was decided that pH should also be used as a unit of measure. The IR values were not yielding a wide range of values for the different fines. Measuring pH was another way to further measure the ions present, especially ions, which could have an accelerating effect on the cement hydration reaction.

The regression analysis examined each of the three measurements as a single parameter of strength gain, then a two-variable parameter of measurements, and finally as a combination of all three measurements.

3.3.1 Single Parameter Analysis, 37.5% Slag Mixtures

The single parameter regression analysis primarily identified what type of regression equation best fit the data. The data used to generate the regression equations were the optimal fines percentages for each of the three different slag percentages at 3-day strength, as described above in Section 3.2. This resulted in seven data points: one each for fines A-F and one for fine H. Not enough data was available for fine G to include in the regression analysis. Figure 6 below shows the regression of strength versus pH for the 37.5% slag percentage. The optimal fines strengths were normalized against the control cube strengths, and then plotted against the pH measurements. The accuracy of the regression equation for the resulting plot was low. Analyzing the graph, fines type E and F were identified as outliers that diminished the predictive accuracy. Figure 7 shows the same plot as Figure 6 with fines types E and F identified as outliers. As the regression equation shows, the predictive accuracy improved dramatically when fines E and F were not used in the analysis jumping from an R^2 value of .0488 to .8801.

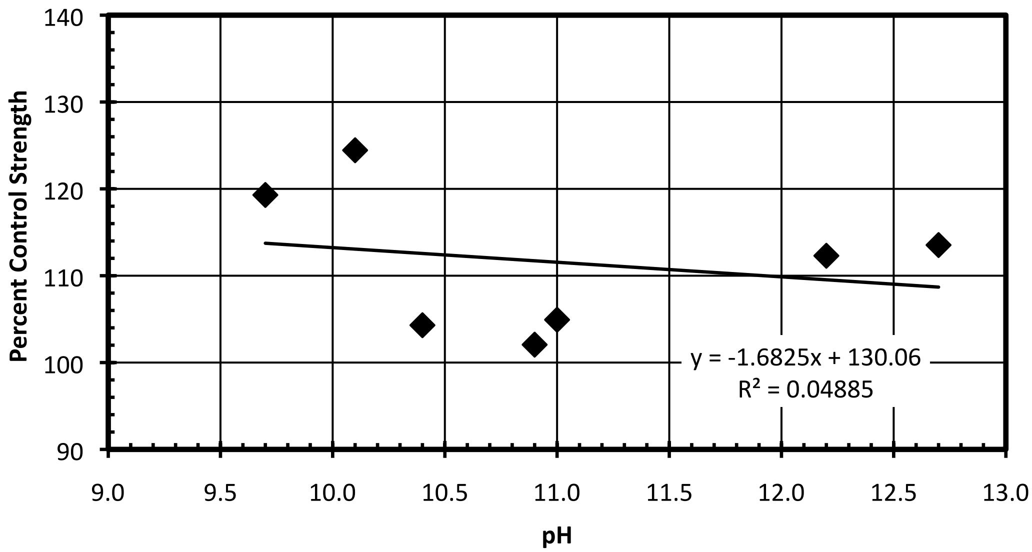

Figure 6 - pH Regression Results 37.5% Slag.

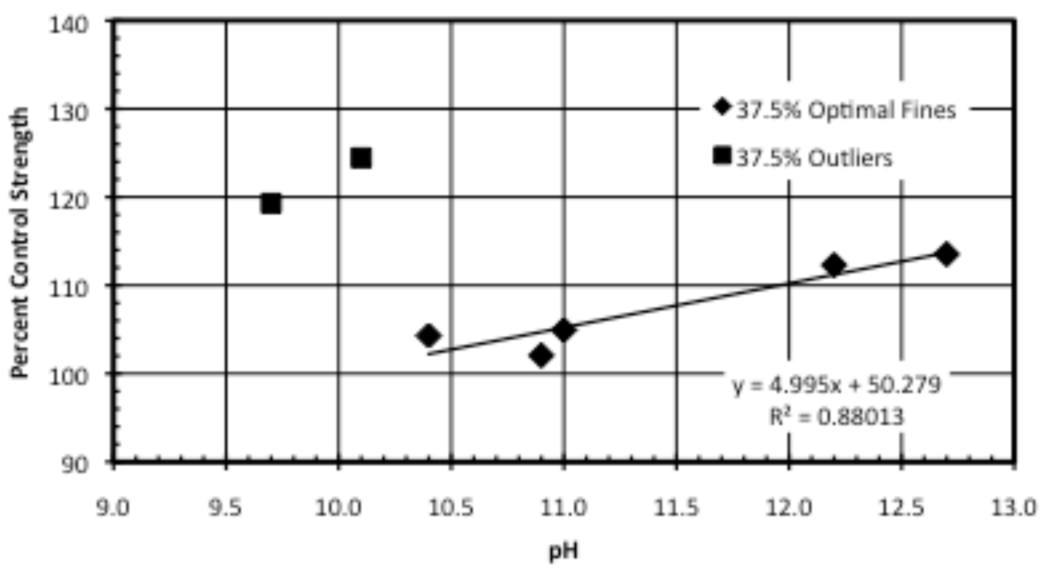

Figure 7. pH Regression Results 37.5% Slag with Outliers Identified.

A similar approach was taken for examining the conductivity results. Initially it was thought that a linear trend line, similar to the pH plot, would best approximate the impact of conductivity on strength gain; however as Figure 8 shows, a cubic trend line best fit the data. Note that for conductivity measurements, fines types E and F do not appear as outliers. This suggests that Fines E and F, while having higher amounts of dissolved ions (hence the higher conductivity values), do not necessarily include many hydroxyl ions among the dissolved ions. As conductivity increased, 3-

day strength increased against the control values. Past 2.00 millisiemens, the strength began to decrease, yet still was above the control value.

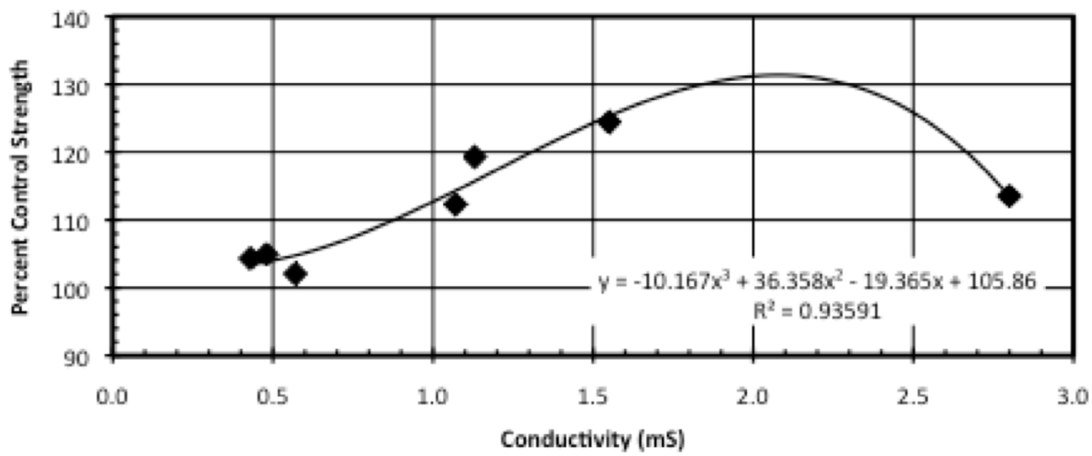

Figure 8. Conductivity Regression Results for 37.5% Slag

The final measurement taken was IR. Linear, parabolic, and cubic trend lines were all used on the data with a cubic equation resulting in the best fit. Figure 9 plots the IR values vs. Percent Control Strength capturing the increase in strength as IR increased and then the decrease in strength past 1.3344.

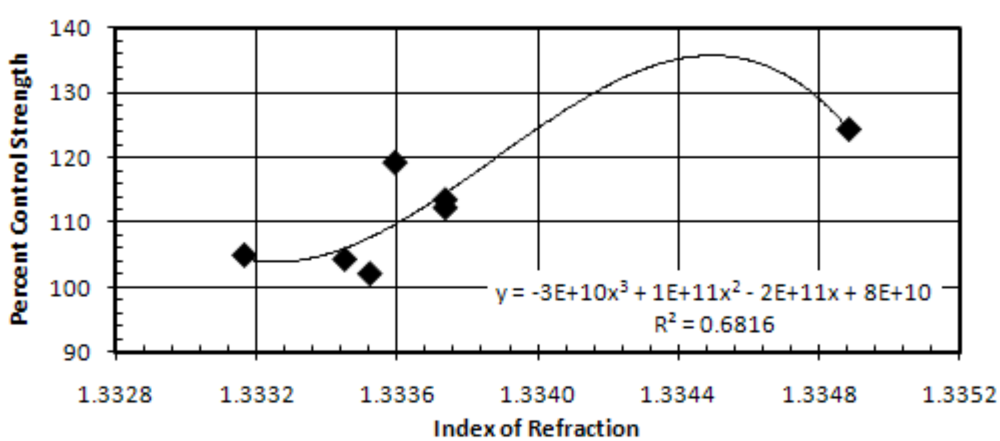

Figure 9. IR Regression Results for 37.5% Slag.

Of all three measurements, the lowest R^2 value was for the IR data. Table 4 summarizes the statistical data provided from the analysis for the three measurements. This table also includes the values for se(y), which is the standard error of the prediction of the percent of control strength.

Table 4 - Stastistical Summary of Single Parameter Analysis.

MEASUREMENT	EQUATION	R^2	SE(Y)
PH (WITH E,F)	Y = -1.68(PH) + 130.06	0.049	8.91
PH (NO E,F)	Y = 5.00(PH) + 50.28	0.880	2.06
CONDUCTIVITY	$Y = -10.17(COND.)^3 + 36.36(COND.)^2 - 19.37(COND.) + 105.86$	0.934	2.98
IR	$Y = -3x^{10}10(IR)^3 + 1x10^{11}(IR)^2 - 2x10^{11}(IR) + 8x10^{10}$	0.623	5.61

Once the best equation forms for correlating percent strength gain to the individual parameters was determined, a better model could be built using combinations of the parameters to obtain more accurate results.

3.3.2 Two-Parameter Analysis, 37.5% Slag Mixtures

The results from the single parameter analysis indicated that merely using one of the measurements to predict strength gain did not fully capture the impact of the fines. Combining the measurements therefore could give a more accurate prediction of strength.

Three different combinations of measurements were used to determine which best predicted the increase in strength over the control cubes. The three different combinations: pH and IR; pH and conductivity; and IR and conductivity provided more accurate regression equations than the single parameter models. Given the accuracy of the PH and conductivity single parameter models it was thought that combining the two would result in a more accurate prediction of strength. Figure 10 shows the plot of Percent Predicted Strength vs. Percent Actual Strength for the two measurements. The data used was the same seven optimal fines percentages for

37.5% slag replacement. The graph shows an accurate prediction of percent of control vs. actual strength recorded.

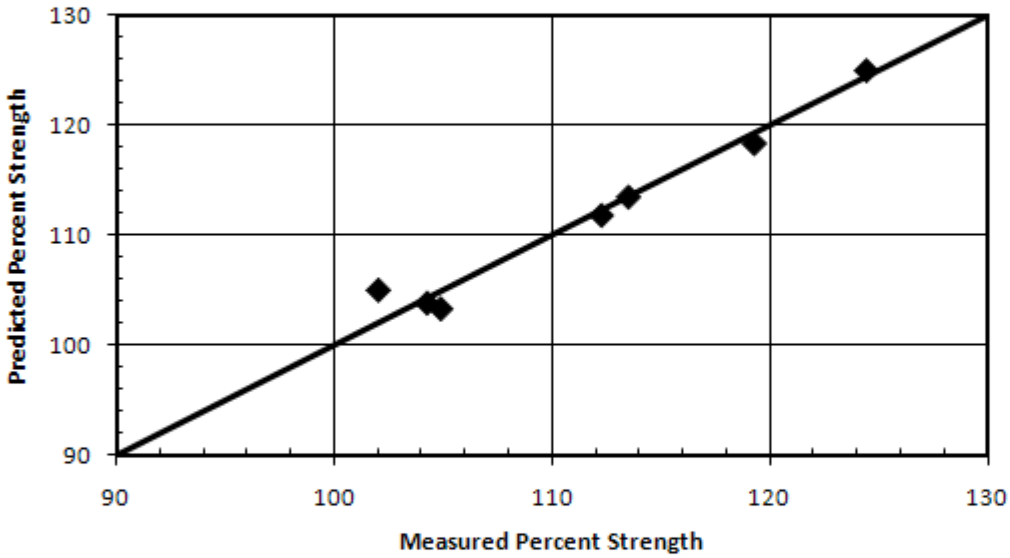

Figure 10 - pH + Conductivity Regression Results for 37.5% Slag.

The next combination of parameters was pH and IR. The results presented in Figure 11 are not nearly as good as the previous combination of pH and conductivity. Percent strength gains for fines type B, D, and F are not predicted as accurately as the previous combination of pH and conductivity.

The final two-parameter regression analysis utilized both conductivity and IR measurements for the 37.5% slag optimal fines. These results presented in Figure 12 show an accurate prediction model that is better than the combination of pH and IR and also slightly better than the pH and conductivity model.

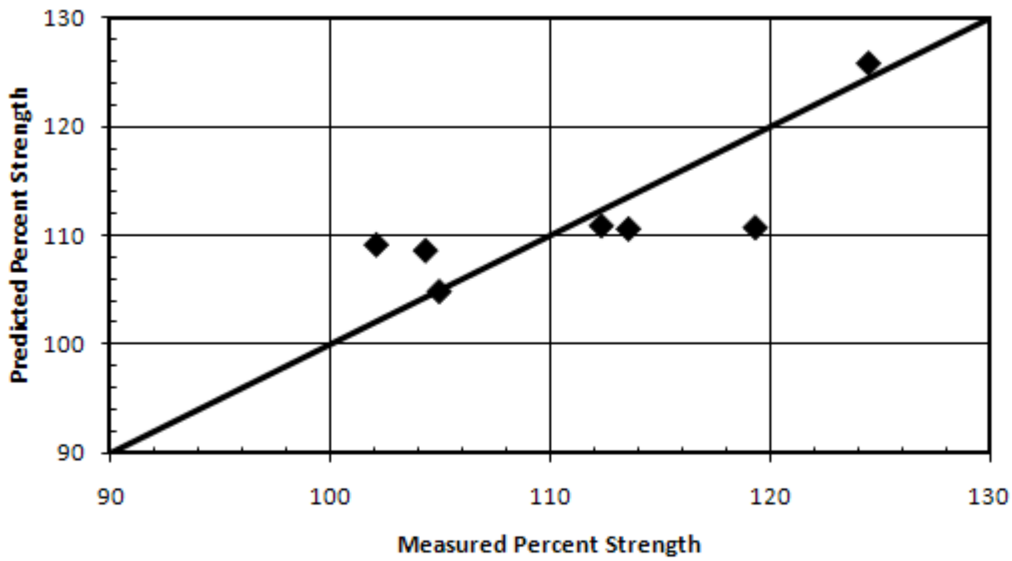

Figure 11 - pH + IR Regression Results for 37.5% Slag.

Table 5 below summarizes the statistical results for the combination of two-parameters. As the table shows, the pH + IR combination was not nearly as accurate as the pH + Conductivity and Conductivity + IR combinations.

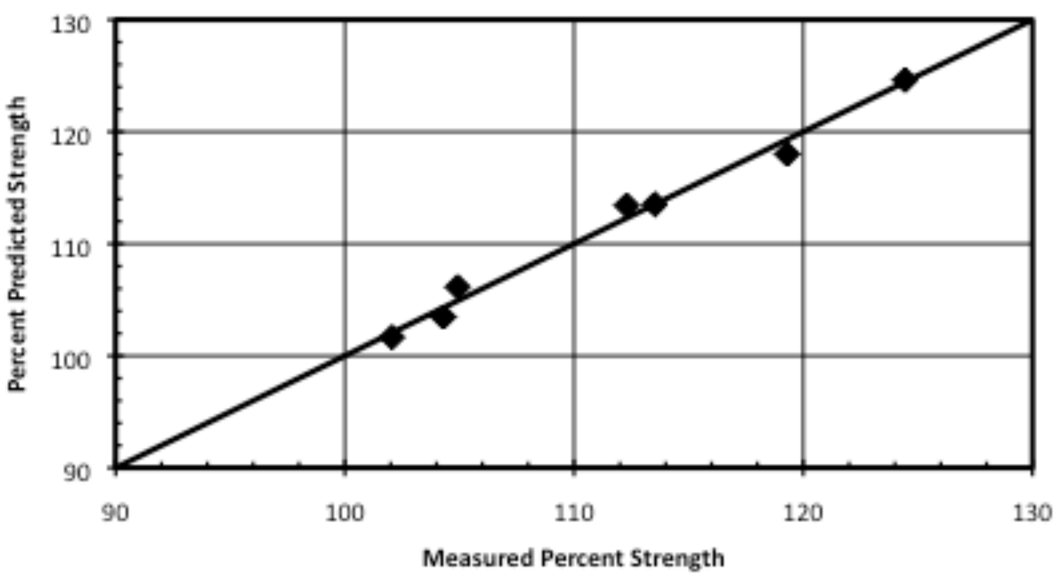

Figure 12 - IR + Conductivity Regression Results for 37.5% Slag.

Table 5 - Statistical Summary of Two-Parameter Analysis

Measurement	Equation	R^2	se(y)
pH + Conductivity	$y = -2.15(pH) - 5.42(Cond.)^3 + 16.15(Cond.)^2 + 4.01(Cond.) + 121.89$	0.969	2.54
pH + IR	$y = -.61(pH) + 2210.73(IR)^3 - 5126.65$	0.629	6.22
Conductivity + IR	$y = -2193.31(IR)^3 - 28.83(Cond.)^3 + 115.24(Cond.)^2 - 100.45(Cond.) + 5327.95$	0.987	1.62

Table 5 also includes the standard error of the prediction for each combination. Conductivity + IR had the lowest standard error at 1.62 along with its R^2 of .987. The final step to the regression analysis is combining all three measurements to determine if an even better model than the two-parameter combinations is possible.

3.3.3 Three-Parameter Analysis, 37.5% Slag Mixtures

The final model to consider was one that took all three measurements and combined them into one equation that accurately predicts the strength gain of concrete containing recycled concrete fines. Using measurements of pH, conductivity, and IR for a certain slag percentage would ideally be able to very accurately predict the performance of the concrete. Figure 13 plots the predicted vs. actual strength using all three parameters.

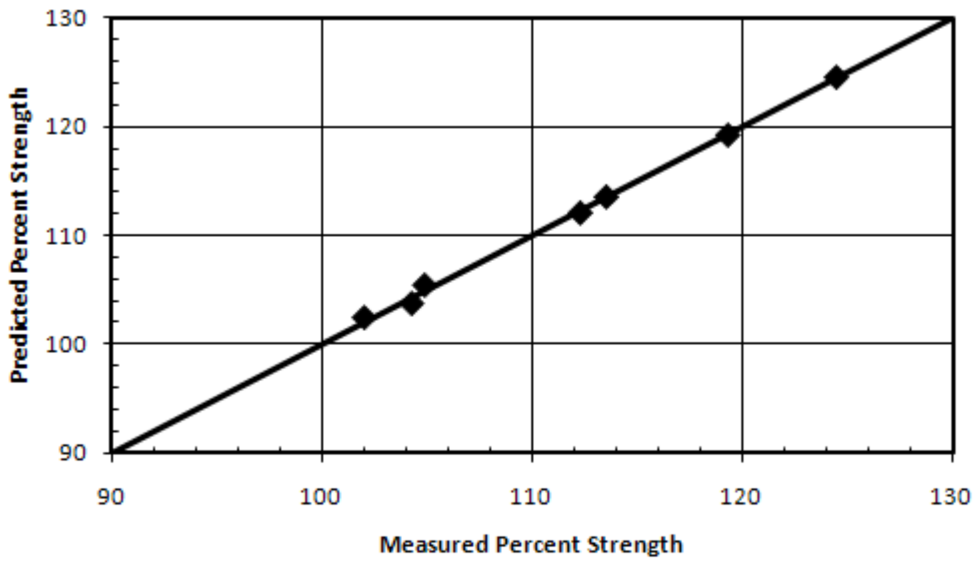

Figure 13 - Three-Parameter Regression Analysis of 37.5% Slag.

Not surprisingly, using all three parameters generates an equation with all seven optimal fines percentages falling close to the line of equity. Table 6 below summarizes the regression equation and statistical data for the three-parameter analysis. The R^2 value for this combination was .998 and was the highest of any combination of parameters. As Figure 13 shows, all seven optimal fines points lie nearly on top of the line of equity indicating a high predictive power for the 37.5% slag replacement.

Table 6 - 3-Parameter Regression Analysis for 37.5% Slag.

Measurement	Equation	R^2	SE(Y)
pH + Conductivity + IR	$Y = -1.33(pH) - 1782.3(Cond.)^3 - 22.40(IR)^3 + 87.96(IR)^2 - 70.78(IR) + 4359.2$	0.998	0.87

For the individual parameters influence on the 3-Day strength gain of the concrete, the pH graph had the most noticeable outliers from the data collected. Those outliers, shown in Figure 7, were clearly not a part of the linear trend the rest of the data indicated. The conductivity and IR measurements did not have any clear outliers. This indicated that the predictive power of these individual parameters were very good. Thus, it made sense that Figure 12 showed a very accurate graph of predicted vs. actual strength for the two parameters that individually had no clear outliers.

3.3.4 Analysis of 25 % and 50% Slag Mixtures

For the other slag percentages, the accuracy of the modeling did not initially appear as good as the 37.5% slag percentages. The single-parameter models generally looked very poor. Removing outliers improved the accuracy, but still did not resolve all of the problems. There was still considerable scatter and further testing would need to be conducted to determine the source of diminished accuracy. Fines type A for 25.0% slag was a consistent outlier that, when removed, increased the R^2 value for the regression analyses by an order of magnitude (and reduced the se(y) in half) for the single parameter pH analysis. Using two-parameter models (specifically the IR plus conductivity), however, increased the accuracy to approximately the same as that for the 37.5% slag. Table 8 below summarizes the statistical results for the 25.0% slag regression analyses. These analyses were conducted in the same manner as the 37.5% analyses discussed in Sections 3.3.1,2,3.

Table 7 - Statistical Summary for 25% Slag Regression Analysis

Measurement	Equation	R^2	se(y)
Single Parameter			
pH	$y = -1.351(pH) + 122.91$	0.067	6.30
pH (no A)	$y = -1.2576(pH) + 121.39$	0.295	3.15
Conductivity	$y = -7.9149(Cond.)^3 + 43.221(Cond.)^2 - 65.055(Cond.) + 131.98$	0.412	6.45
IR	$y = -3x10^{10}(IR)^3 + 1x10^{11}(IR)^2 - 2x10^{11}(IR) + 7x10^{10}$	0.259	6.27
Two-Parameter			
pH + Conductivity	$y = -.67(pH) - 7.12(Cond.)^3 + 39.56(Cond.)^2 - 60.91(Cond.) + 138.17$	0.416	7.88
pH + IR	$y = -1.24(pH) + -4137816.7(IR)^3 + 8279906.95(IR)^2 - 4911554.8$	0.310	7.00
Conductivity + IR	$Y = -419.84(IR)^3 - 7.04(COND.)^3 + 39.13(COND.)^2 - 60.80(COND.) - 864.58$	0.453	7.62
Conductivity + IR (NO A)	$y = 58.44(IR)^3 - 6.72(Cond.)^3 + 37.80(Cond.)^2 - 60.93(Cond.) - 4.17$	0.995	0.81
Three- Parameter			
pH + Conductivity + IR	$y = -.50(pH) + 413.266(IR)^3 - 6.46(Cond.)^3 + 36.477(Cond.)^2 - 57.79(Cond.) - 844.39$	0.455	10.76

Figures 14 and 15 below present the best two and three-parameter model as represented in the regression equations from Table 7. The best two parameter model was the conductivity + IR without fines type A.

It was surprising that although the single parameter regression equations had low R^2 values that when conductivity and IR were paired together for a two-parameter analysis the R^2 value increased dramatically to 0.995. For the 37.5% regression analyses, the single parameter R^2 values were well above .50, so it seemed consistent that the two-parameter combinations resulted in R^2 values of over .90.

The 25% analyses had only one parameter with a R^2 value above .50, but had equally accurate two-parameter equations as the 37.5% slag percentage.

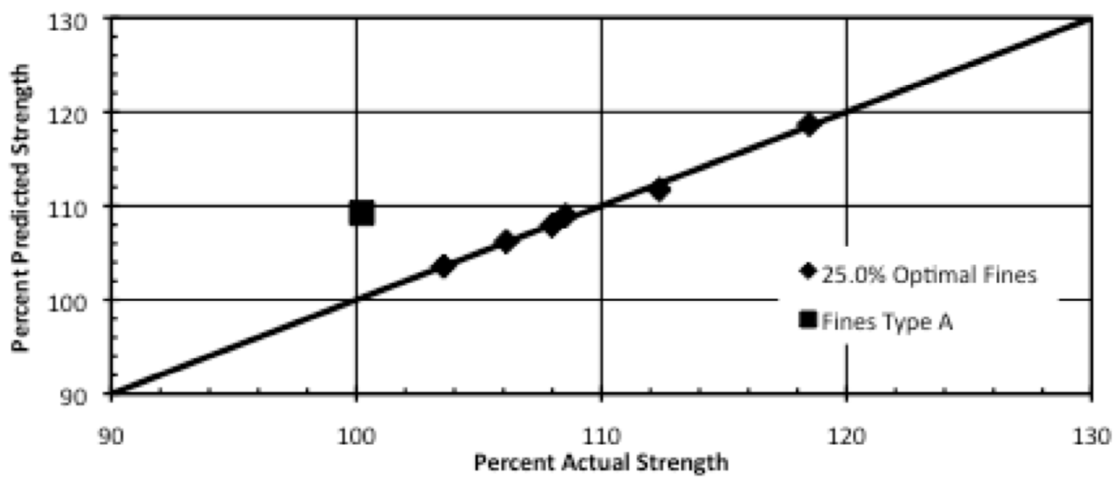

Figure 14 - Conductivity + IR Regression Results Without Type A 25% Slag

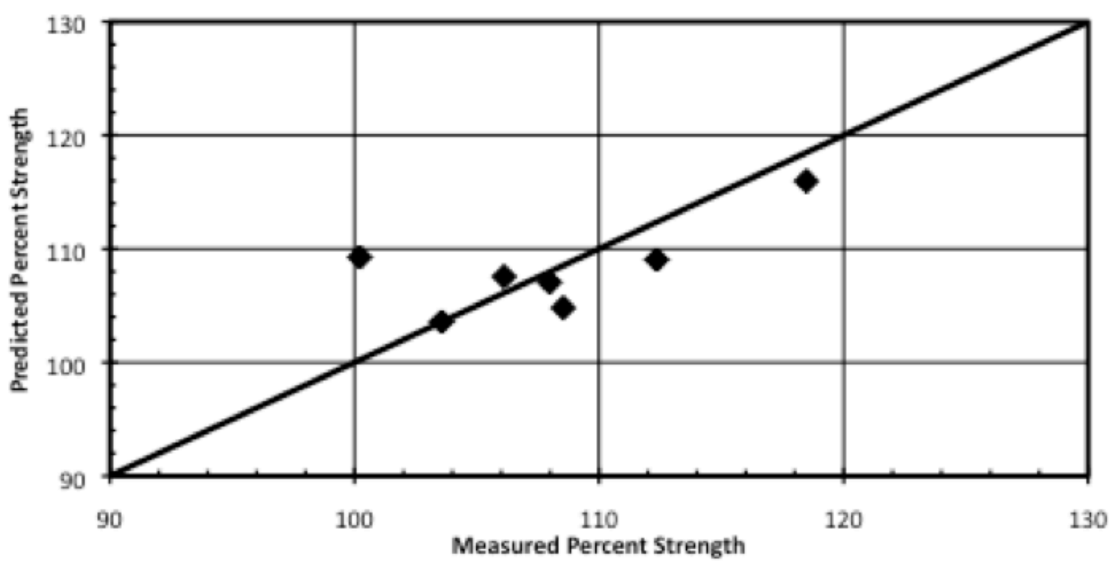

Figure 15 - Three-Parameter Regression Results 25% Slag

The final slag percentage to examine was for 50%. Similarly to the 25% slag percentage, 50% had lower predictive accuracy for the single parameters, but significantly increased accuracy for the two and three-parameter combinations. Unlike the two other slag percentages, 50% saw a pH where strength did not increase linearly with increase in pH, but was rather parabolic in shape. Table 8 below summarizes the statistical information for the 50% slag regression analyses.

Table 8 - Statistical Summary for 50.0% Slag Regression.

MEASUREMENT	EQUATION	R^2	SE(Y)
	SINGLE PARAMETER		
PH	$Y = -4.78(PH)^2 + 107.21(PH) - 484.64$	0.638	4.06
CONDUCTIVITY (PARABOLIC)	$Y = 4.47(COND.)^2 - 17.39(COND.) + 121.94$	0.334	5.51
CONDUCTIVITY (CUBIC)	$Y = -7.91(COND.)^3 + 43.22(COND.)^2 - 65.10(COND.) + 131.98$	0.334	6.37
IR	$Y = -1X10^{11}(IR)^3 + 5X10^{11}(IR)^2 - 7X10^{11}(IR) + 3X10^{11}$	0.187	5.75
	TWO-PARAMETER		
PH + CONDUCTIVITY	$Y = -17.62(PH)^2 + 386.66(PH) - 3.85(COND.)^3 + 10.72(COND.)^2 + 19.56(COND.) - 2014.29$	0.985	1.68
PH + IR	$Y = -4.92(PH)^2 + 110.17(PH) + 241.61(IR)^3 - 1073.13$	0.640	4.68
CONDUCTIVITY + IR	$Y = 1340.03(IR)^3 + 6.45(COND.)^3 - 22.37(COND.)^2 - 8.70(COND.) - 3061.53$	0.370	7.59
CONDUCTIVITY + IR (NO A)	$Y = 4864.03(IR)^3 - 32.16(COND.)^3 - 134.44(COND.)^2 + 133.09(COND.) - 11455.96$	0.694	5.87
	THREE-PARAMETER		
PH + CONDUCTIVITY + IR	$Y = -17.84(PH)^2 + 391.71(PH) - 573.66(IR)^3 - 6.85(COND.)^2 + 41.68(COND.) + 690.43$	0.988	1.50

Fines type A also was a clear outlier when performing a two-parameter analysis on conductivity + IR. When removed from the analysis, the R^2 value increased from .37

to .64 and the standard error went from 7.59 down to 4.68. Yet when performing the three-parameter analysis, type A did not impact the results and a high R^2 value was found. Figures 16 and 17 below present the best two-parameter graph and the three-parameter graph of the 50% slag percentage.

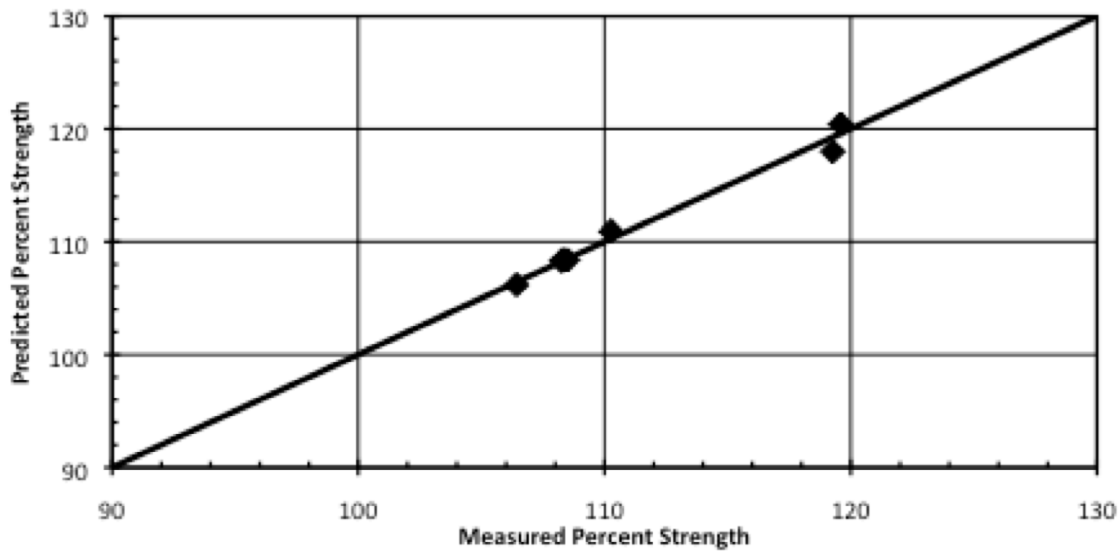

Figure 16. pH + Conductivity Regression Analysis Results for 50% Slag

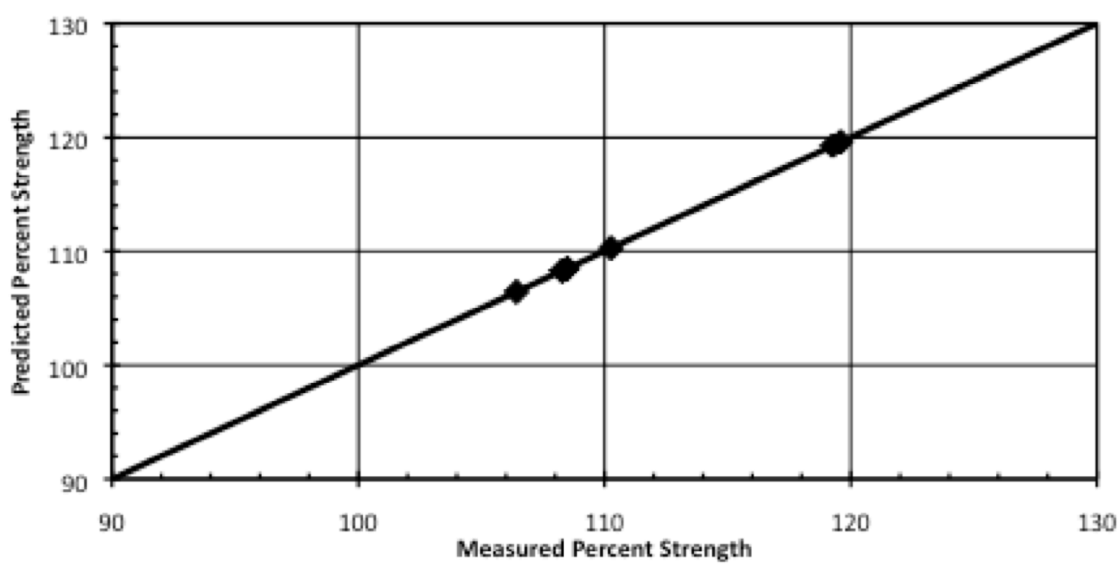

Figure 17 - Three-Parameter Regression Results Analysis for 50% Slag

4.0 Conclusions and Recommendations

4.1 Comparison of Washout and Grinding Fines

The two major sources of recycled concrete fines utilized in the testing were concrete grinding fines and concrete wash-out fines. The concrete wash-out fines contain hydrated and unhydrated cement particles, as well as, dissolved ions, whereas grinding fines may contain a smaller proportion of hydrated cement particles depending on the concrete mixture. Comparing the 3-day and 28-day strength proved that there was no clear advantage between WOF and grinding fines for 50% and 25% slag replacement levels. Within the 37.5% slag replacement level, grinding fines displayed a higher percentage of 3-day strength compared to the WOF. Figure 18 portrays the 3-day compressive strength (at optimal fines percentage) versus fines types for 37.5% slag replacement levels. The WOF are displayed in white while the grinding fines are signified in grey. The grinding fines control three out of the four highest 3-day strengths, while the remaining WOF display much lower early strengths. All fines types resulted in higher 3-day strength compared to the baseline (0% fines) strength (displayed in black).

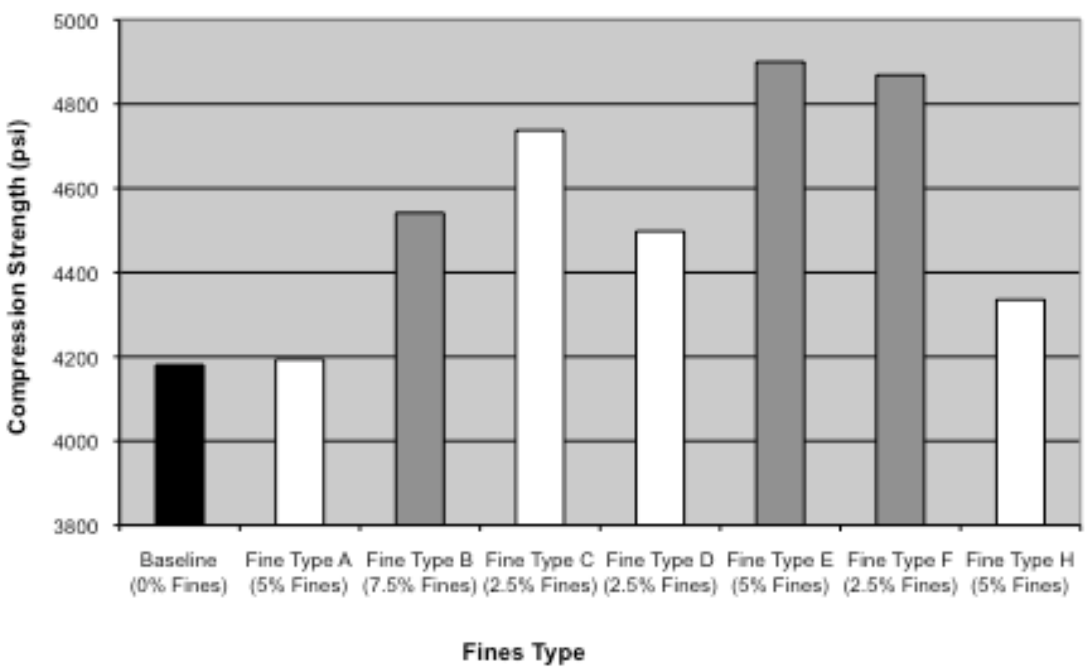

Figure 18. Compressive Strength (3-day) vs. Fines Type - 37.5% Slag

4.2 Regression

The three-parameter regression equations yielded accurate predictions with R^2 values for slag percentages of 37.5 and 50% close to 1.0 and standard errors close to 1.0. 25% slag replacement saw significantly lower predictive accuracy. This stemmed from fine type A being an outlier in the data set. The biggest difference between the slag percentages was the accuracy of the one-parameter regression equations. The 37.5% slag percentages saw a pH and conductivity analyses, adjusted for outliers, which were nearly as accurate as the three-parameter analysis. This did not hold true for either the 25.0% or 50.0% slag percentages with low predictive accuracy for all three measurements. Consequently, multiple tests would need to be performed on the fines solution to have an accurate prediction of the expected percent strength gain versus the control.

More research is needed to identify why fines type A was an outlier for both 25.0 and 50.0% slag percentages and fines type E and F for 37.5%. Additional analysis might also yield useful information on why the fines type E and F were not an outlier for other slag percentages.

4.3 Summary

Various types and sources of recycled concrete fines were shown to have beneficial effects on the early-strengths of Portland cement-slag mixtures (with various slag contents) when used at the optimal fines percentage. Measurements methods that can be made using on-line probes (IR, pH and conductivity) were shown to accurately quantify the fines so that strength improvement predictions can be made.

Further work is needed to expand these results for use with other percentages of slag, as well as other cement-pozzolan combinations.

5.0 References

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6.0 Acknowledgements

The researchers would like to thank Dr. Robert Shogren of LaFarge Northwest for providing the recycled concrete fines and the equipment used for the fines characterization.

7.0 Appendices

7.1 Appendix A: Fines Characterization Graphs

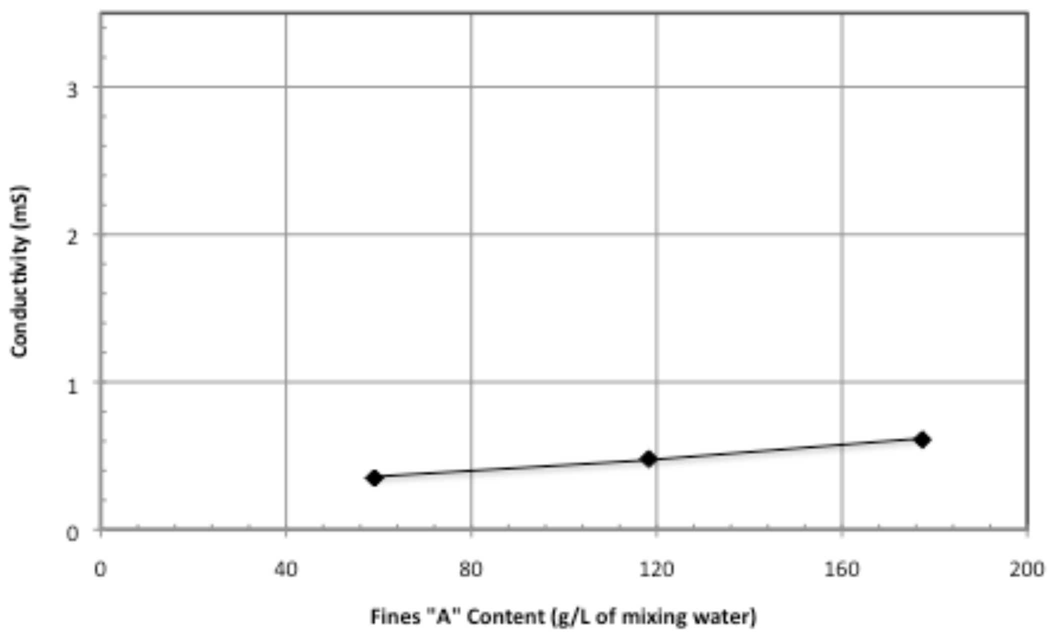

Figure 19. Conductivity vs. Fines "A" Content

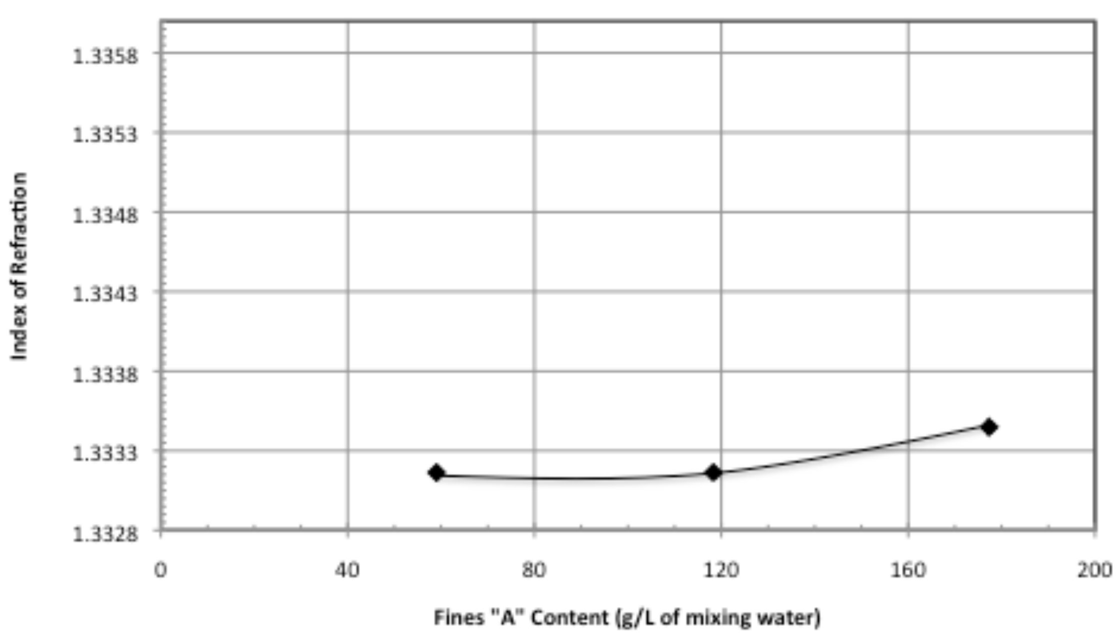

Figure 20. Index of Refraction vs. Fines "A" Content

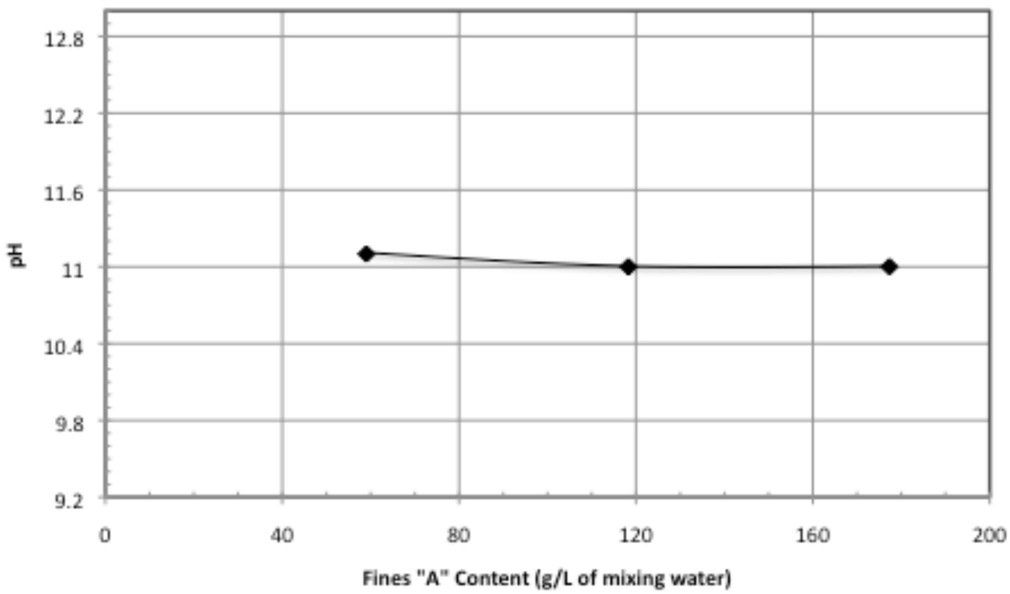

Figure 21. pH vs. Fines "A" Content

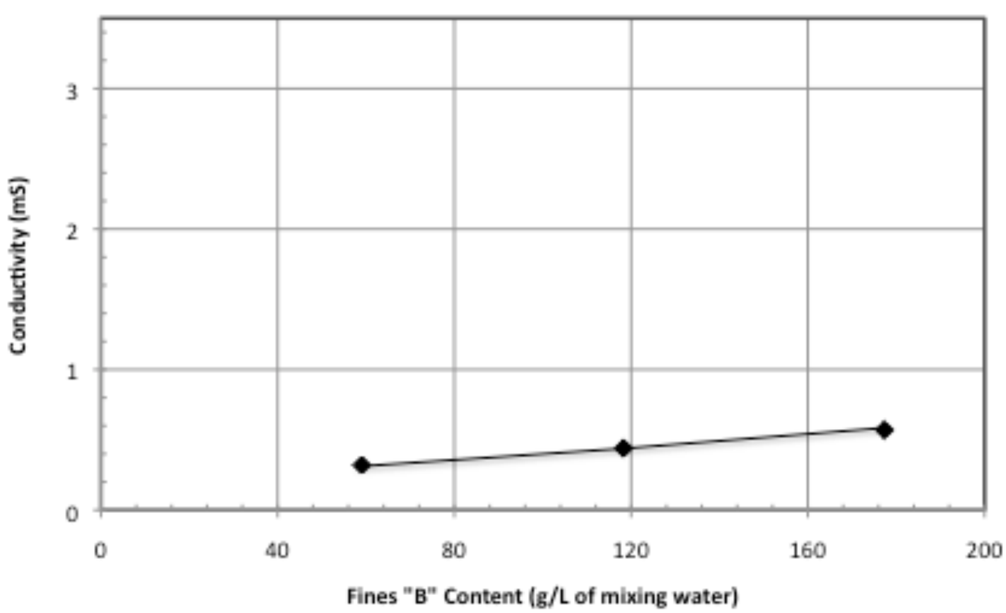

Figure 22. Conductivity vs. Fines "B" Content

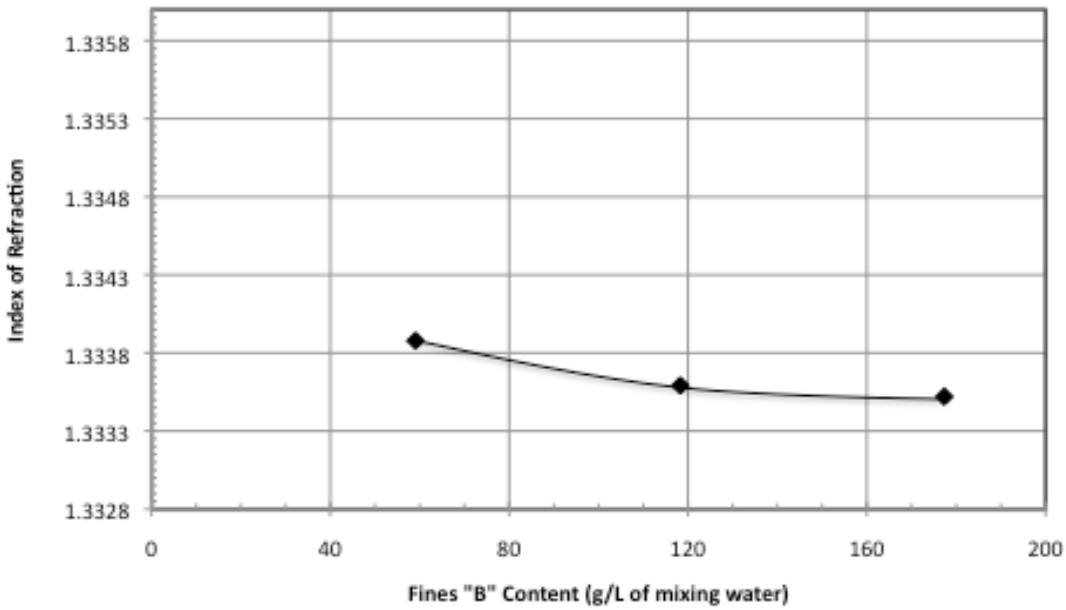

Figure 23. Index of Refraction vs. Fines "B" Content

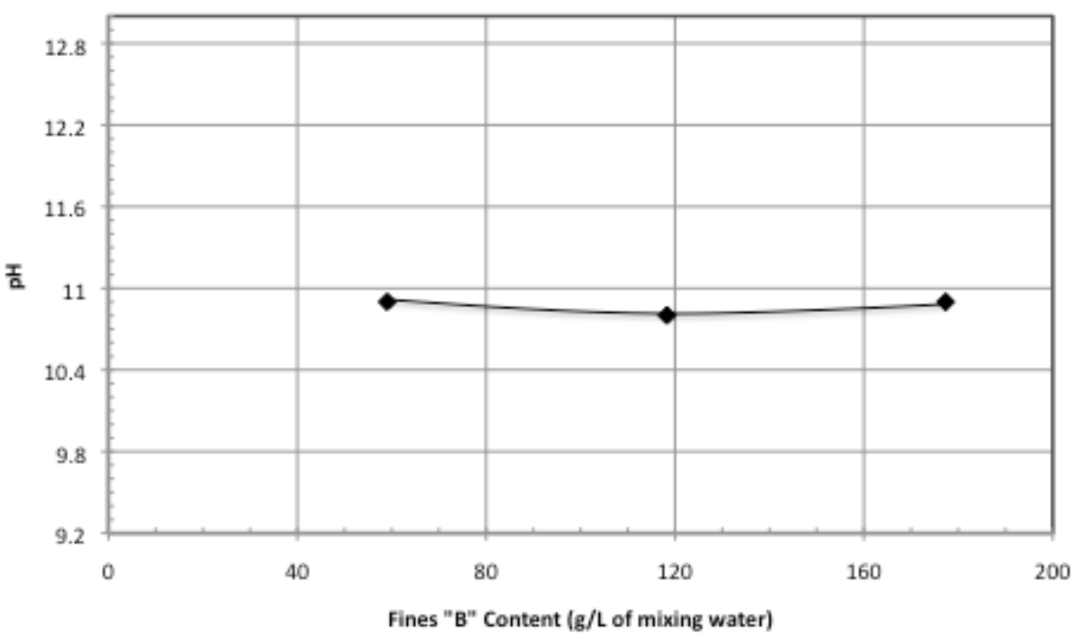

Figure 24. pH vs. Fines "B" Content

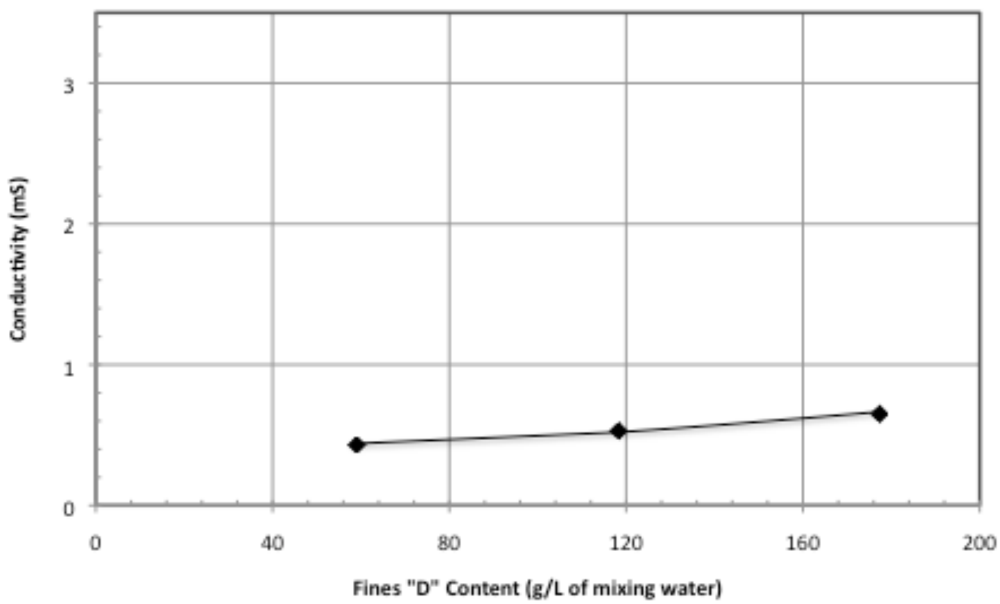

Figure 25. Conductivity vs. Fines "D" Content

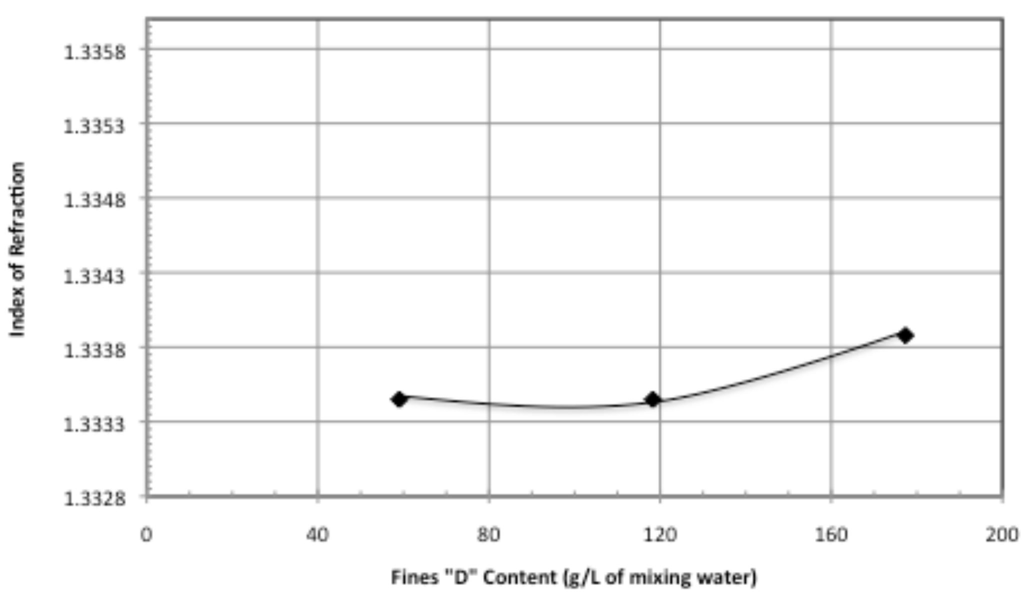

Figure 26. Index of Refraction vs. Fines "D" Content

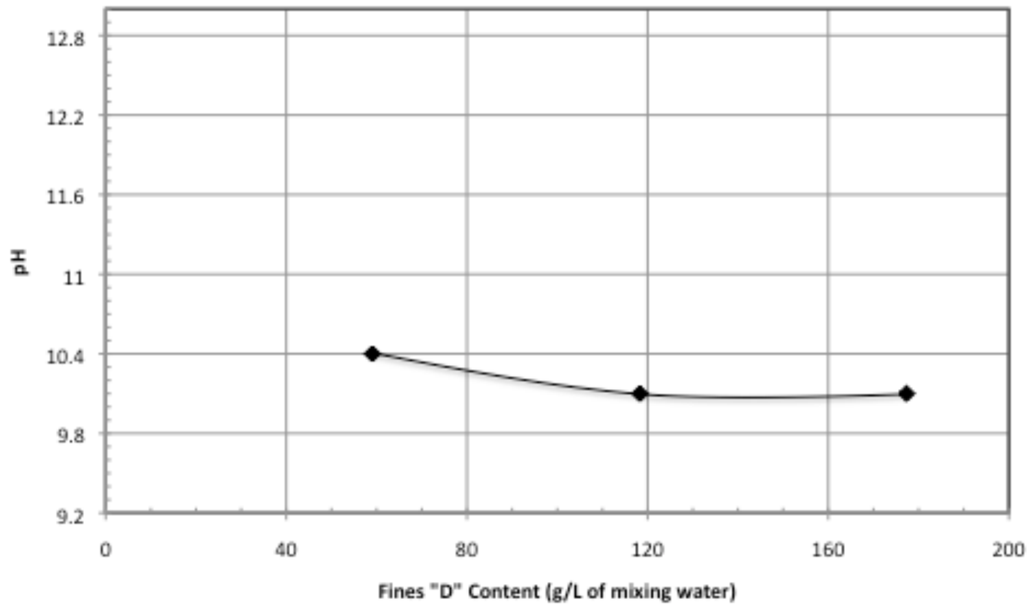

Figure 27. pH vs. Fines "D" Content

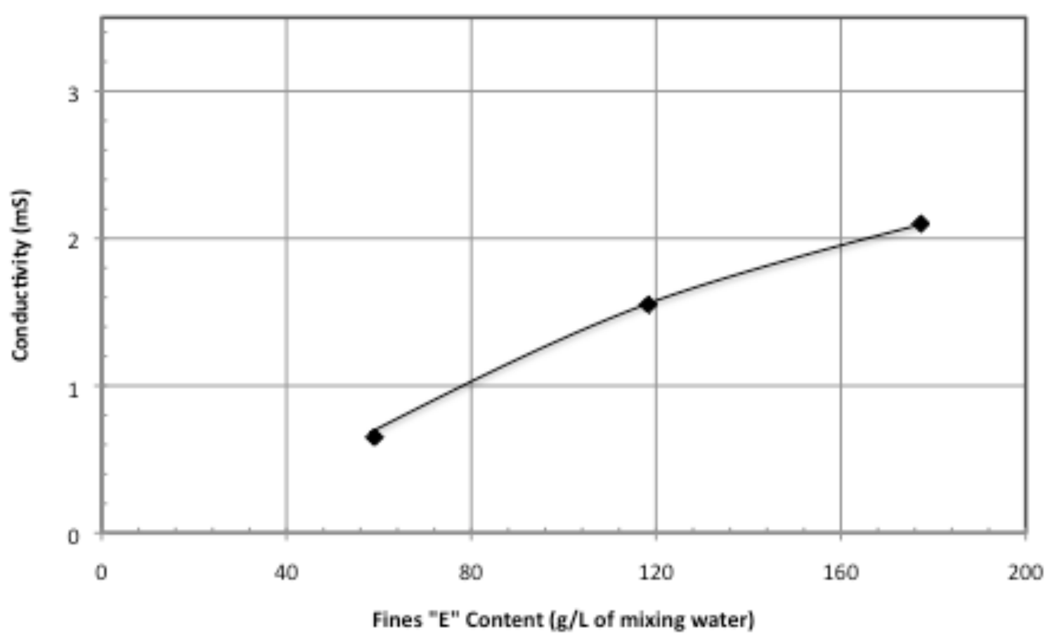

Figure 28. Conductivity vs. Fines "E" Content

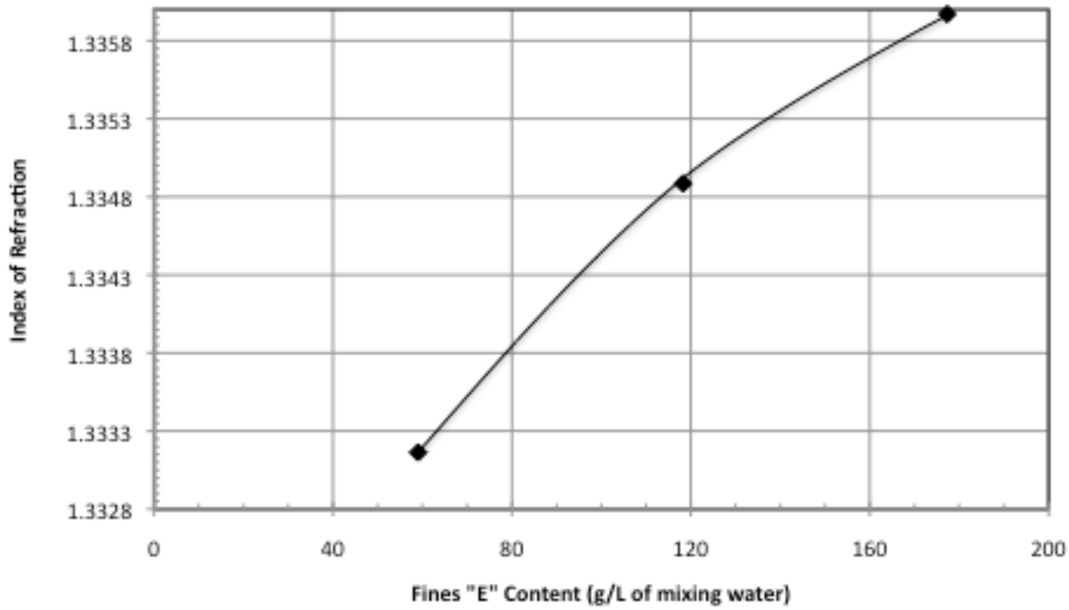

Figure 29. Index of Refraction vs. Fines "E" Content

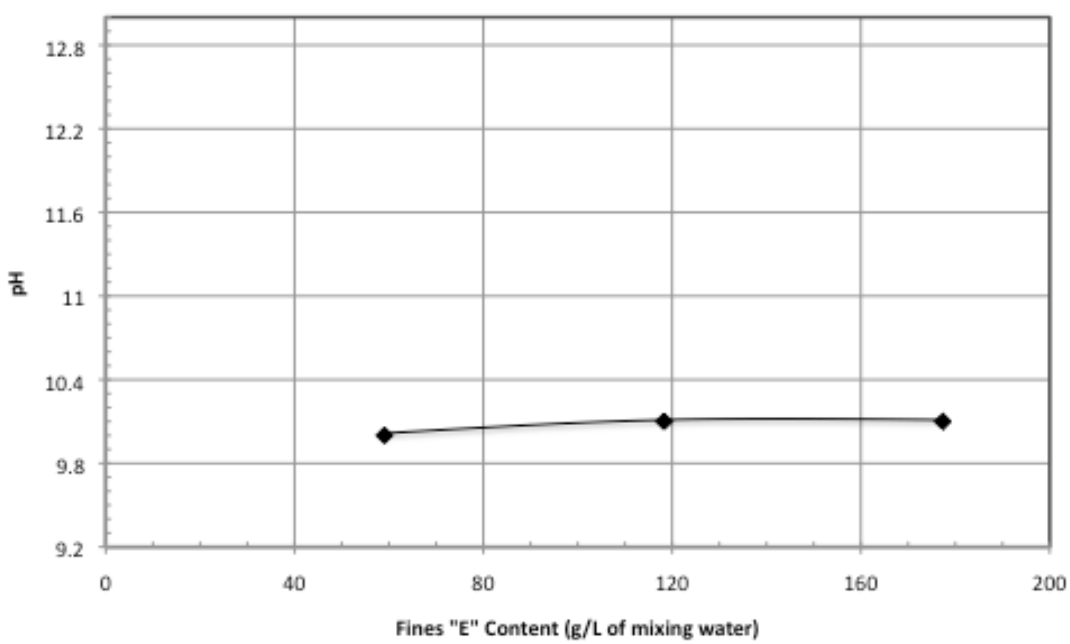

Figure 30. pH vs. Fines "E" Content

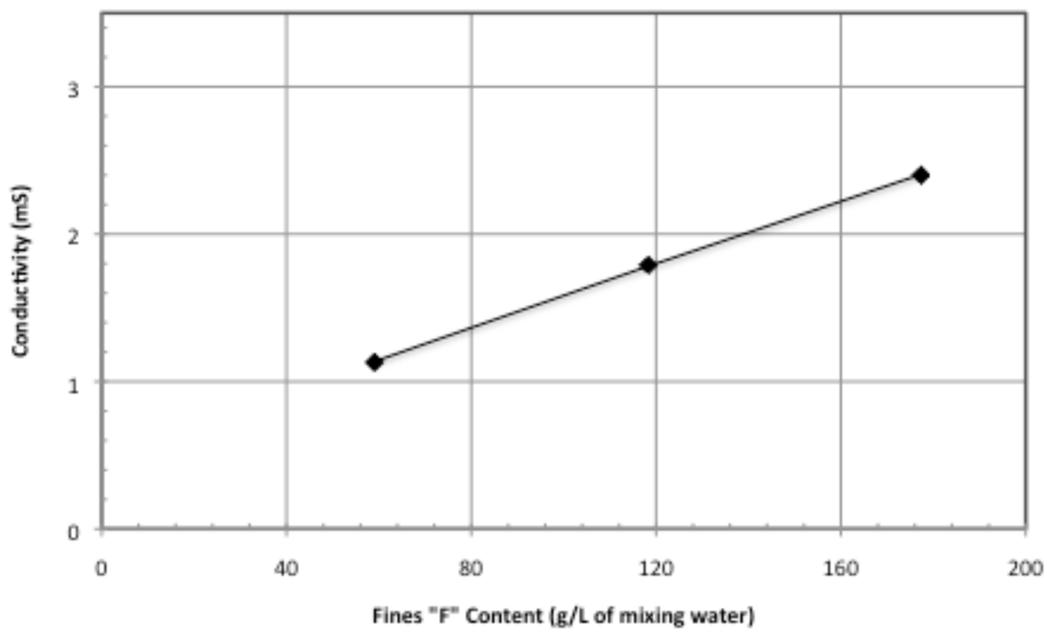

Figure 31. Conductivity vs. Fines "F" Content

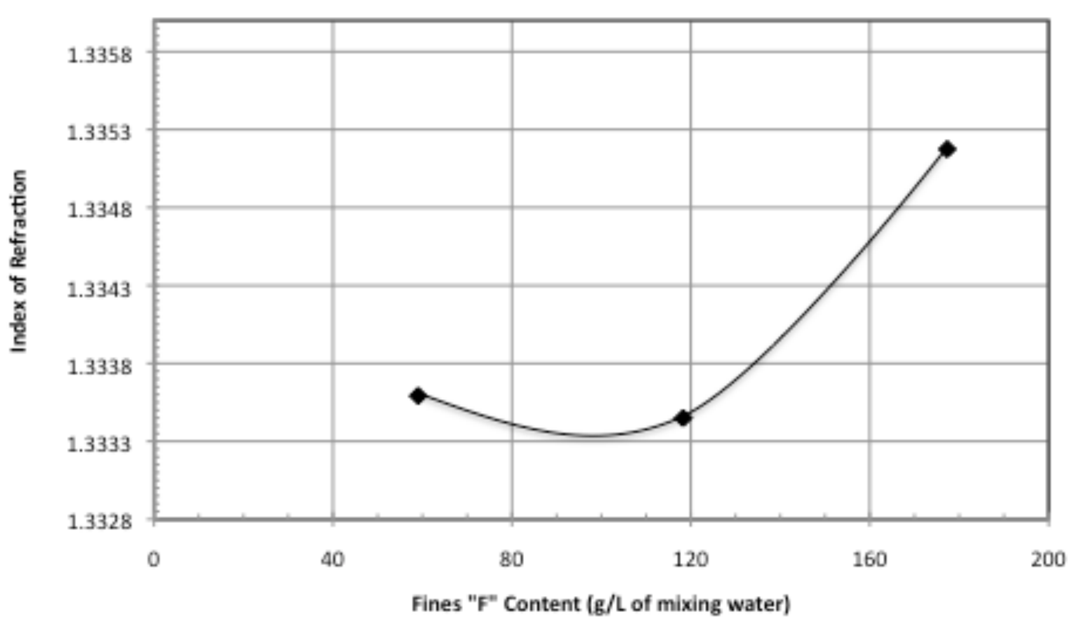

Figure 32. Index of Refraction vs. Fines "F" Content

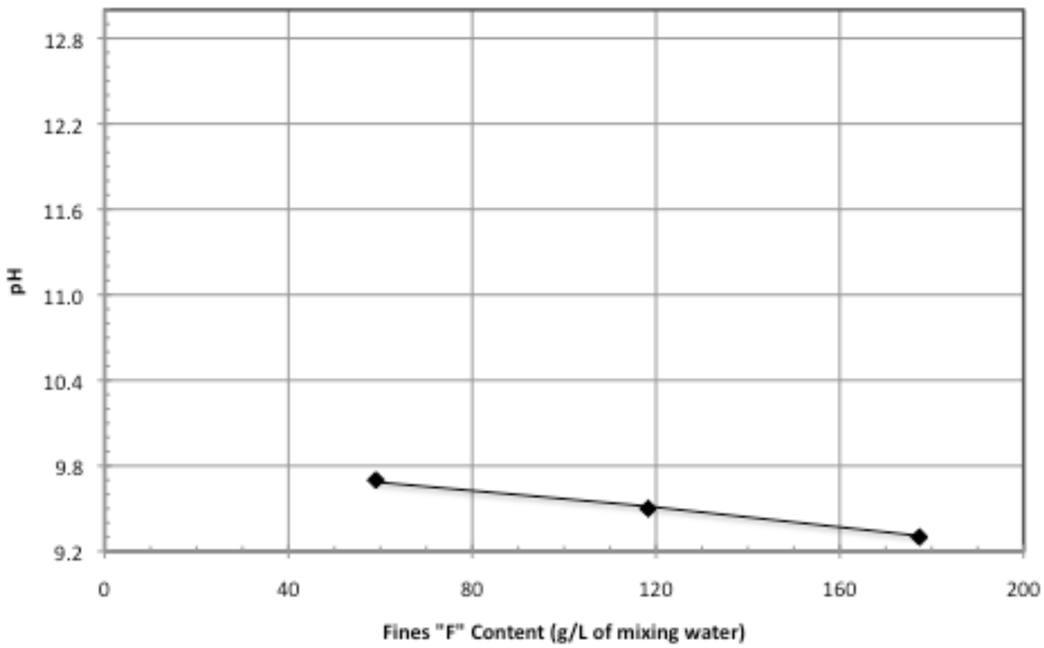

Figure 33. pH vs. Fines "F" Content

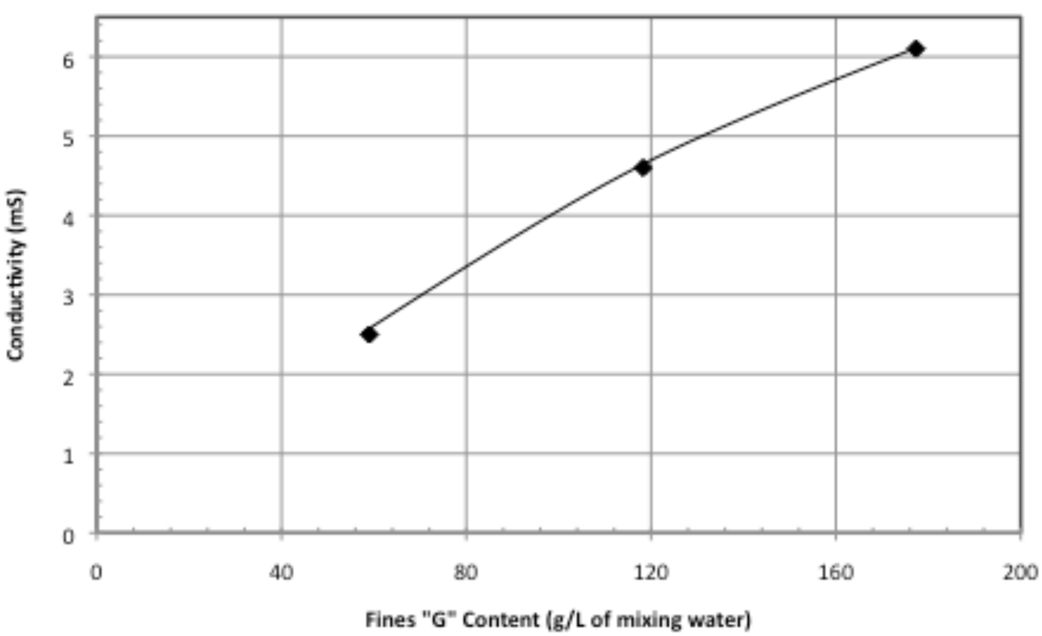

Figure 34. Conductivity vs. Fines "G" Content

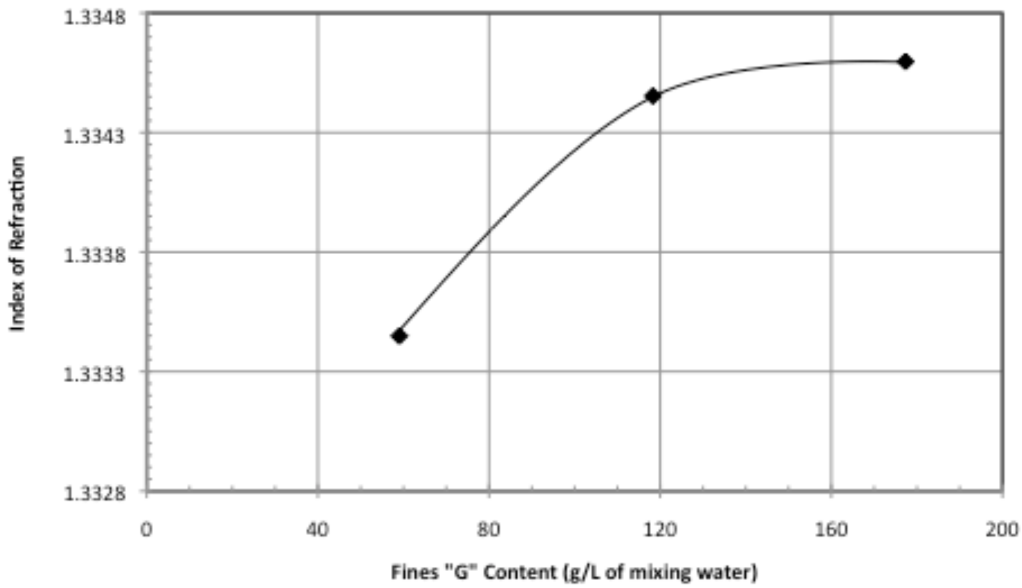

Figure 35. Index of Refraction vs. Fines "G" Content

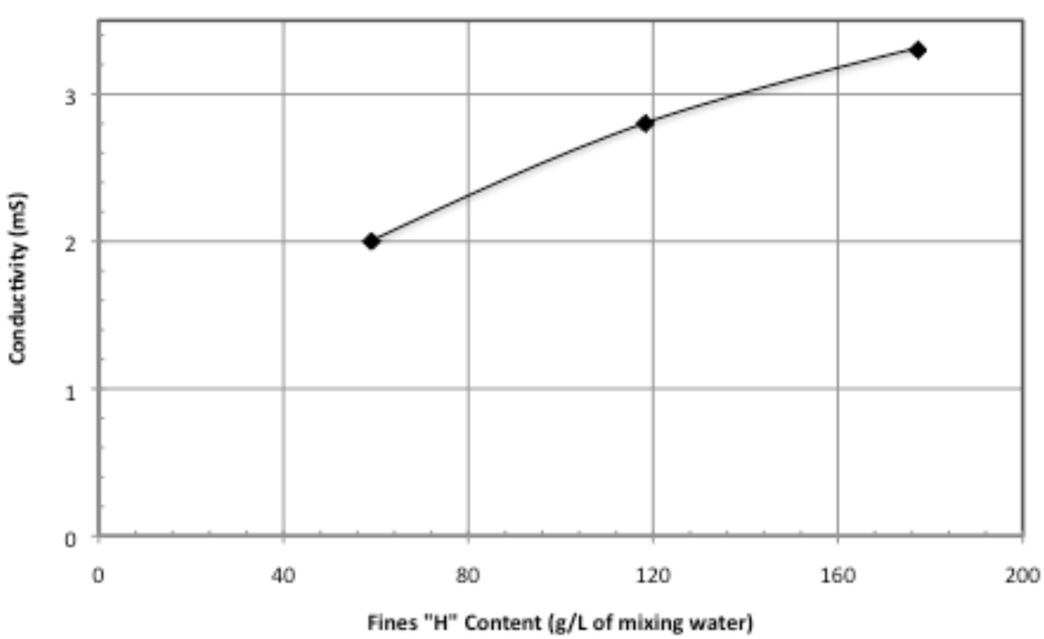

Figure 36. Conductivity vs. Fines "H" Content

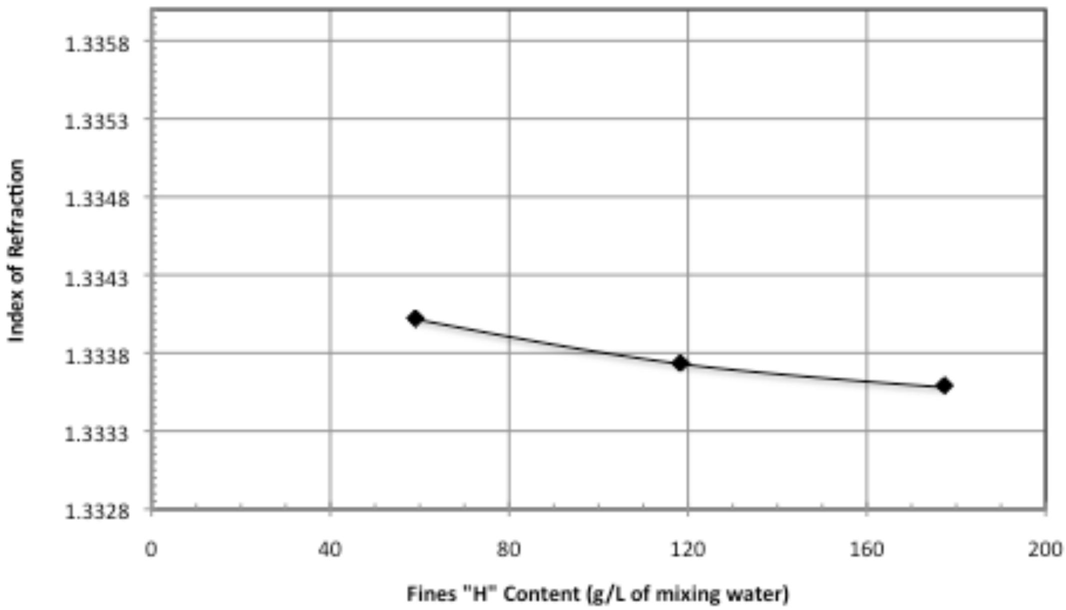

Figure 37. Index of Refraction vs. Fines "H" Content

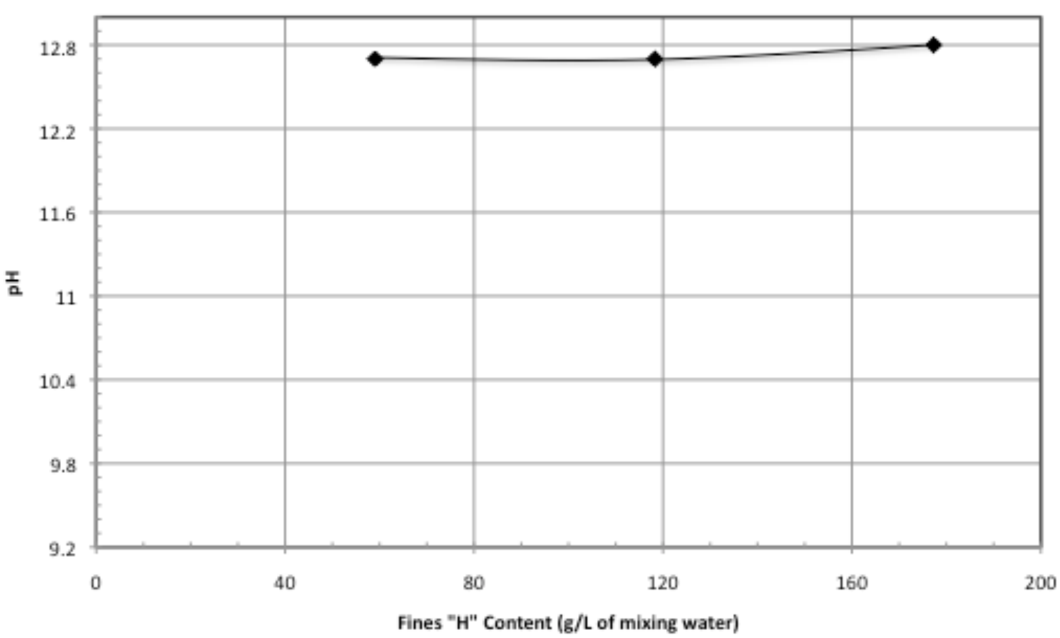

Figure 38. pH vs. Fines "H" Content

7.2 Appendix B: Strength vs. Percent Fines Graphs

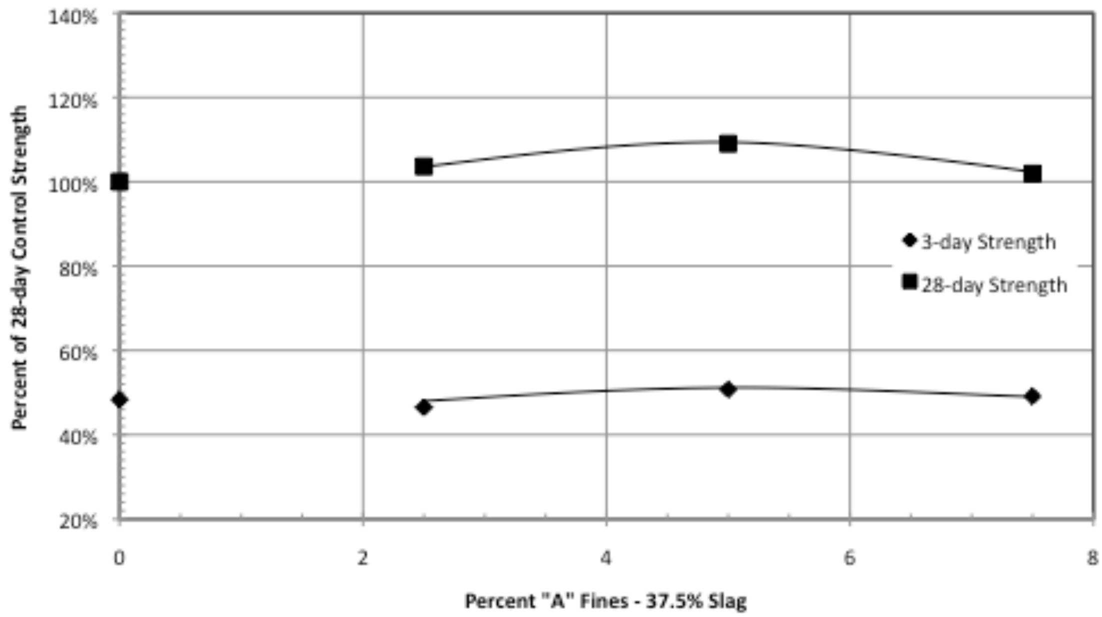

Figure 39. Compressive Strength vs. Percent "A" Fines - 36.5% Slag

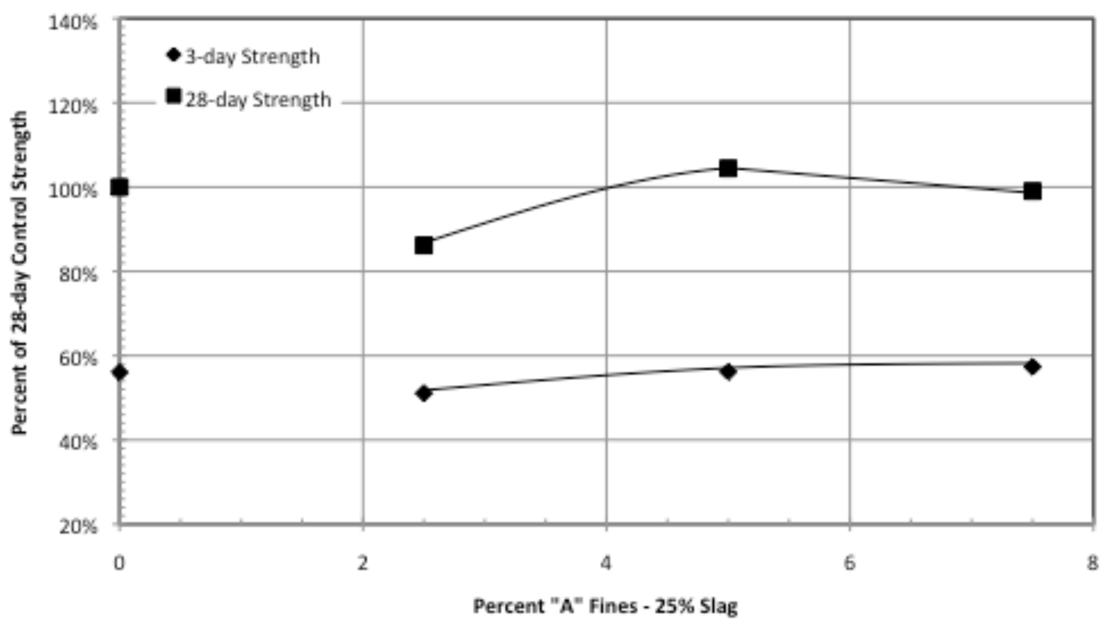

Figure 40. Compressive Strength vs. Percent "A" Fines - 25% Slag

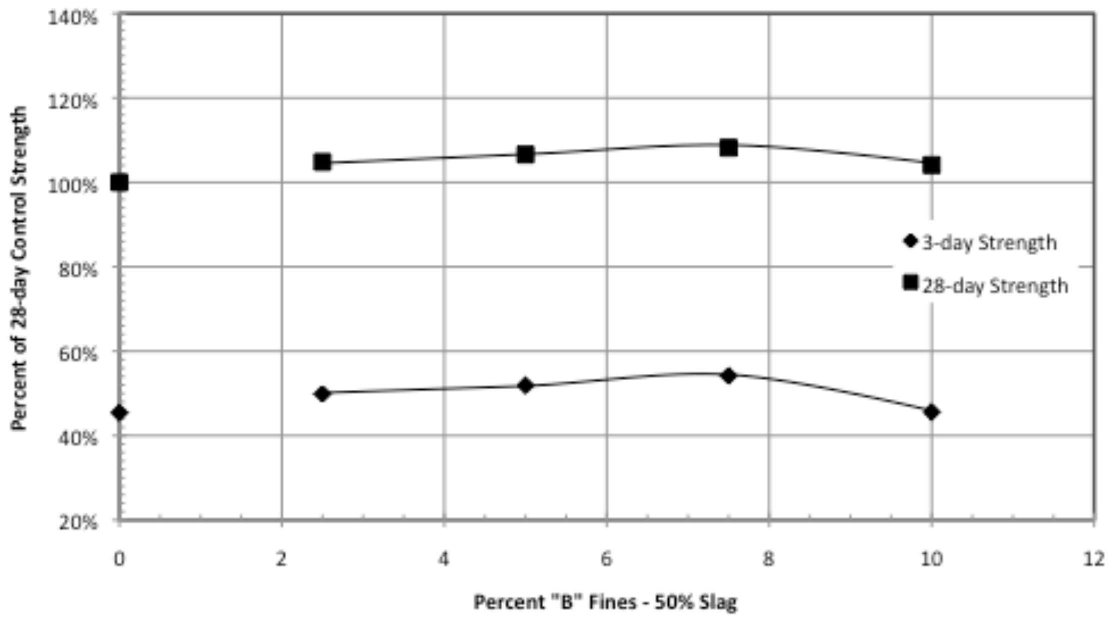

Figure 41. Compressive Strength vs. Percent "B" Fines - 50% Slag

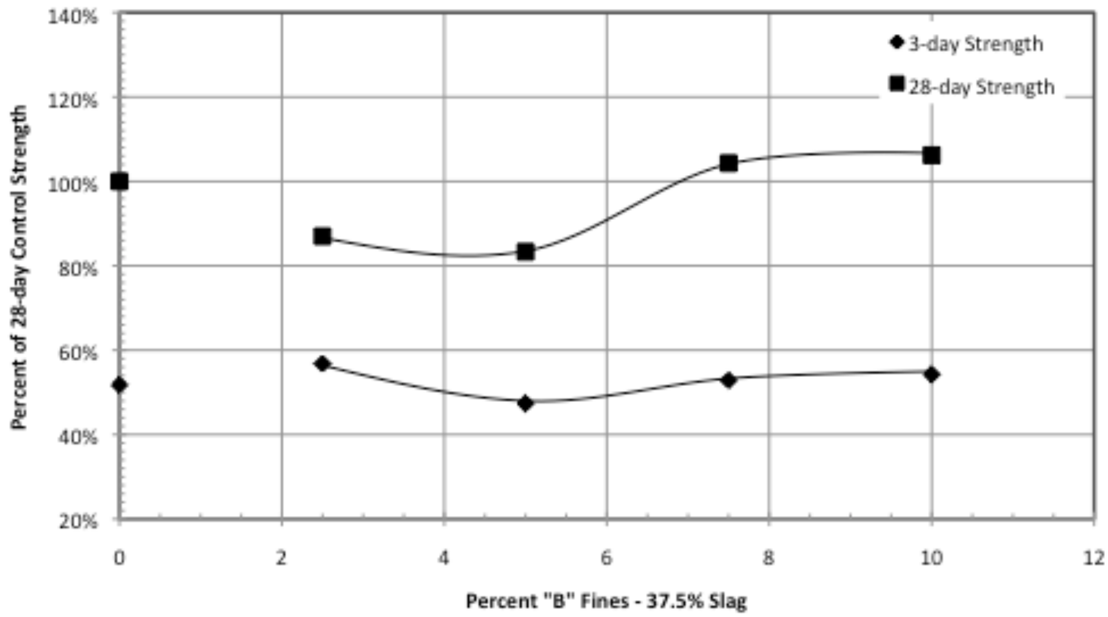

Figure 42. Compressive Strength vs. Percent "B" Fines - 37.5% Slag

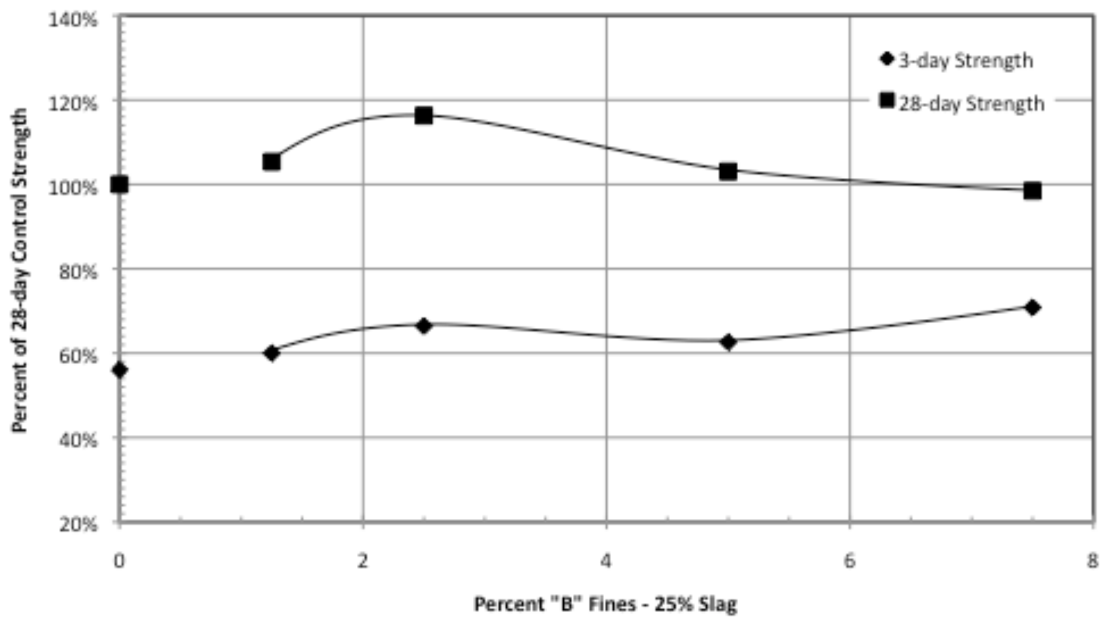

Figure 43. Compressive Strength vs. Percent "B" Fines - 25% Slag

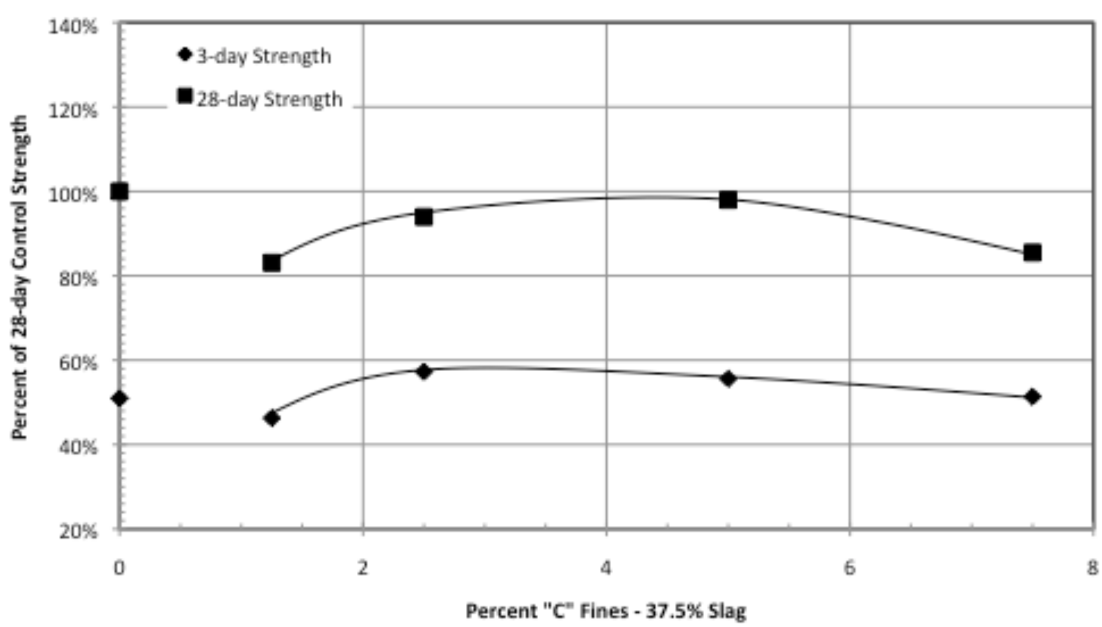

Figure 44. Compressive Strength vs. Percent "C" Fines - 37.5% Slag

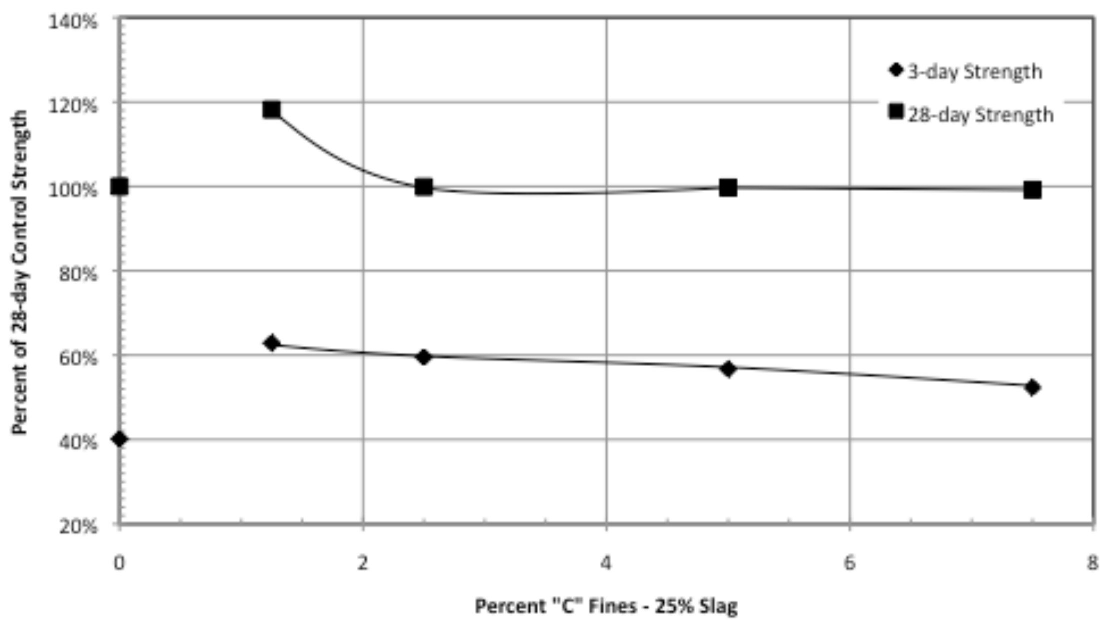

Figure 45. Compressive Strength vs. Percent "C" Fines - 25% Slag

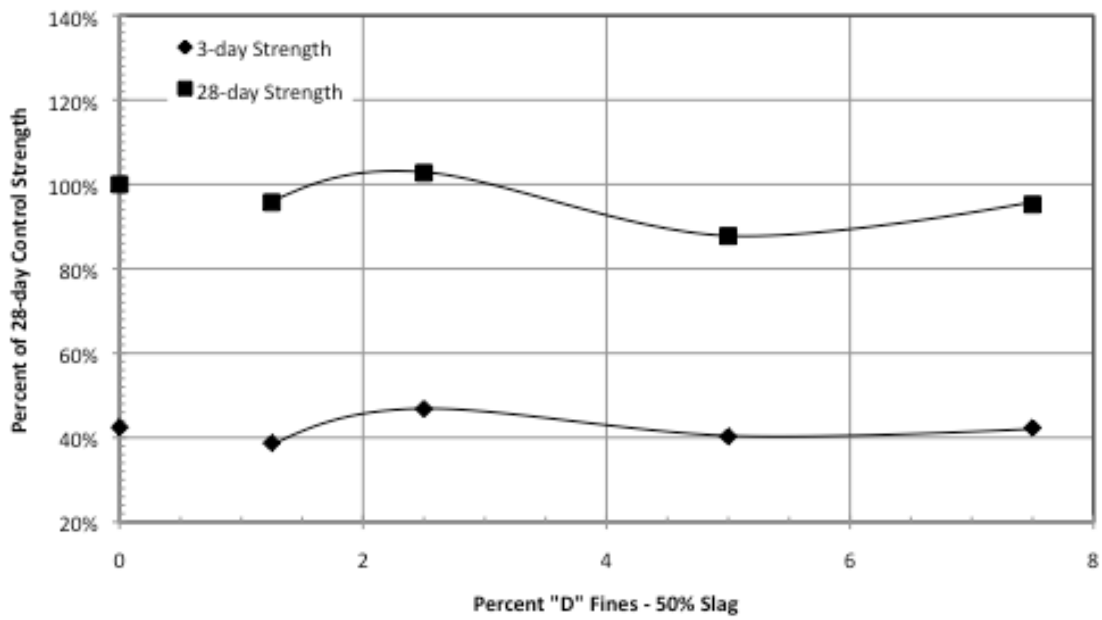

Figure 46. Compressive Strength vs. Percent "D" Fines - 50% Slag

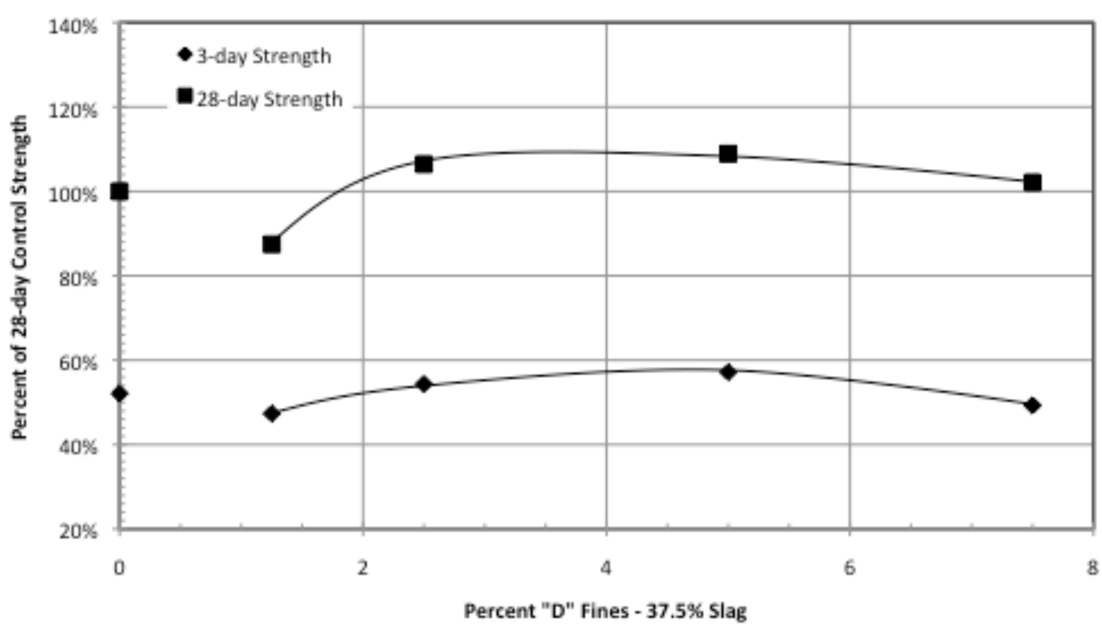

Figure 47. Compressive Strength vs. Percent "D" Fines - 37.5% Slag

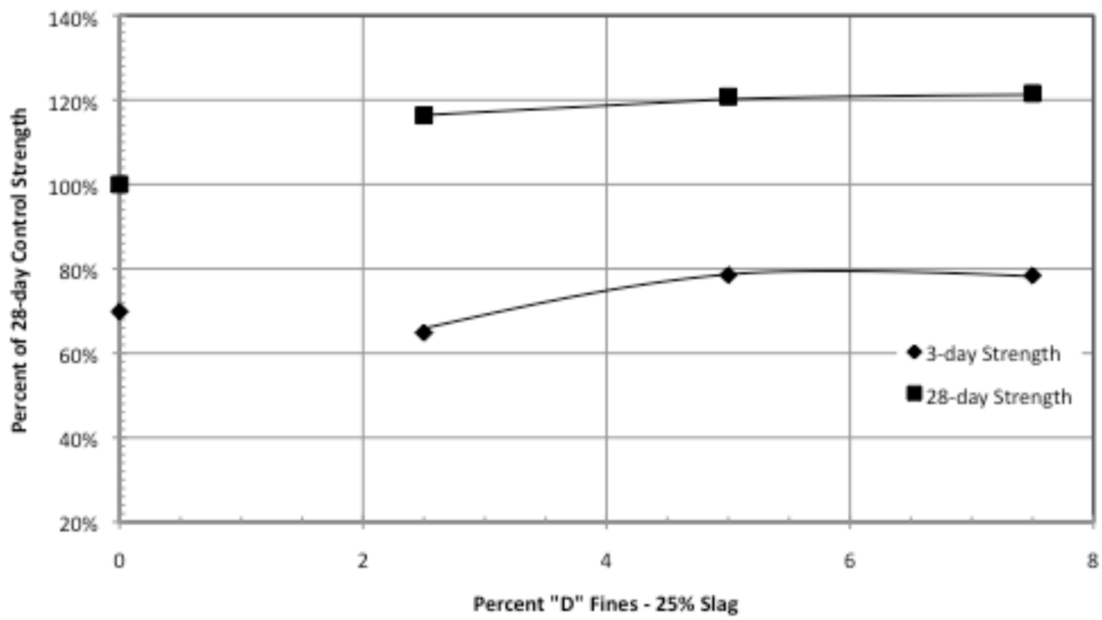

Figure 48. Compressive Strength vs. Percent "D" Fines - 25% Slag

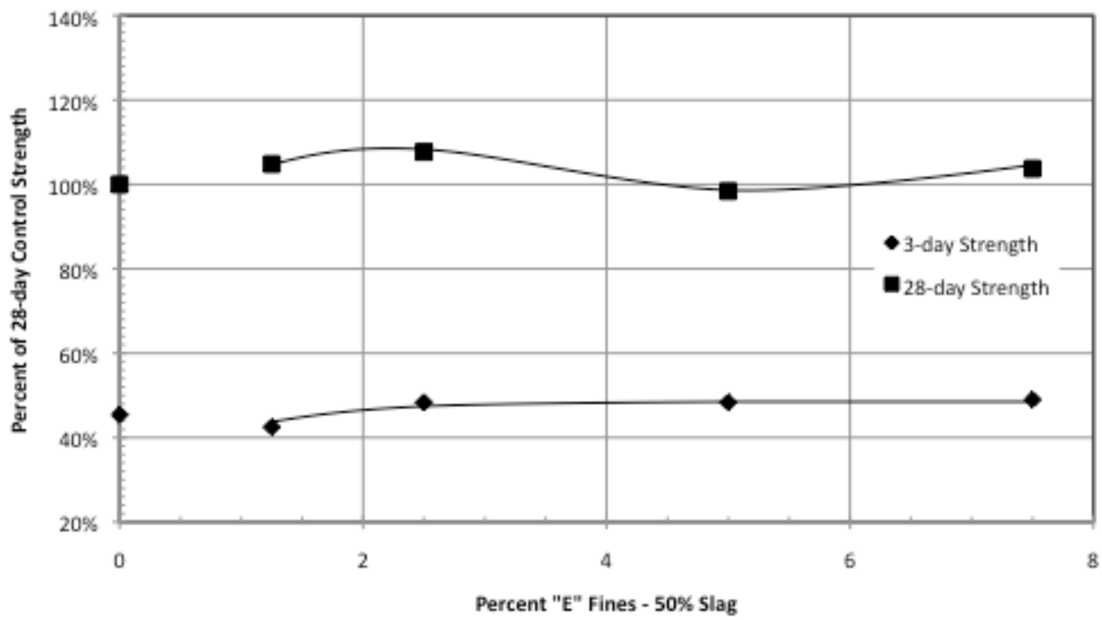

Figure 49. Compressive Strength vs. Percent "E" Fines - 50% Slag

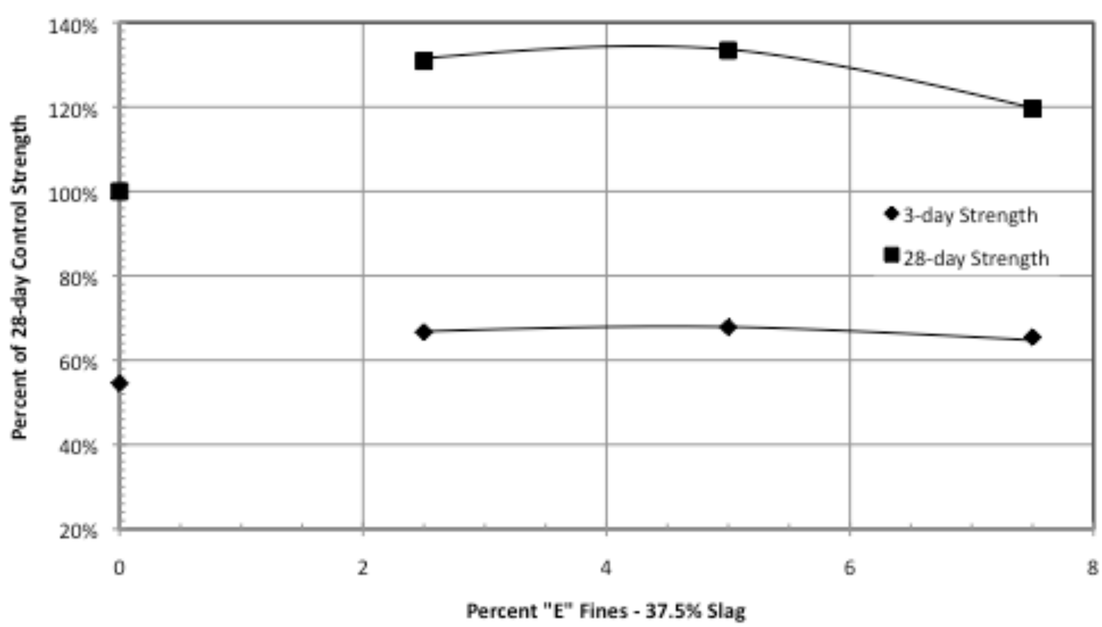

Figure 50. Compressive Strength vs. Percent "E" Fines - 37.5% Slag

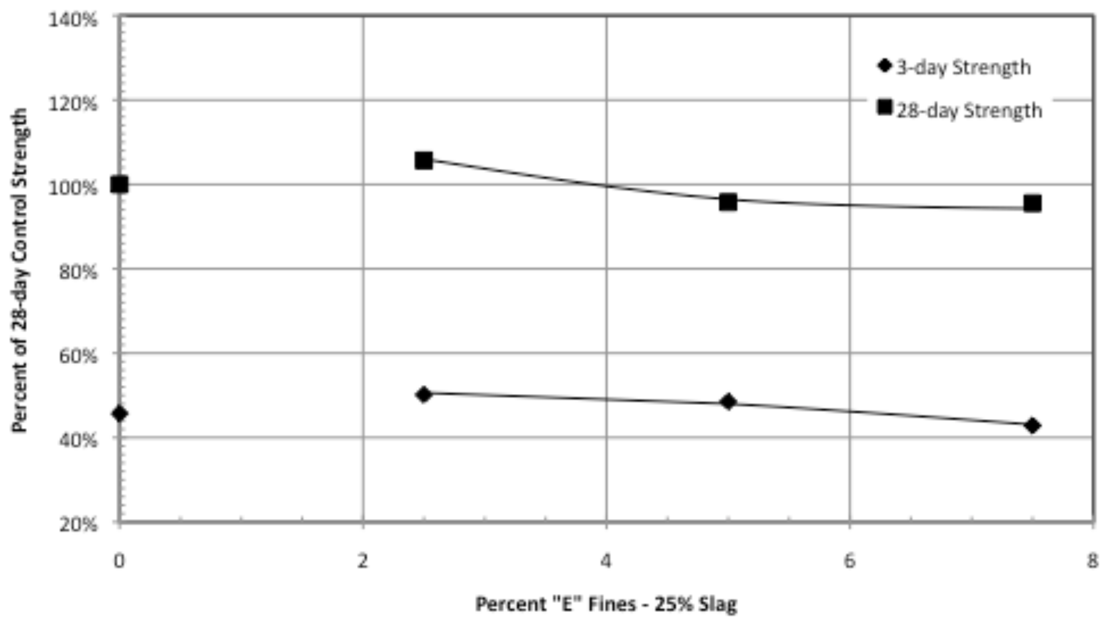

Figure 51. Compressive Strength vs. Percent "E" Fines - 25% Slag

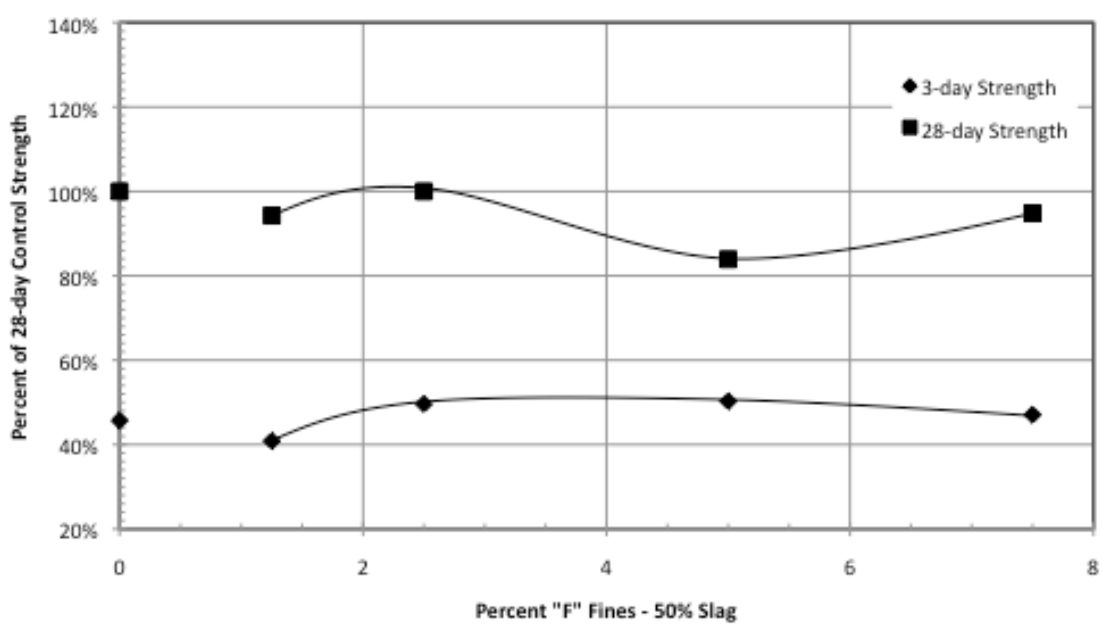

Figure 52. Compressive Strength vs. Percent "F" Fines - 50% Slag

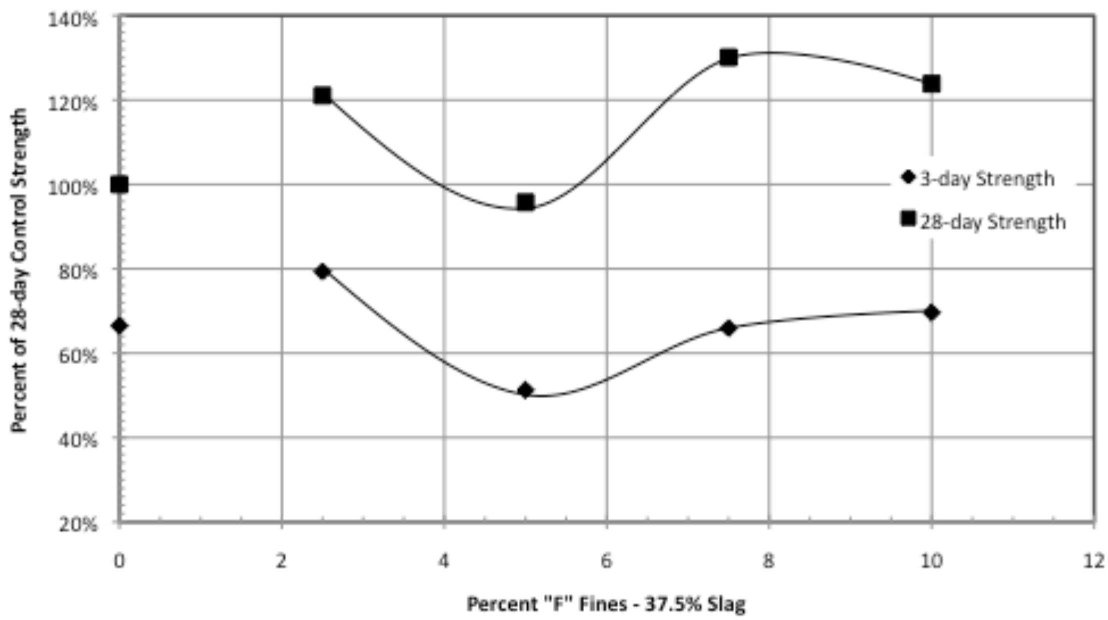

Figure 53. Compressive Strength vs. Percent "F" Fines - 37.5% Slag

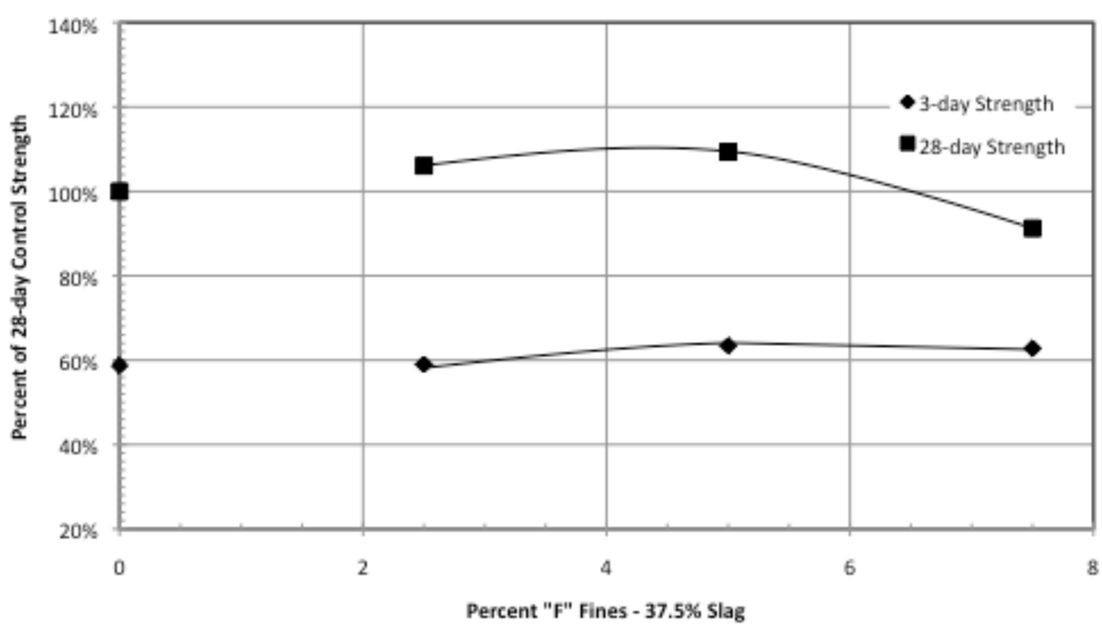

Figure 54. Compressive Strength vs. Percent "F" Fines - 25% Slag

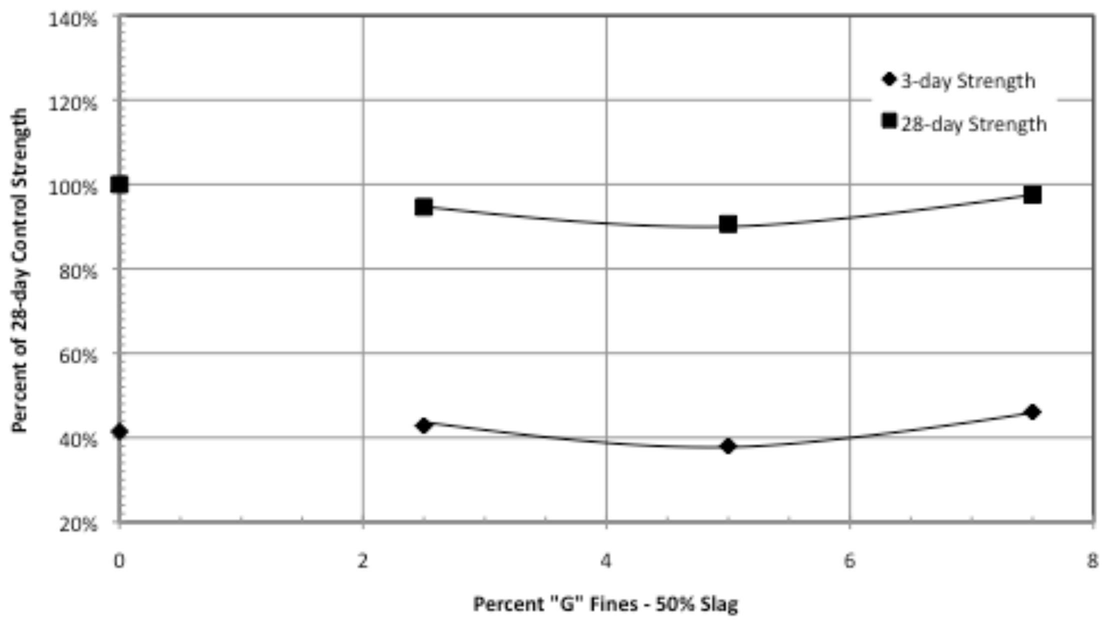

Figure 55. Compressive Strength vs. Percent "G" Fines - 50% Slag

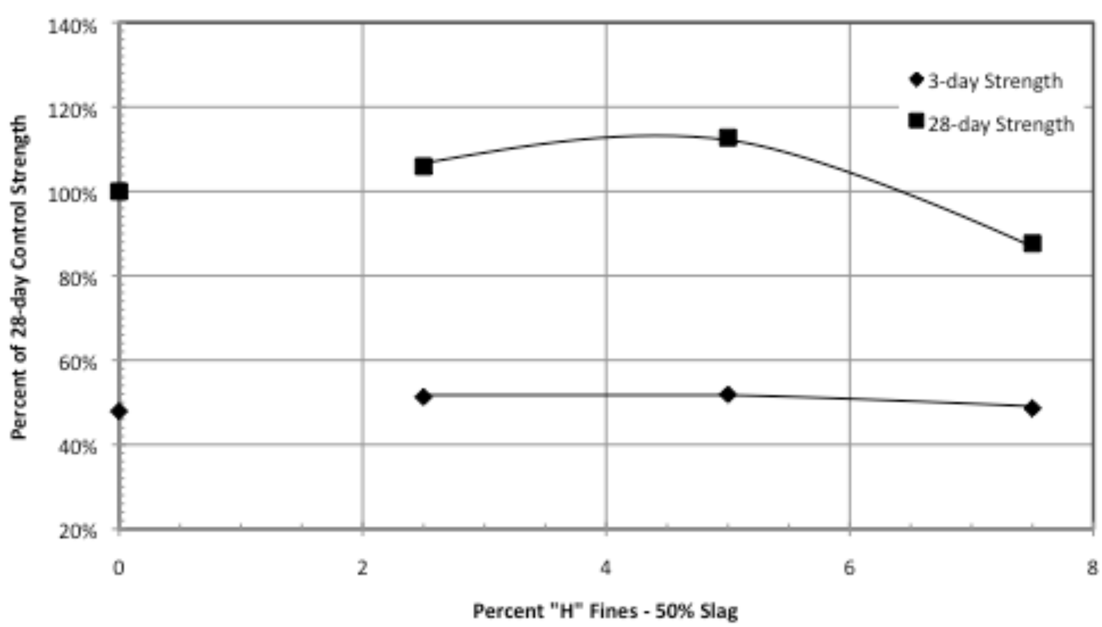

Figure 56. Compressive Strength vs. Percent "H" Fines - 50% Slag

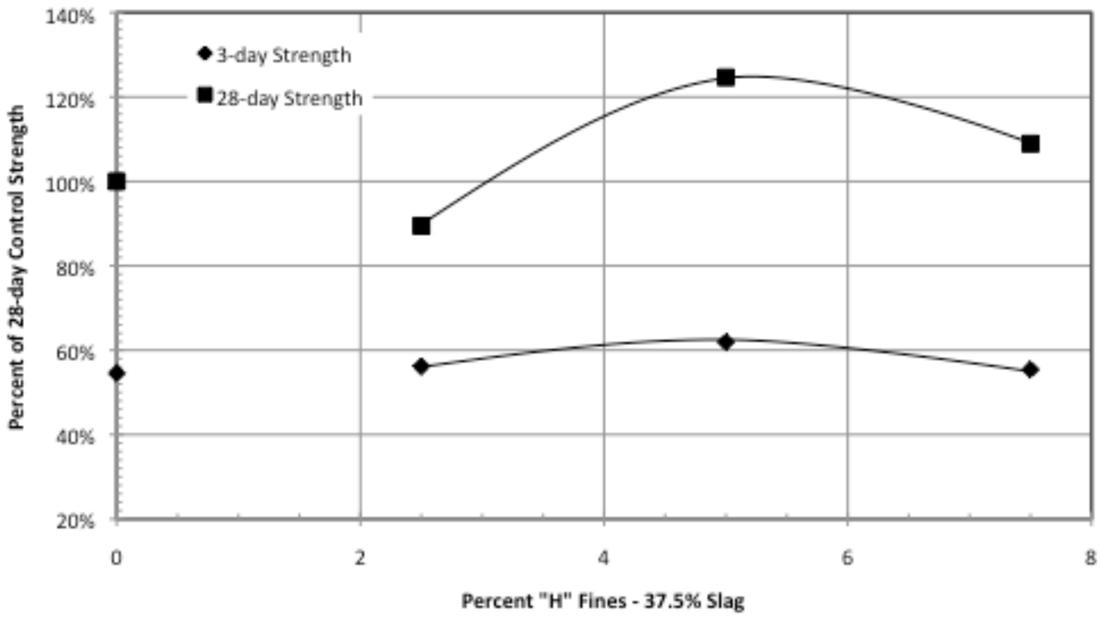

Figure 57. Compressive Strength vs. Percent "H" Fines - 37.5% Slag

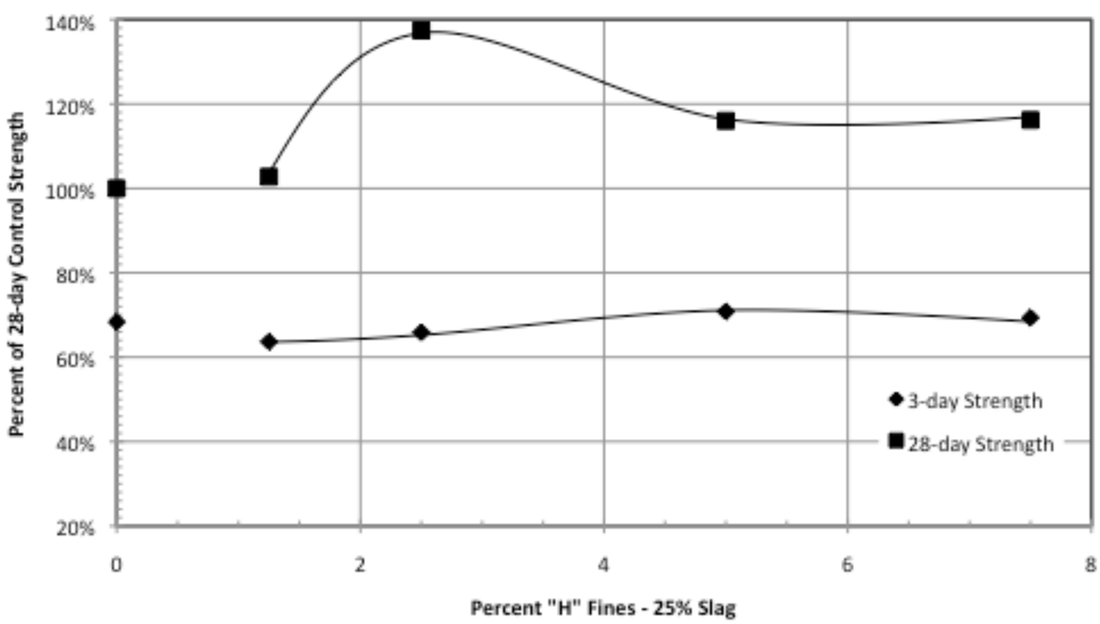

Figure 58. Compressive Strength vs. Percent "H" Fines - 25% Slag

7.3 Appendix C: Additional Regression Analysis Graphs

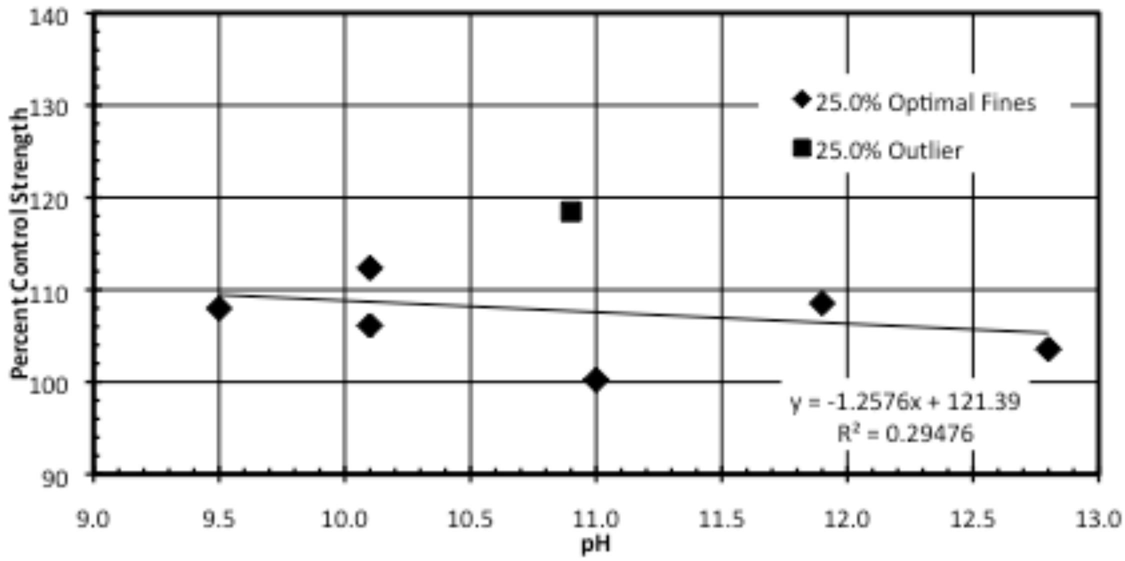

Figure 59 - pH Regression Analysis Without A for 25.0% Slag.

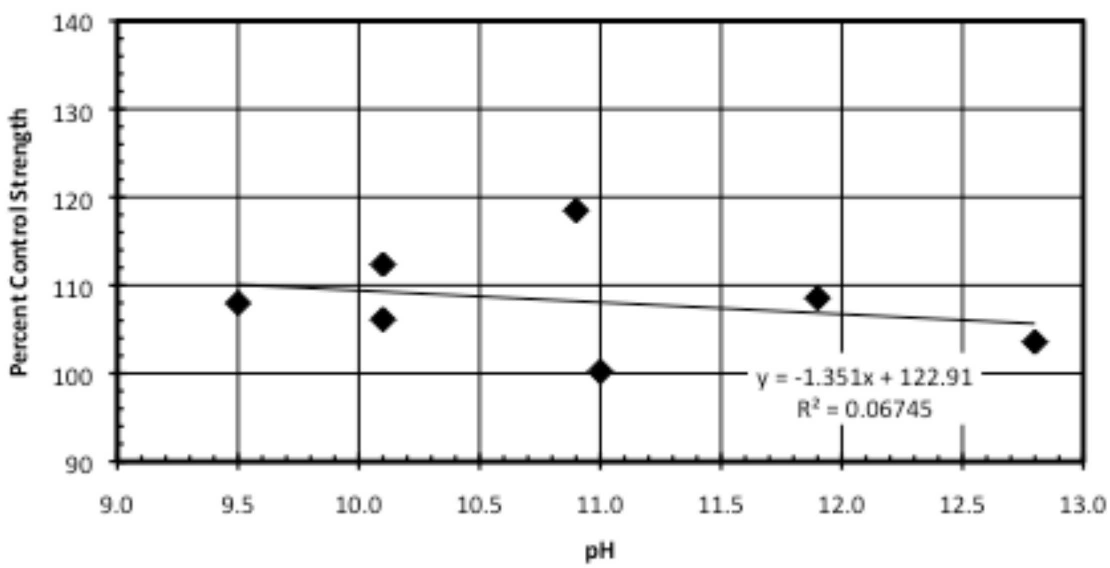

Figure 60 - pH Regression Analysis for 25.0% Slag.

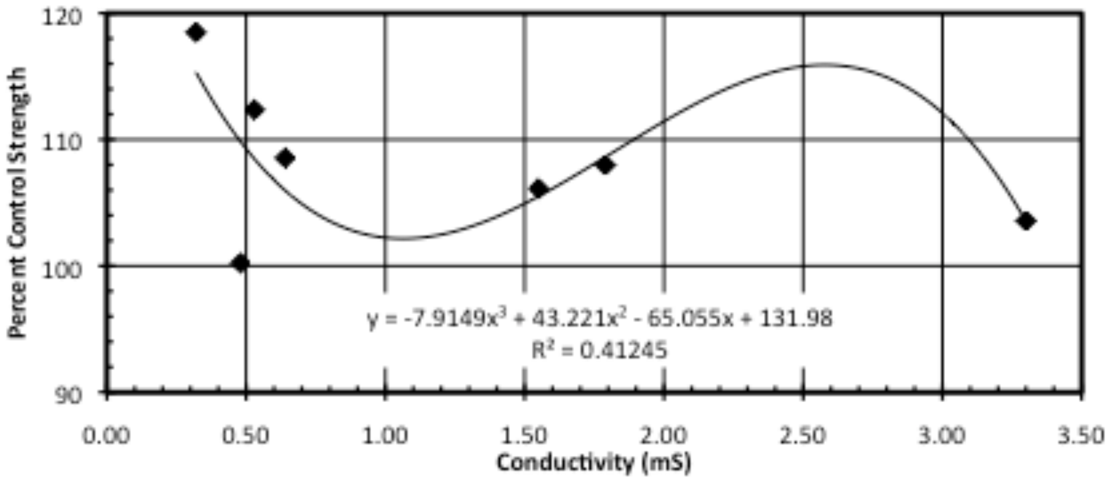

Figure 61 - Conductivity Regression Analysis for 25.0% Slag.

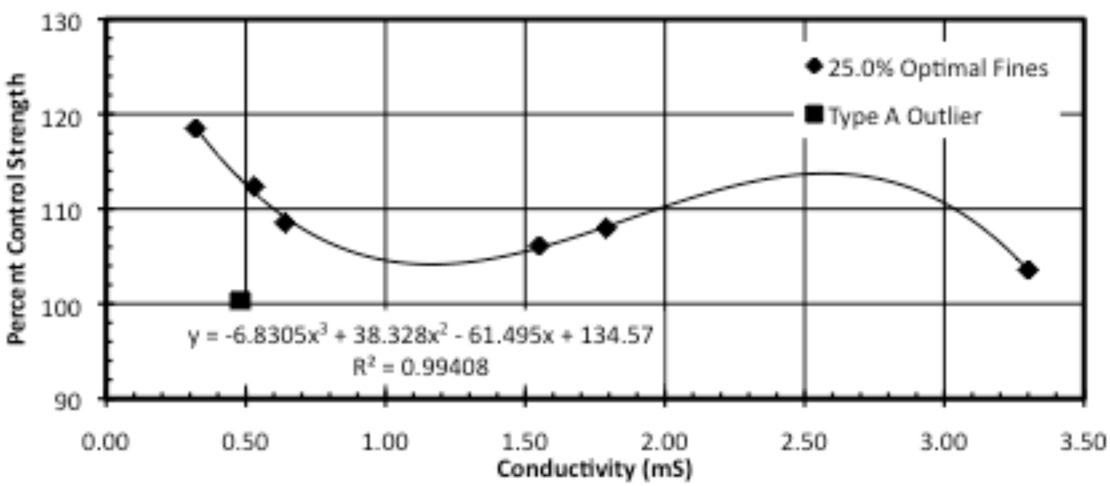

Figure 62 - Conductivity Regression Analysis Without A for 25.0% Slag.

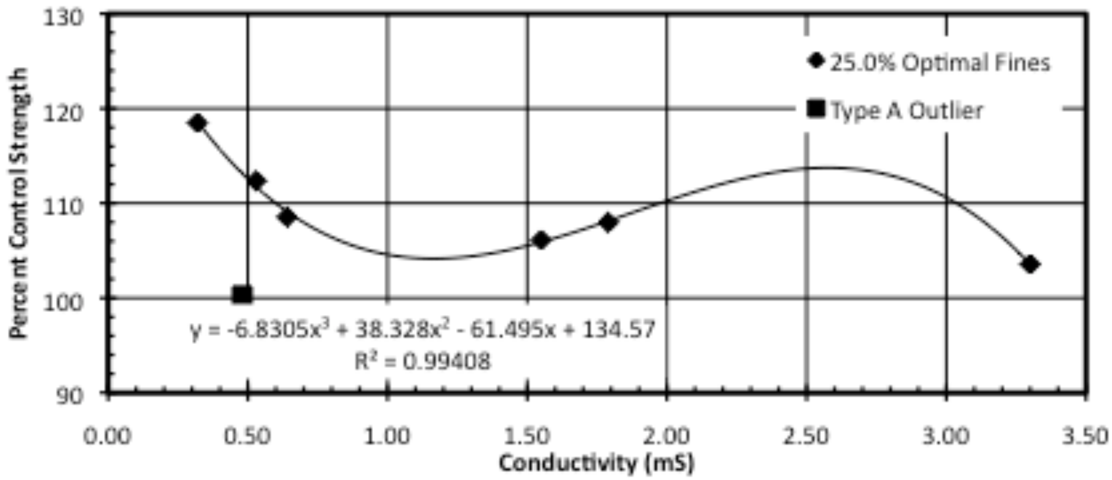

Figure 63 - IR Regression Analysis for 25.0% Slag.

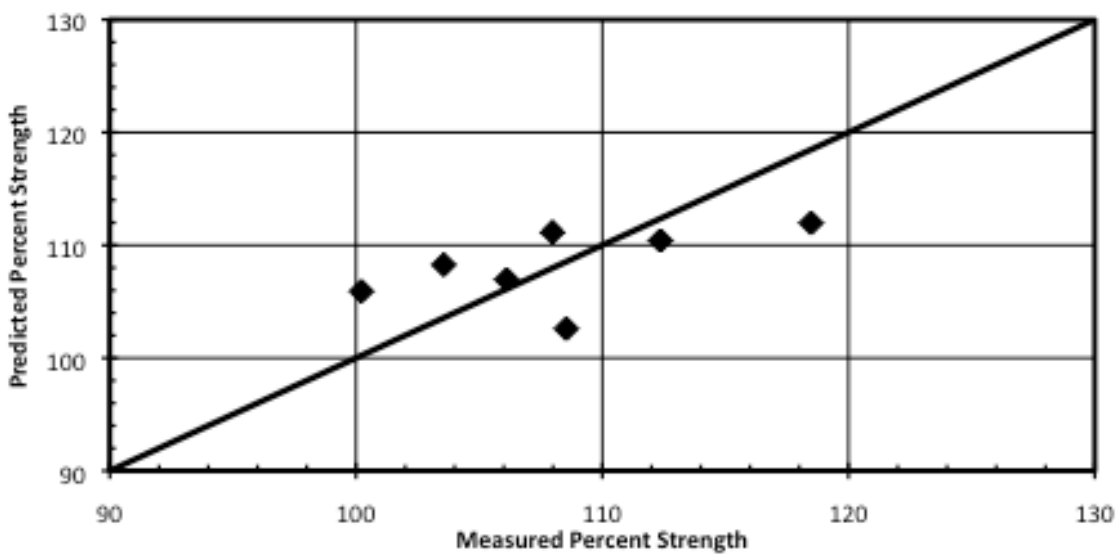

Figure 64 - pH + Conductivity Regression Analysis for 25.0% Slag.

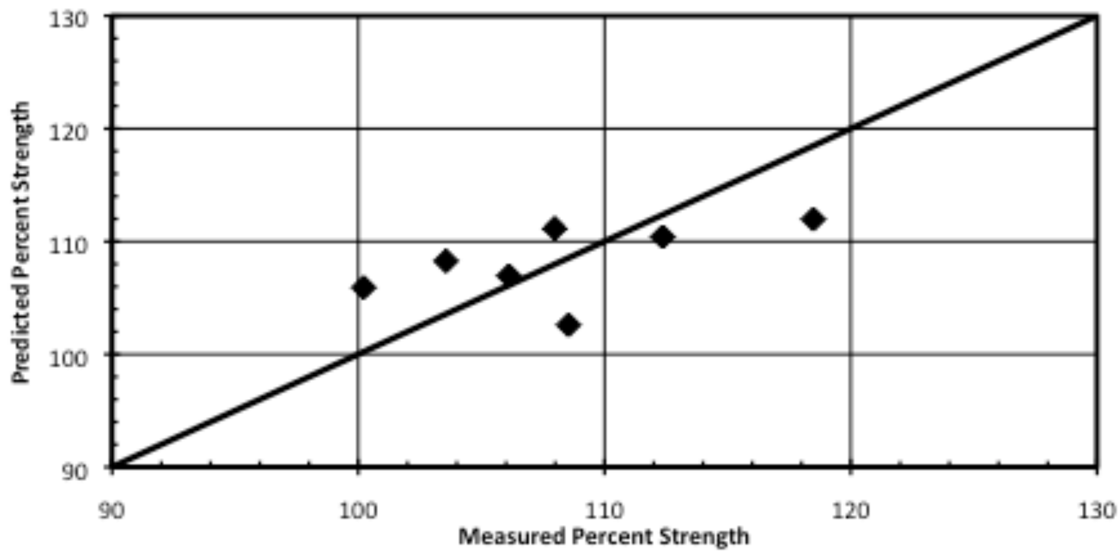

Figure 65 - pH + IR Regression Analysis for 25.0% Slag.

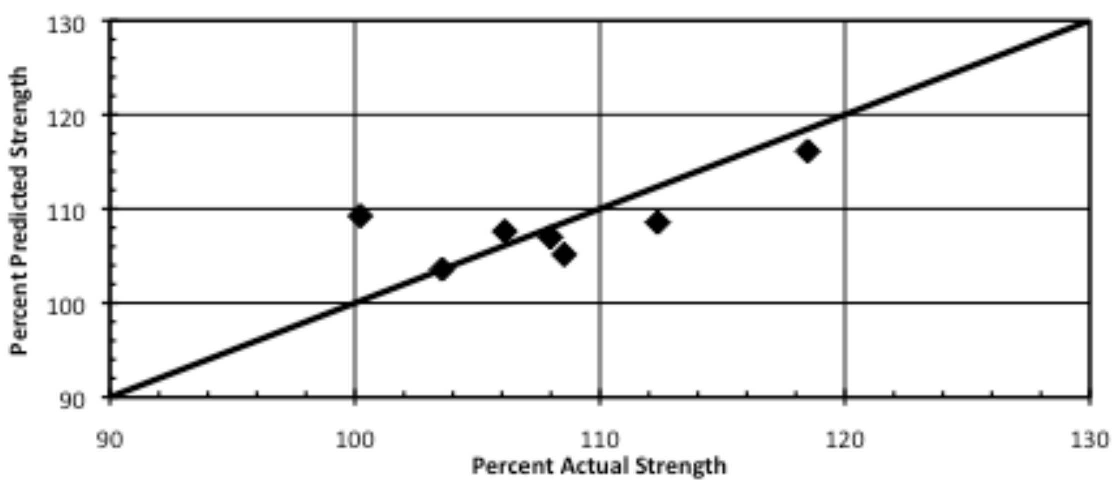

Figure 66 - Conductivity + IR Regression Analysis for 25.0% Slag.

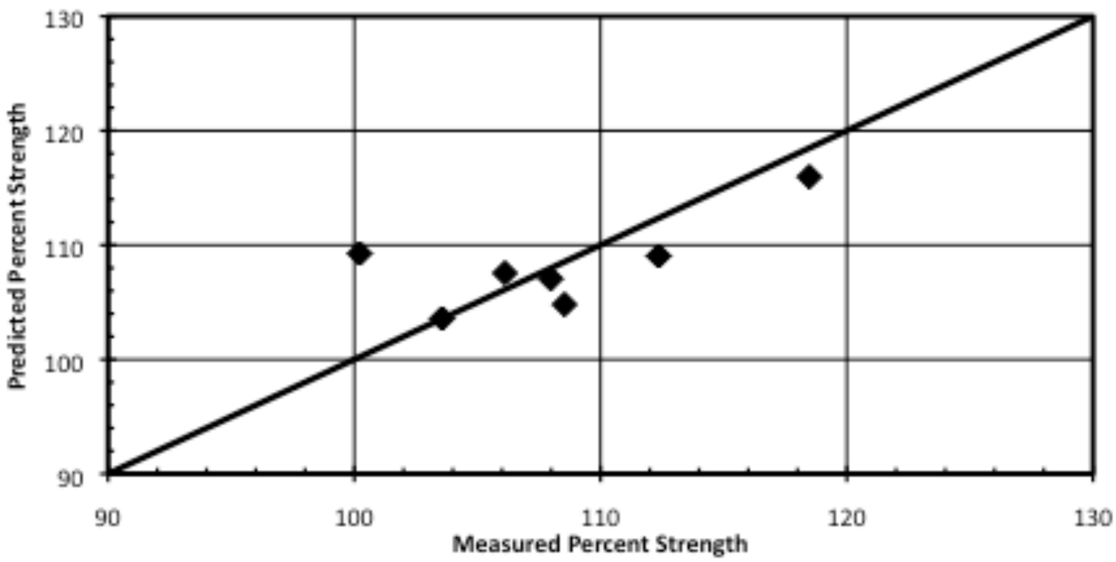

Figure 67 - Three Parameter Regression Analysis for 25.0% Slag.

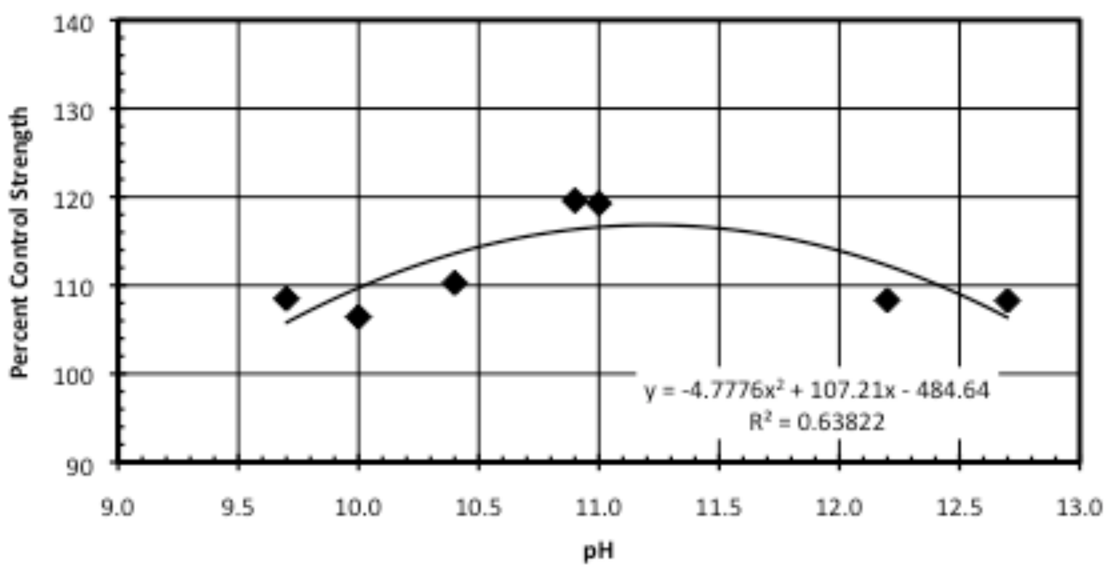

Figure 68 - pH Regression Analysis for 50.0% Slag.

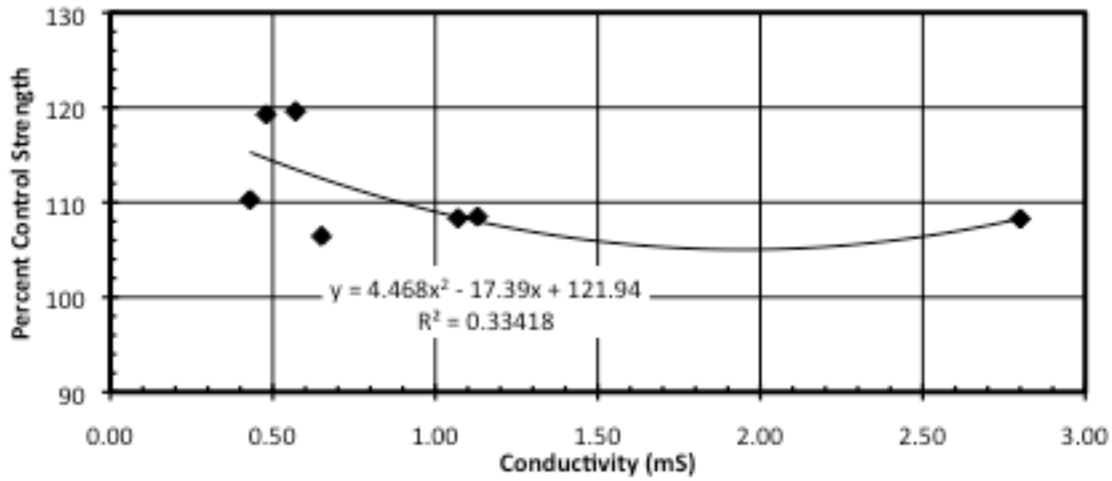

Figure 69 - Parabolic Conductivity Regression Analysis for 50.0% Slag

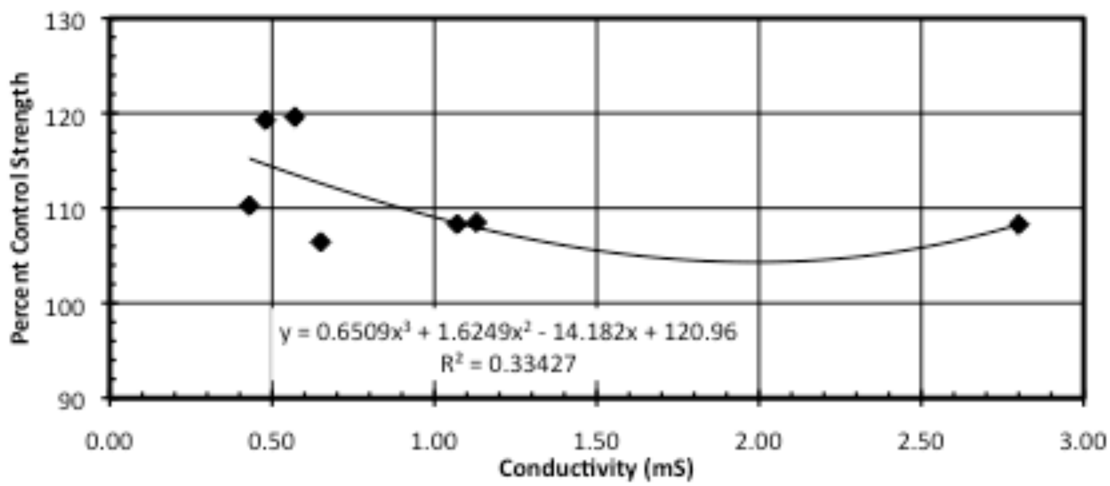

Figure 70 - Cubic Conductivity Regression Analysis for 50.0% Slag.

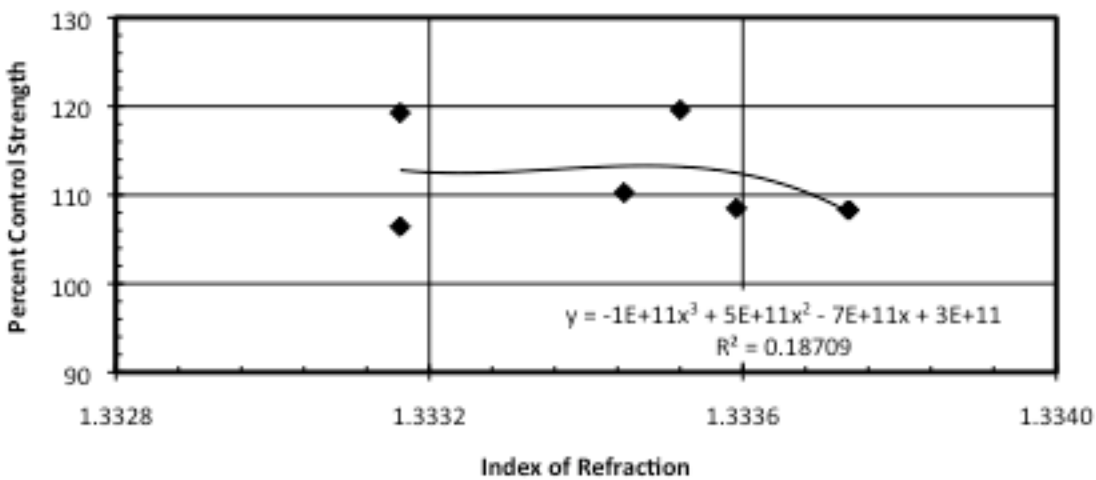

Figure 71 - IR Regression Analysis for 50.0% Slag.

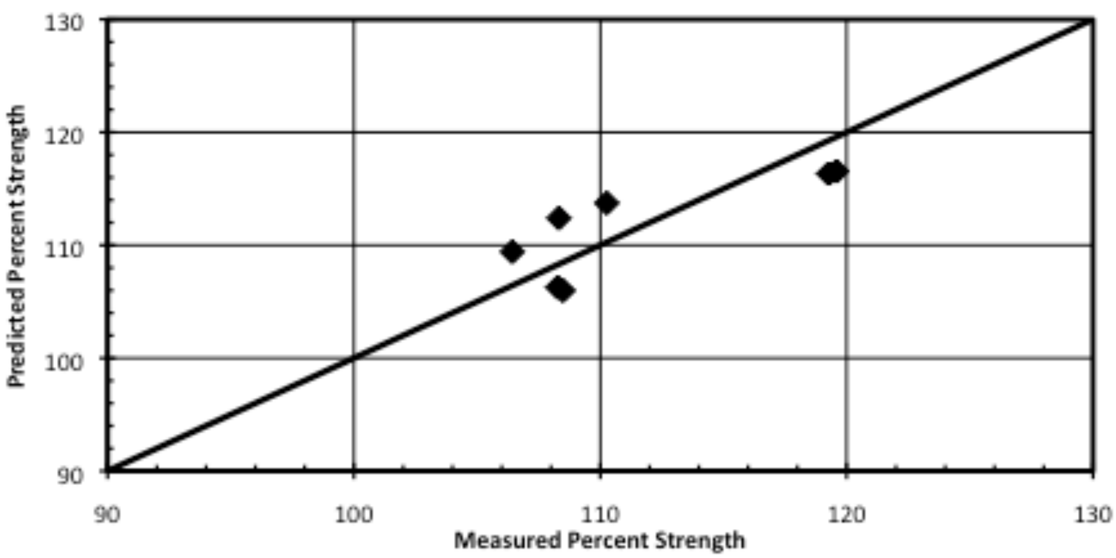

Figure 72 - pH + IR Regression Analysis for 50.0% Slag.

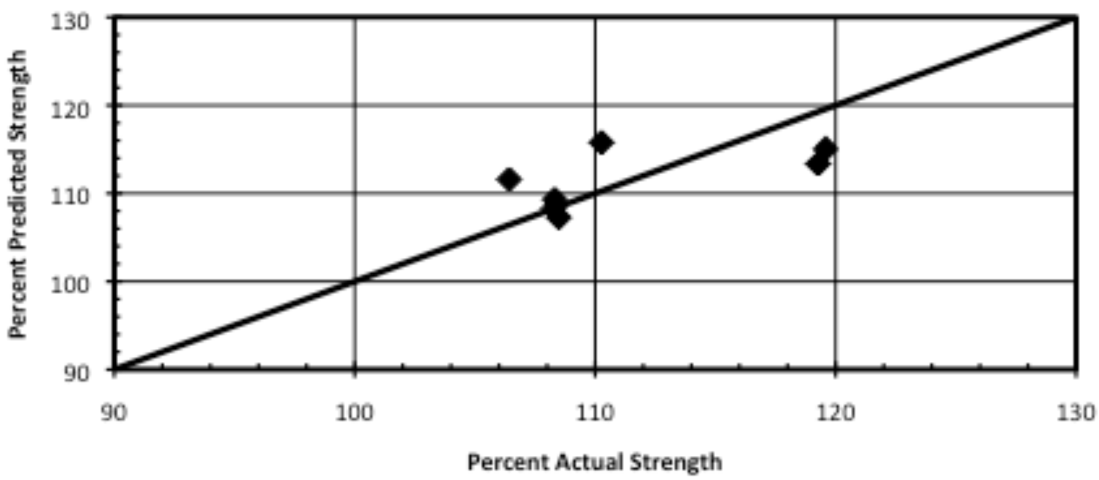

Figure 73 - Conductivity + IR Regression Analysis for 50.0% Slag.

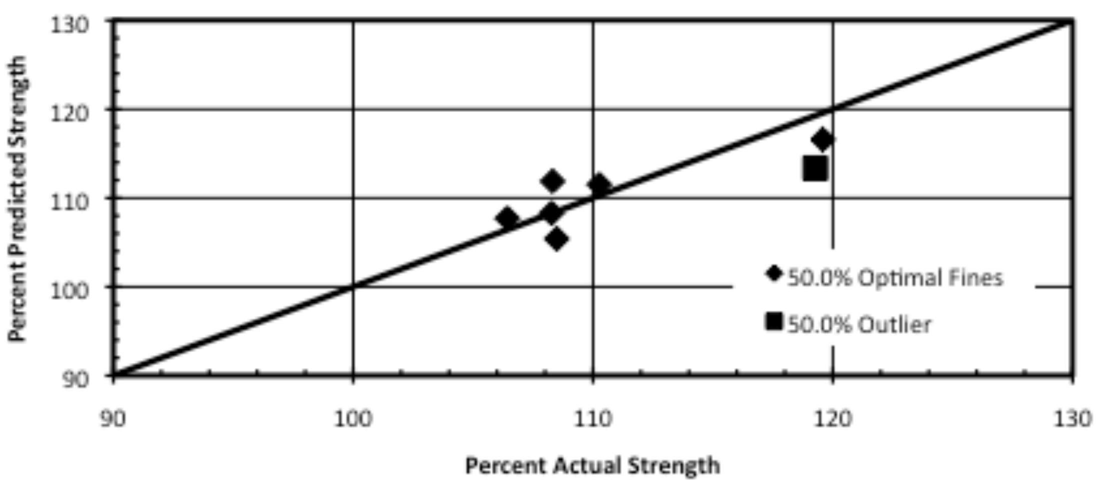

Figure 74 - Conductivity + IR Regression Analysis Without A for 50.0% Slag.