Field Validation of Recycled Concrete Fines Usage

FINAL PROJECT REPORT

by

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16. Abstract

The amount of recycled concrete fines permitted in concrete mixing water is limited by ASTM C 1602 to 5.0 percent of the mixing water, by mass, in order to avoid detrimental effects on concrete properties. Depending upon the exact nature of the recycles concrete fines, researchers have reported no detrimental effects at significantly higher fines contents in some cases, and unacceptably-lowered strengths at fines contents below the allowed limits in other cases.

In practically all instances, concrete producers control the quantity of recycled concrete fines by measuring the specific gravity of the mix water containing the fines. This measurement, while providing an indication of the total amount of fines in the water, is unable to distinguish between dissolved and suspended solids. In addition, the effect of pH – significant in terms of the rate of cement hydration, is ignored. Recent work has looked at characterizing the fines in terms of both the conductivity of the mix water containing the fines and the pH of the mix water. Correlations relating performance of mortar mixtures and the conductivity and pH of the mix water have been developed. Performance characteristics included set time as well as compressive strength at 3 and 28 days.

This report documents results of using revised performance correlations on concrete produced at a ready-mix concrete plant. An instrumentation assembly with conductivity and pH probes was placed into the tank used to weigh the mix water. Mixtures with either no recycled fines or two different levels of recycled fines content were then prepared in full-truck batches and compression specimens were prepared from concrete obtained from the trucks. This was repeated for a total of four separate sampling days, in order to achieve some variation in the exact nature of the recycled fines. Compression results indicated that all of the mixtures achieved at least 90 percent of the control 3-day strength and the only mixture to not achieve 90 percent of the control 28-day strength was correctly predicted. The occurrence of some false-negative predictions for mixtures with higher pH mixing water indicates that additional work is needed in order to refine the predictive equations so they are reliable for a larger range of recycled concrete-fines mixing water parameters.

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Abstract

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This report documents results of using revised performance correlations on concrete produced at a ready-mix concrete plant. An instrumentation assembly with conductivity and pH probes was placed into the tank used to weigh the mix water. Mixtures with either no recycled fines or two different levels of recycled fines content were then prepared in full-truck batches and compression specimens were prepared from concrete obtained from the trucks. This was repeated for a total of four separate sampling days, in order to achieve some variation in the exact nature of the recycled fines. Compression results indicated that all of the mixtures achieved at least 90 percent of the control 3-day strength and the only mixture to not achieve 90 percent of the control 28-day strength was correctly predicted. The occurrence of some false-negative predictions for mixtures with higher pH mixing water indicates that additional work is needed in order to refine the predictive equations so they are reliable for a larger range of recycled concrete-fines mixing water parameters.

Executive Summary

The amount of recycled concrete fines permitted in concrete mixing water is limited by ASTM C 1602 to 5.0 percent of the mixing water, by mass, in order to avoid detrimental effects on concrete properties. Depending upon the exact nature of the recycles concrete fines, researchers have reported no detrimental effects at significantly higher fines contents in some cases, and unacceptably-lowered strengths at fines contents below the allowed limits in other cases.

In practically all instances, concrete producers control the quantity of recycled concrete fines by measuring the specific gravity of the mix water containing the fines. This measurement, while providing an indication of the total amount of fines in the water, is unable to distinguish between dissolved and suspended solids. In addition, the effect of pH – significant in terms of the rate of cement hydration, is ignored. The recently-completed National Cooperative Research Program (NCHRP) IDEA Project No. 166 looked at characterizing the fines in terms of both the conductivity of the mix water containing the fines and the pH of the mix water. Set time as well as mortar strengths were measured as 3 and 28 days for each of the cementitious and recycled fines combinations examined in the study. The dataset from that study was used to develop equations to predict whether or not a concrete mixture would be expected to achieve at least 90 percent of the control strength (concrete made with tap water instead of recycled water) for both 3- and 28-day tests.

A sensor assembly for measuring pH and conductivity was prepared and then was used at a ready-mix concrete plant to characterize the water being used to prepare concrete batches. The water used for the concrete mixing was either recycled water from truck wash-out operations, surface runoff water from the concrete plant facilities, or a combination of those two sources.

After concrete was discharged from the mixer into the concrete truck, a small amount was discharged into a wheelbarrow and used to make concrete test cylinders. These cylinders were tested to determine 3- and 28-day compressive strengths. Sampling was conducted on four separate days in order to cover a range of potential recycled concrete fines contents.

All of the mixtures achieved at least 90 percent of the control 3-day strength and the only mixture to not achieve 90 percent of the control 28-day strength was correctly predicted. The occurrence of some false-negative predictions for mixtures with higher pH mixing water indicates that additional work is needed in order to refine the predictive equations so they are reliable for a larger range of recycled concrete-fines mixing water parameters.

Chapter 1 – Introduction

The purpose of this work is to investigate the use of recycled concrete fines in actual ready-mix concrete production, and at levels of recycled fines higher than permitted by ASTM C 1602-12, Section 5.4, "Optional Limits for Combined mixing Water". This work is a field implementation of work funded as National Cooperative Highway Research Program (NCHRP) IDEA Project 166, "Guidelines for the use of Recycled Concrete Fines". [Dufalla, et al, 2014] Background information is provided in the following sections.

1.1 Sources of Recycled Concrete Fines

Portland cement concrete is a very versatile construction material that uses mostly local materials to produce energy-efficient pavements and structures. Use of concrete, however, results in the production of waste concrete fines as summarized in the following sections.

1.1.1 Concrete Truck Wash-out

Every ton of concrete requires almost 35 gallons of water to produce, and about another 10 gallons for clean-up – washing out the concrete truck prior to filling it with the next batch of concrete. After extracting aggregates from the wash-out water for re-use, there still remains a considerable amount of fine material (mostly smaller than 75 microns - #200 sieve) in the water, as well as dissolved materials. Elchalakani and Elgaali, 2012]

1.1.2 Sawcutting/Pavement Grooving

Sawcutting joints in concrete slabs-on-grade, pavements and sidewalks also produces recycled fines – sawcutting joints in a lane-mile of concrete pavement produces a bit over 2 tons along with 400 gallons of water to cool the sawblade and control dust. Grooving an airfield runway (cutting shallow grooved into the pavement, often done as a part of new construction) can produce almost 600 tons of fines as well as almost 120,000 gallons of water. These operations generally occur as a part of new construction – once in the life of the concrete.

1.1.3 Diamond Grinding

Diamond-grinding concrete pavement to restore ride quality (make it smoother and safer) also produces recycled concrete fines. The grinding of one lane-mile of pavement could produce 50 tons of fines and require over 10,000 gallons of water to control the dust. Given that pavements contain multiple lanes and extend for many miles, diamond-grinding can be a major source of concrete fines even though a pavement may only be diamond ground once in its functional life.

1.2 Need for Recycling

Many years ago, water with concrete fines was allowed to sit in ponds so that the fines could settle out and then the water was discharged into local streams. The fines were then removed to a landfill. As much as 60 years ago, however, it was recognized that this water had a high pH and discharge may need to be regulated. [Building, 1956] Today, most jurisdictions require that the water (after settling the solids out) be treated to reduce the pH before it can be discharged, and many require treatment of the fines as well before they can be landfilled. In the United States, the Environmental Protection Agency Water Quality Act, part 116, categorizes concrete wash out water as a hazardous substance based on the regulations of corrosivity and the high pH of the wash water [Chini. 1996]. The Environmental Protection Agency published recommendations for the recycling of concrete wash out water suggest filtering the waste water through a series of filters and reusing the final water as wash out water for more concrete mixing trucks. Alternatively, the filtered wash water can be treated until its metal levels and pH fall within acceptable limits for standard disposal. The EPA also recommends recycling concrete aggregate if separation from the mortar matrix is feasible [EPA 1987].

1.3 Limitations on Recycling Concrete Fines into New Concrete

All of these fines mentioned above can be described as being a mixture of inert powder, hydrated cement particles, unhydrated cement and dissolved ions. It has long been known that finely-ground particles of hydrated portland cement can have a significant accelerating effect on the hydration rate of portland cement concrete. [Mindess, et al., 2002, Su, 2002] This effect is believed to be primarily due to the hydrated cement particles acting as nucleation sites, facilitating the hydration reaction. Minor accelerating affects may also be due to calcium hydroxide and/or alkalis in the hydrated portland cement. Strength of the concrete, both early (3-day) and long-term (28-days) can also be effected. This effect, however, cannot easily be predicted based only on the amount of recycled fines in the water. At some levels of fines the strength will be higher than mixtures with no recycled fines while at other levels the strength will be lower. [Janssen, et al, 2012, Dufalla, et al, 2014]

ASTM C 1602-12 requires process water to not accelerate set time more than 60 minutes and to not delay set time more than 90 minutes. This specification also contains an optional provision that limits the total solids in the water to 5 percent by mass of the mixing water. Note 3 in ASTM 1602-12 indicates that this solids content corresponds to a specific gravity of the mixing water of about 1.03

DIN EN 1008 also limits the total solids in the mixing water, though the limit varies by concrete mixture and is equal to 1 percent of the total aggregates, by mass. For a typical concrete mixture this limitation translates to about 10 percent fines by mass in the mixing water.

Set time change is also limited to no more than 25% from the set time of a mixture made with de-ionized water.

Both specifications limit the strength effects to mixtures made with recycled fines in the mixing water to achieving no less than 90 percent of the control (no-fines mixing water) strength at seven days.

Chapter 2 - NCHRP-IDEA Study on Recycled Concrete Fines

In 2012 the National Cooperative Highway Research Program IDEA program provided funding to the University of Pittsburgh to investigate the effects of recycled concrete fines on measurable properties of the mixing water as well as set-time, early (3-day) and long-term (28-day) strength. Details of the study are provided by Dufalla, et al, (2014) and are summarized below.

2.1 Recycled Fines Used

Recycled fines were obtained from both the states of Pennsylvania and Washington. Three fines samples were obtained from concrete plant truck wash-out operations, two from pavement diamond-grinding operations and one from a pavement grooving job. All fines samples were obtained as slurries and dried at 40°C to facilitate handling. The drying typically required 3-5 days.

2.2 Cementitious Materials

The cementitious materials used consisted of various combinations of Type I Portland cement, ground-granulated blast furnace slag and Class F flyash. These are referred to as cement, slag and flyash in the following section.

The chemical analysis of the various cementitious materials were used to determine the percentage of CaO in the total cementitious material (CaO%) as well as the ratio of CaO to Al_2O_3 + SiO_2 (CaO-ratio). The CaO% and CaO-ratio was first determined for each cementitious material individually, and then weighted CaO% and CaO-ratio values were determined using the mass percentages in the different cementitious materials in the mixtures described in Table 2.1.

2.3 Mortar Mixtures

All mixtures were prepared with a w/cm of 0.42. Mixture proportions for the base mixtures are listed in Table 2.1.

Recycled fines were used in amounts of either 0, 30.6, 61.3 or 91.9 grams to produce a total of 28 mixtures for each fines source and amount tested. This is equivalent to 0.0, 5.6, 10.6 and 15.1 percent fines in the total "recycled" water, respectively. The cementitious material was reduced by the amount of recycled fines added to each mixture to keep workability close to constant. This resulted in slight increases in w/cm with increasing fines contents.

Set times were determined and mortar cubes were prepared for testing at ages of 3 and 28 days.

Table 2.1 Base Mortar Mixture Proportions (after Dufalla, et al, 2014).

Designation	Cement grams	Slag grams	Flyash grams	Water grams	Sand grams
C	1,225.0	0.0	0.0	518.2	1,947.0
CS25	918.8	306.3	0.0	518.2	1,947.0
CS375	756.6	459.4	0.0	518.2	1,947.0
CS50	612.5	612.5	0.0	518.2	1,947.0
CF10	1,102.5	0.0	122.5	518.2	1,947.0
CF20	980.0	0.0	245.0	518.2	1,947.0
CF30	857.5	0.0	367.5	518.2	1,947.0

2.4 Fines Characterization

Measurements of the water-recycled fines solutions were made in order to characterize the fines by some measurement than just the total mass of fines in the water. Measurements were made for solutions ranging from 2.3 to 19.1 percent recycled concrete fines (as a percentage of the total mas of fines plus water) as well as in the recycled fines solutions described earlier for the mortar mixtures.

2.4.1 Conductivity

Conductivity was measured with the intent to capture the quantity of dissolved ions in the recycled concrete fines-water mixtures. Dissolved ions could affect the rate of hydration in a concrete mixture. [Mindess, et al, 2002] It was measured with a hand-held conductivity meter by placing a couple of drops of the recycled concrete fines-water solution into the sensor well of the meter. Units for the conductivity measurements was μSiemens/cm.

2.4.2 pH

The pH of a cementitious material can be influenced by the pH of the water-cementitious mixture, with higher pH values leading to accelerated reaction rates but possibly lower long-term strengths. [Kosmatka, et al, 2002] Measurement of pH was accomplished using a hand-held pH probe which could be immersed into the mixing cup while the recycled concrete fines and mixing water was being blended.

2.4.3 Index of Refraction

Index of refraction is sensitive to both suspended solids and dissolved ions, though at different rates. Index of refraction was measured in order to provide supplementary information to the conductivity measurements to help differentiate between dissolved and suspended solids in the recycled fines. Index of refraction was measured with a hand-held meter by placing a couple of drops of the recycled concrete fines-water solution into the sensor well of the meter.

2.5 Significant Parameters

Regression analysis of the various parameters measured showed that pH and conductivity were the most significant recycled fines characterization measurements. The index of refraction was much less significant. When chemical analysis of the cementitious material was included in the regression analysis, the CaO% was found to most important for predicting the percent of the 3-day strength while the CaO-ratio was most important for predicting the relative 28-day strength.

2.6 Bench-Top Proof of Concept

A recycled water circulation system was modeled in the Pavement Materials laboratory at the University of Pittsburgh. It consisted of a submersible water pump in a sump connected to a tube loop that discharged back into the sump. The loop contained in-line sensors for measuring conductivity and pH as well as a tap to dispense water for concrete mixing.

Two different blends of recycled concrete fines from the mortar testing described earlier were prepared. The testing procedure consisted of placing one of the recycled concrete fines mixtures into the sump and starting the submersible pump. Once the in-line sensor readings stabilized the readings were recorded and the tap was opened to obtain sufficient water for preparing a concrete mixture. Concrete cylinders for determining 3- and 28-day compression strengths were prepared. The procedure was repeated for the second recycled concrete fines blend. Also, a control mixture using tap water was also prepared. Results are summarized in Table 2.2.

Table 2.2 Bench-Top System Concrete Results (after Dufalla, et al, 2014).

Mixture	pH	Cond µSiemens/cm	CaO%	CaO-ratio	3-day Comp. psi	28-day Comp. psi
Control	-	-	53.1	2.21	4,020	6,060
Mixture 1	11.27	1,184	53.1	2.21	4,280	6,370
Mixture 2	11.14	680	53.1	2.21	4,390	6,210

Chapter 3 – Predictive Equation Development

Data from Dufalla, et al, 2014 was used to develop predictive equations to determine whether a given recycled fines water would produce acceptable concrete. Acceptable concrete was defined as concrete having a compressive strength of at least 90 percent of the control strength (concrete made with tap water) at an age of either 3 or 28 days. The standard error of the predictive equation was considered in the acceptance criteria – the concrete had to be predicted to have a strength greater than 90 plus the standard error of the equation in terms of percent of the control strength.

3.1 Modifications to the Dataset

The purpose of the predictive equations was to determine when the measured parameters for a given mixture would likely produce a concrete mixture with less than 90 percent of the control strength for that mixture. In some cases, Figure 3.1, the strength results showed an optimal amount with strength increasing up to an "optimal" fines amount and then decreasing. When this happened, the data prior to the optimal strength was removed from the full dataset.

3.2 Parameters Considered

The recycled concrete fines water parameters identified in the NCHRP study [Dufalla, et al, 2014] as having the greatest significance, pH and conductivity were used in the new analysis of the data. The range of pH values in the study was 9.0 to 12.1 and the range of conductivity values in the study was 207 to 1,554 μSiemens/cm. In addition, both cementitious materials parameters, CaO% and CaO-ratio were investigated. The range in CaO% values in the study was 44.39 to 61.95 and the range of CaO-ratio was 1.788 to 2.592. Strength values were normalized to the zero-fines control strength for each cementitious combination. A non-linear regression program was used for the analysis, which permitted the use of variations of the parameters such as exp(pH) and 1/conductivity as well as combinations such exp(pH)/conductivity. The resulting predictive equations are presented in the next section.

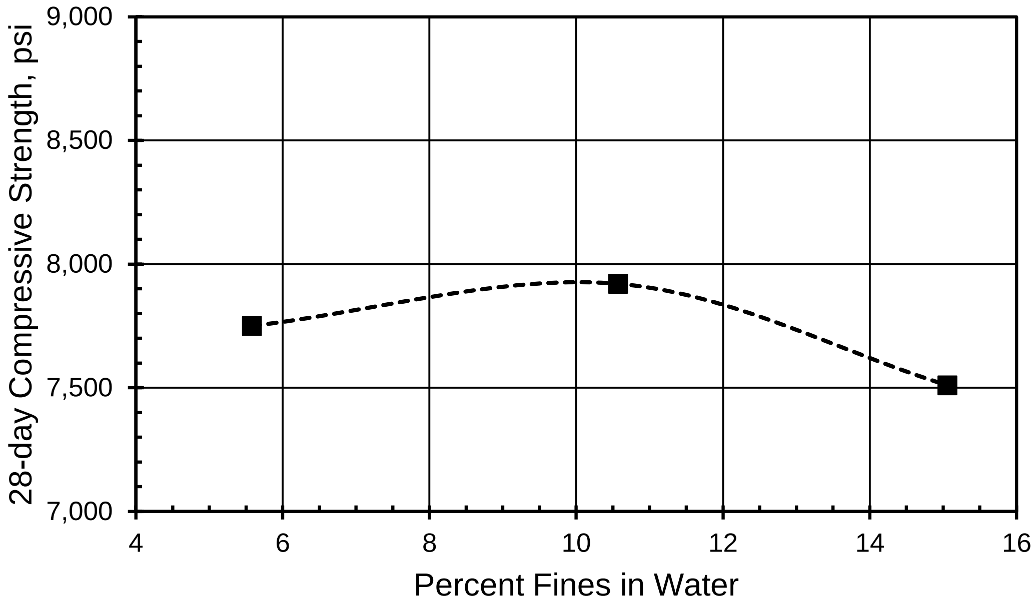

Figure 3.1 28-day Compressive Strength for 37.5% Slag Mixture with Stoneway Hauser Wash-out Fines [after Dufalla, et al, 2014]

3.3 Predictive Equation for 3-day Strength

The predictive equation for the percent of the 3-day control strength (no recycled fines) is given in Equation 3.1: % 3-day = –0.0108*(exp(pH)/cond)+2,222/cond+0.3752*CaO%+78.1

Where % 3-day is the percent of the 3-day control strength,

pH is the pH measured in the recycled concrete fines-water solution,

cond is the measured conductivity, µSiemens/cm, and

CaO% is the percent of CaO in the combined cementitious materials in the mixture.

The standard error of the prediction was 9.1 percent of the 3-day control strength. This is fairly high and means that a prediction of 99.1 percent of the 3-day control strength would be necessary to be assured of meeting a 90 percent control strength with 84% confidence (a one-sided confidence interval is used as over-strength concrete is not a problem).

Figure 3.2 shows Equation 3.1 presented graphically for a range of CaO% values. The curves represent 90 percent of the 3-day control strength at a 90% confidence level. When the pH and conductivity of the recycled concrete waste fines solution plotted to the left of the curve for a particular mixture's CaO%, there would be a 90% chance that the mixture would achieve at least 90 percent of the 3-day control strength.

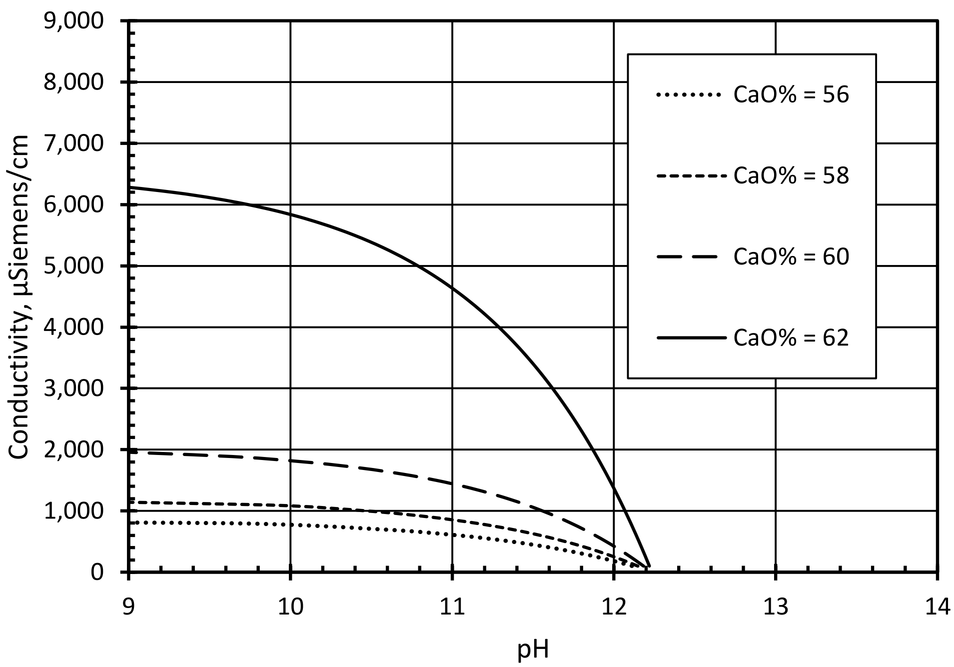

Figure 3.2 Prediction Curves for 90 Percent of 3-day Strength at 90% Confidence.

The curves in Figure 3.2 are plotting so far to the left in the graph because the standard error for the 3-day strength prediction was quite high. Curves for 90 percent of 3-day control strength at 85% confidence are shown in Figure 3.3.

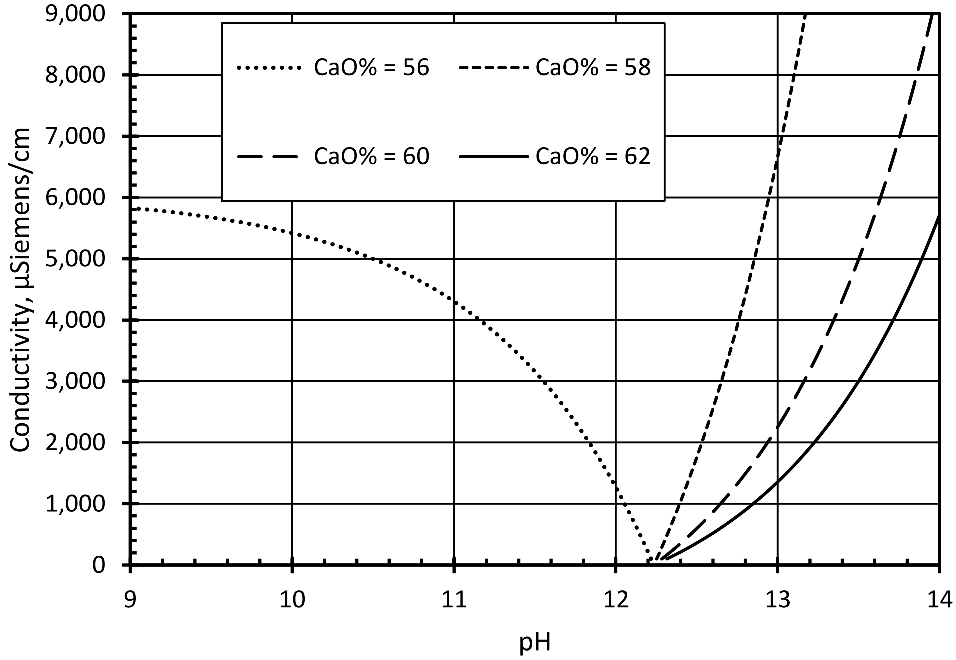

Figure 3.3 Prediction Curves for 90 Percent of 3-day Strength at 85% Confidence.

3.4 Predictive Equation for 28-day Strength

The predictive equation for the percent of the 28-day control strength (no recycled fines) is given in Equation 3.2:

$$\% \text{ 28-day} = -.00001516*\exp(pH)+2{,}897/cond+4.128*CaO\text{-}ratio+86.4 \qquad (3.2)$$

where CaO-ratio is the ratio of the CaO to the Al_2O_3 + SiO_2 in the combined cementitious materials in the mixture

The standard error of the predicted 28-day percent of control strength was 3.3. Curves for 90 percent of the 28-day control strength, at a 90% confidence level, are presented in Figure 3.4. When the measured pH and conductivity for the recycled concrete fines water plots to the left of the curve representing the CaO-ratio for the particular concrete mixture, the concrete with the recycled concrete fines in the mixing water should achieve at least 90 percent of the strength of a control mixture (made with tape water rather than water containing recycled concrete fines).

Because the standard error for this prediction was much better than was found for the percent 3-day strength, only 90%-confidence curves are presented.

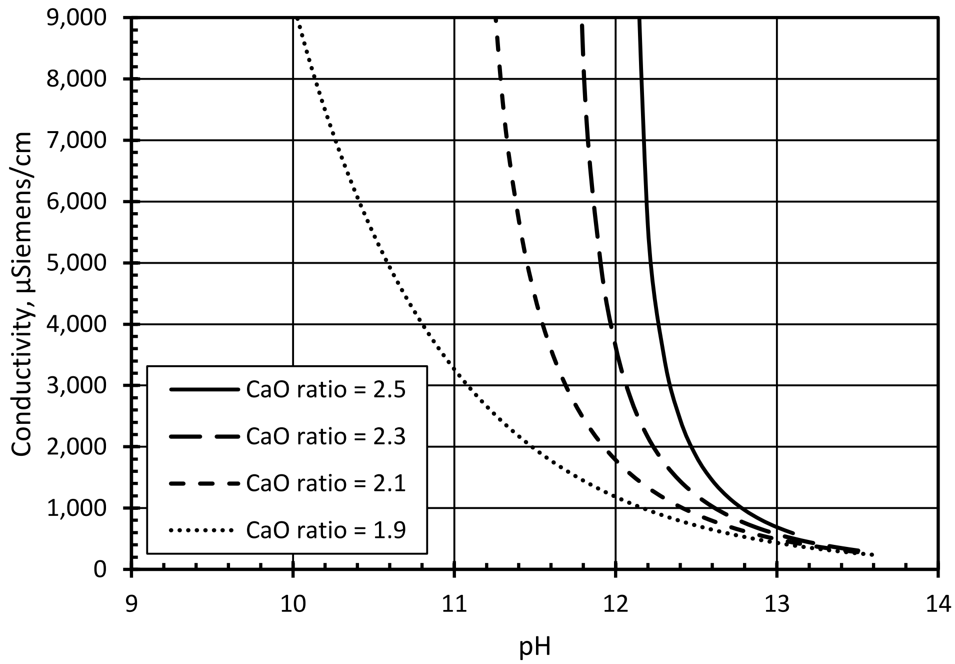

Figure 3.4 Prediction Curves for 90 Percent of 28-day Strength at 90% Confidence.

Chapter 4 – Ready-Mix Concrete Plant Sampling

Sampling was performed at the Stoneway Concrete plant on Houser Way in Renton, WA. The following sections describe the equipment and procedures used for the sampling program.

4.1 Instrumentation

A sensor assemble for measuring pH and conductivity of the concrete mix water was assembled, and is shown in Figure 4.1. The assembly consisted of a submersible pump (lower right in Figure 4.1) connected to PVC tubing (white, in Figure 4.1).

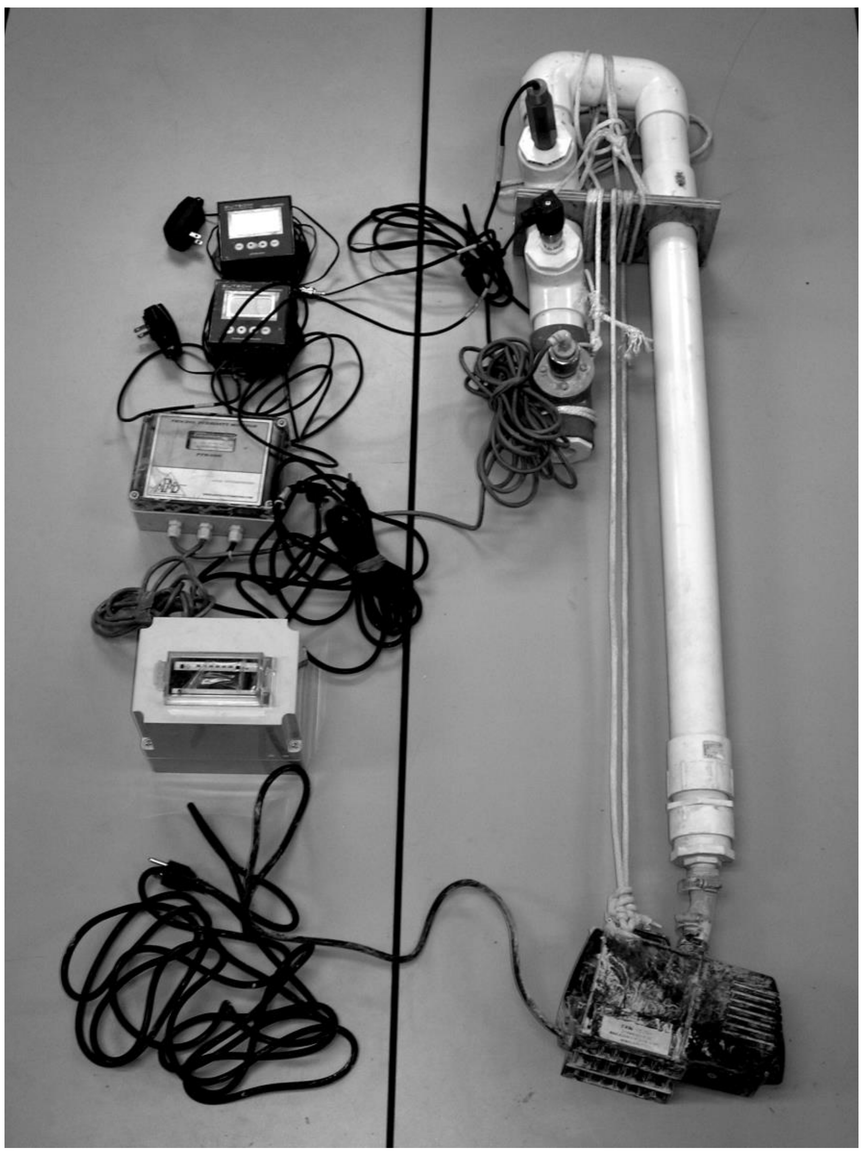

Figure 4.1 Sensor Assembly.

The upside-down U-shape of the tubing was intended to reduce turbulence as well as to make sure that air bubbles were not present in the section of the tubing with the sensors. PVC T-fittings were adapted to fit the pH and conductivity probes. (Note – a third fitting with a turbidity probe was installed as well, but readings from this sensor were not usable due to calibration problems.) Below the final T-fitting and probe the tubing diameter was reduced to assist with reducing turbulence and air bubbles in the large-diameter section containing the T-fittings and sensors. The electrical leads for the sensors were connected to respective read-out devices, left side of Figure 4.1.

The sensor assembly was suspended in the mix-water weigh hopper located above the concrete mixer at the ready-mix concrete plant. The weigh-hopper as well as the top of the sensor-assembly tubing is shown in Figure 4.2. Prior to mixing a batch of concrete, water is added to the weigh hopper until the correct amount of water for the next batch of concrete is reached. The quantity of water in the weigh hopper is determined by the use of electronic load cells that measure the weight of the water in the hopper. When a concrete batch was being sampled for this research, readings from the sensor readouts were manually recorded by a researcher on the weigh-hopper platform. The water was then discharged into the concrete mixer as part of the regular concrete batching process.

4.2 Mixture Water Differences

The ready-mix concrete plant maintains two separate sources of water: "pond" water, which is collected surface run-off water (mostly rainfall) from the concrete plant site and buildings, and "recycled" water, which is water obtained from washing out ready-mix concrete trucks after the aggregate is extracted for re-use. The recycled water is maintained in a circulation system to keep particles suspended rather than allowing them to settle out (which would require separate disposal).

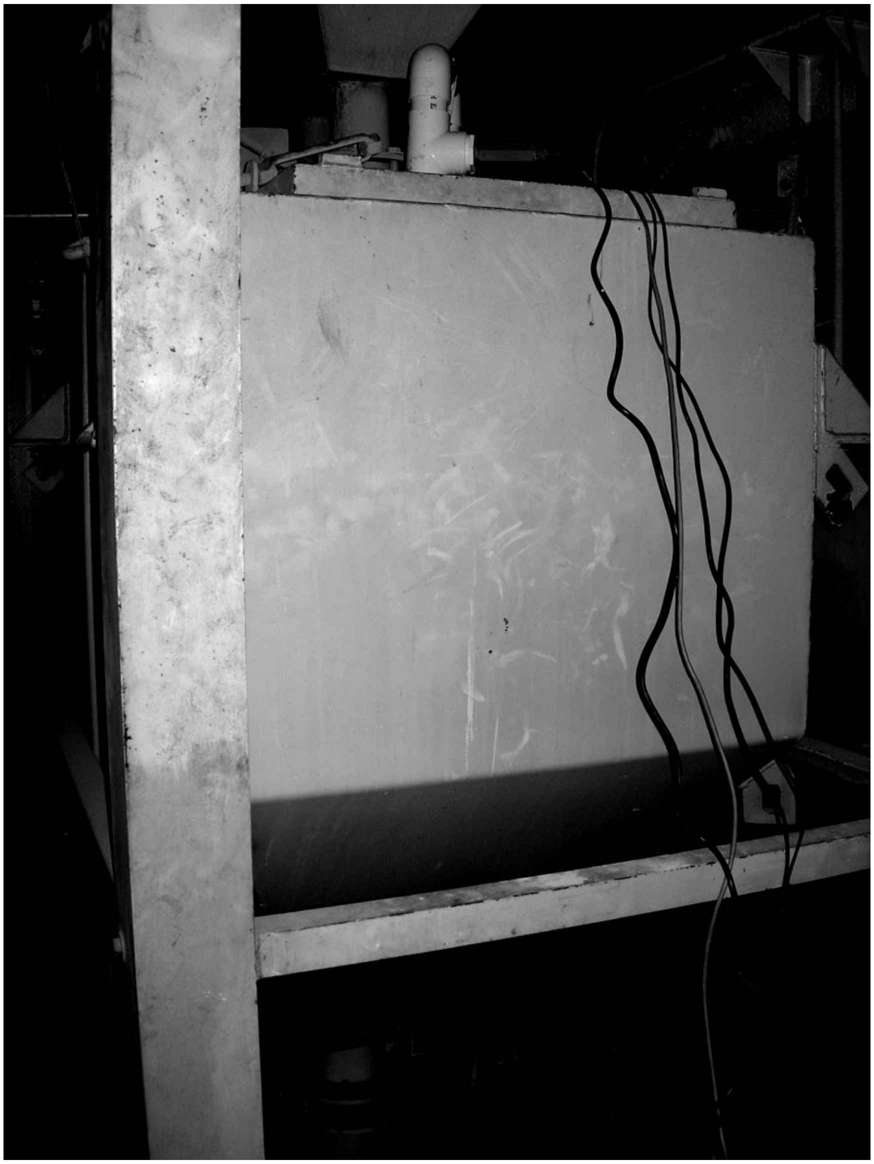

Figure 4.2 Sensor Assembly in Mix-water Weigh Hopper.

Concrete batches are usually prepared using a mixture of pond and recycled water. For this project, three separate batches of the same concrete mixture proportions were sampled. One batch was prepared using 100% pond water, one was prepared using 100% recycled water and a third batch was prepared using a blend of both pond and recycled water.

4.3 Concrete Sampling

After a concrete batch to be samples had been mixed and discharged into a ready-mix truck, the truck drove to a location adjacent to the concrete mixer building at the concrete plant. A small amount of the concrete was discharged into a wheelbarrow and the concrete truck went on to whatever construction project had ordered that concrete. A researcher would them prepare a minimum of six 4”x8” concrete cylinders. These samples were transported back to the University of Washington concrete materials lab the following day, demolded, and capped with a standard capping compound and placed in a moist curing room until being tested in compression at either three or 28 days.

Concrete was sampled on four separate days (5/20/2014, 9/16/2014, 10/17/2014 and 11/7/2014). The mixture sampled on 5/20/2014 and 9/16/2014 had control strengths (batches made with tap water) of 3,020 psi at 3-days and 6,390 psi at 28-days. The batches sampled on 10/17/2014 and 11/7/2014 had control strengths of 3,370 psi at 3-days and 7,280 psi at 28-days. (values provided by the concrete producer).

4.4 Results

A summary of the test results is presented in Table 4.1. Control strength values are included for comparison purposes. In addition to the measurements shown in Table 4.1, specific gravity values for the water in the recycled water recirculation system were obtained from the plant operator on 9/16/2014, 10/17/2014 and 11/7/2014. These values were 1.062, 1.078 and 1.040, respectively.

On the 10/17/2014 and 11/7/2014 sampling dates actual water samples were obtained from the weigh-hopper at the same time that the pH and conductivity readings were taken.

These samples were used to determine the percentage of solids in the mix-water by oven-drying. The values are presented in Table 4.2.

Table 4.1 Concrete Plant Sampling Results.

Sampling Date	Water Description	pH	Conductivity µSiemens/cm	3-day Str. psi	28-day Str. psi
5/20/2014	Control	-	-	**3,020**	**6,390**
	Pond	9.98	200	3,210	7,100
	Blend	11.68	5,350	3,130	6,620
	100% Recycled	12.57	7,710	3,450	6,690
9/16/2014	Control	-	-	**3,020**	**6,390**
	Pond	12.11	240	3,230	6,520
	Blend	12.59	5,620	2,960	5,240
	100% Recycled	12.67	8,440	3,640	6,090
10/17/2014	Control	-	-	**3,370**	**7,280**
	Pond	10.84	200	3,680	6,720
	Blend	11.82	2,990	3,980	6,880
	100% Recycled	12.45	4,360	4,130	7,030
11/7/2014	Control	-	-	**3,370**	**7,280**
	Pond	10.28	170	3,960	7,890
	Blend	11.08	2,150	3,980	7,910
	100% Recycled	12.38	3,800	3,720	7,330

Table 4.2 Percent Solids of Mix-water.

Sampling Date	Pond	Blend	100% Recycled
10/17/2014	0.0	4.4	13.0
11/7/2014	0.0	5.5	11.1

It should be noted that the values shown in Table 4.2 represent the precision of the measurements. Though the pond water is listed as having 0.0 percent, there was a visible film on the sides of the evaporation containers for these samples.

Chapter 5 – Analysis of Results

The results are analyzed in the following sections. Graphs as in Chapter 3 have been prepared for each set of mixture proportions (CaO% or CaO-ratio), and the datapoints (pH and conductivity) are plotted on each graph. Solid symbols are used for strengths that met the "90 percent of control strength" criterion on each graph and hollow symbols are used for mixtures that failed the criteria. Points that plotted to the left of the curve are predicted to be acceptable while points plotting to the right of the curve are predicted to have a strength less than 90 percent of the control strength.

5.1 Laboratory Simulation

The laboratory simulation concrete mixtures from the NCHRP-IDEA study [Dufalla, et al, 2014] are shown in Figures 5.1 (3-day strengths) and 5.2 (28-day strengths).

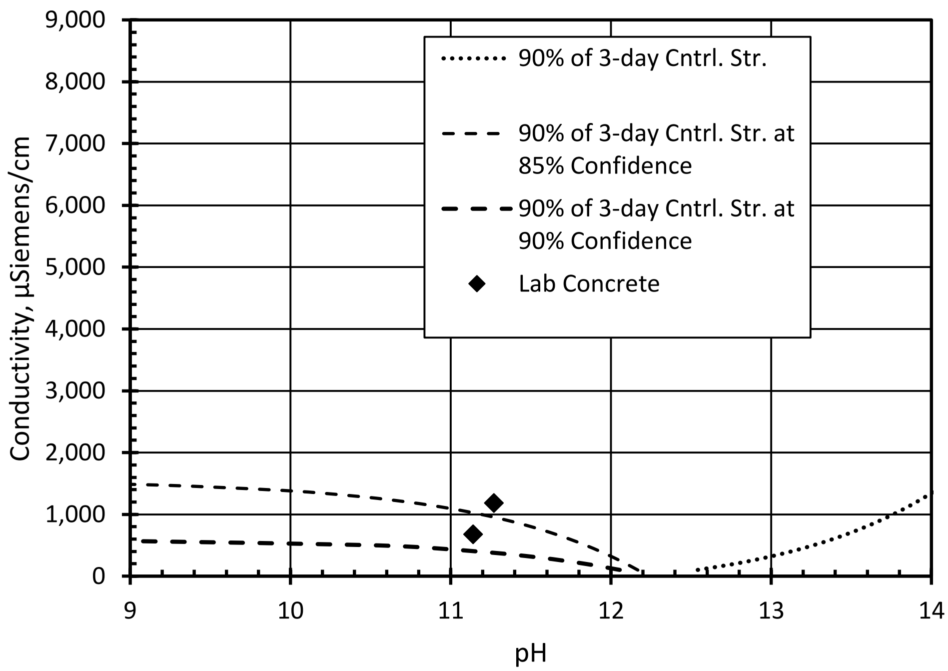

Figure 5.1 3-day Strength Graph for Laboratory Simulation (CaO% = 53.1).

Though both mixtures met the 90-percent 3-day strength criteria, both mixtures are predicted to fail at 90% confidence and one is predicted to fail at 85% confidence.

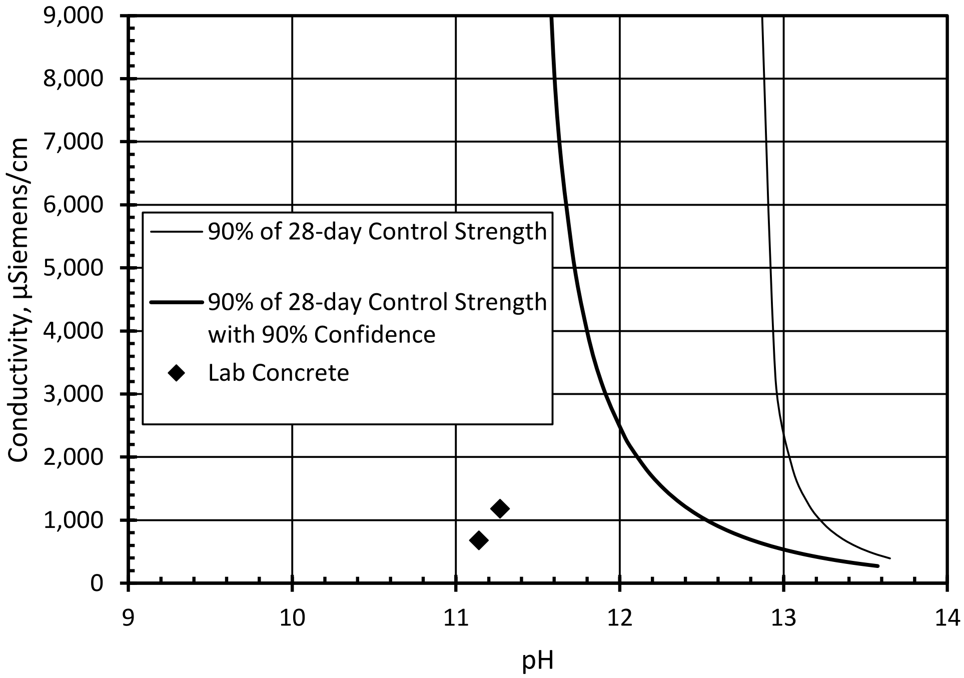

Figure 5.2 28-day Strength Graph for Laboratory Simulation (CaO-ratio = 2.21).

The 28-day prediction performed much better, with both mixtures predicted to meet the 90-percent strength criteria (which they actually did).

5.2 Sampling on 5/20/2014 and 9/16/2014

The mixtures samples on 5/20/2014 and 9/16/2014 are plotted in figures 5.3 for 3-day strength criteria and Figure 5.4 for 28-day strength criteria. Only the "Pond" mixtures (lowest conductivity values) were predicted to achieve 90 percent strength at 90% confidence while the other mixtures satisfied the prediction at 85% confidence. All mixtures actually achieved at least 90 percent of the control 3-day strength.

At 28-days, half of the mixtures (those with the highest pH values) did not meet the 90 percent strength prediction at 90% confidence while the other half did. One of the mixtures that did not meet the strength prediction only achieved 82% of the control strength in actual testing (indicated on the graph as an open symbol) while the other two did. All three mixtures predicted to achieve 90% strength did.

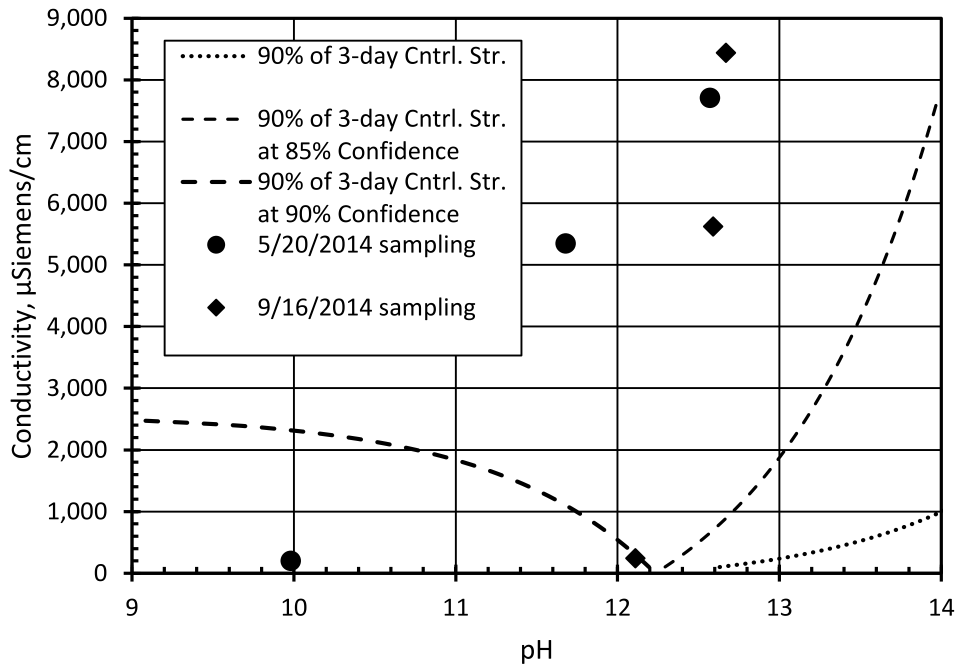

Figure 5.3 3-day Strength Graph for 5/20/2014 and 9/16/14 Sampling (CaO% = 60.6).

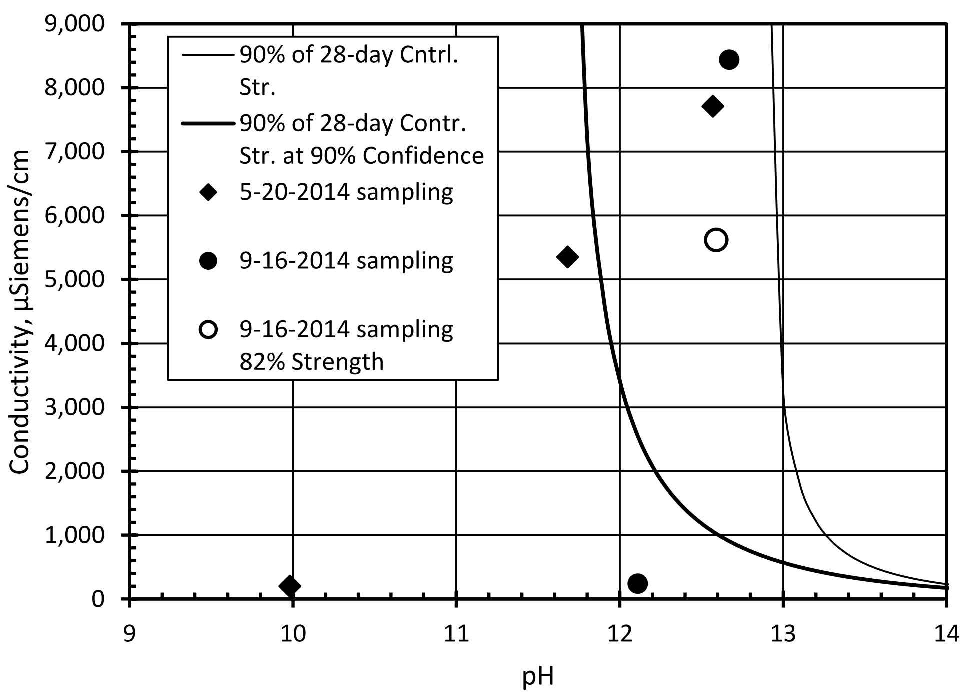

Figure 5.4 28-day Strength Graph for 5/20/2014 and 9/16/14 Sampling (CaO-ratio = 2.28).

5.3 Sampling on 10/17/2014 and 11/7/2014

The mixtures samples on 10/17/2014 and 11/7/2014 are plotted in figures 5.5 for 3-day strength criteria and Figure 5.6 for 28-day strength criteria.

All of the 3-day strength predictions were acceptable at 85% confidence while only the three mixtures with the lowest pH and conductivity readings were predicted to be acceptable at 90% confidence. All six mixtures actually tasted above 90 percent of the 3-day control strength.

For the 28-day testing, only the two mixtures with the highest pH readings were predicted to not meet the 90 percent strength criterion. The remaining four mixtures were predicted to meet the 90 percent strength criterion and all six mixtures actually achieved at least 90 percent of the control strength when tested.

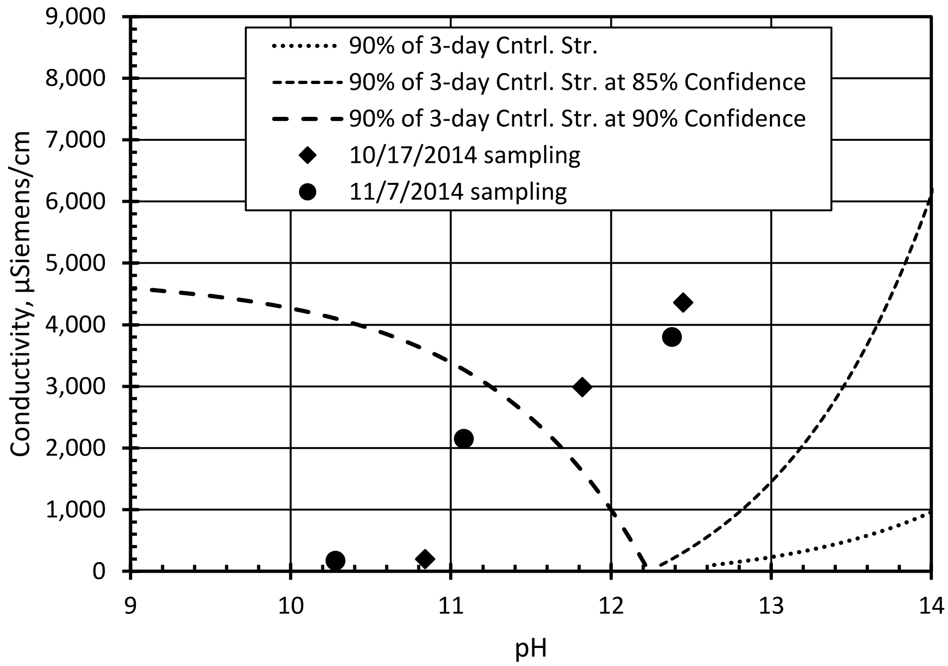

Figure 5.5 3-day Strength Graph for 10/17/2014 and 11/7/2014 Sampling (CaO% = 61.7).

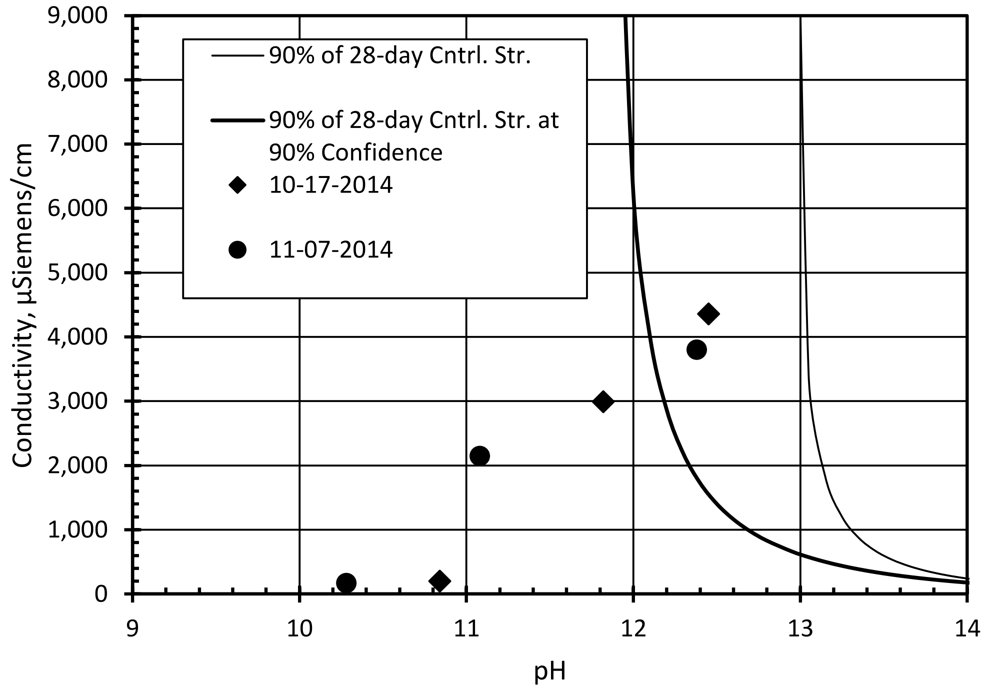

Figure 5.6 28-day Strength Graph for 10/17/2014 and 11/7/2014 Sampling (CaO-ratio = 2.38).

Chapter 6 – Discussion

The accuracy of the predictive equations as well as strengths and weakness of the models are discussed in the following sections

6.1 Strengths at 3 Days

The predictive accuracy of the model for achieving at least 90 percent of the 3-day compressive strength is illustrated in Table 6.1. The model was correct at an 85% level of confidence for all mixtures except 1. At a 90% confidence level the prediction was incorrect (False Negative) for 9 of the 14 mixtures. The prediction for 3-day strength is poor, but it should be noted that the incorrect predictions were all False Negative – that is, the prediction was that the concrete would not achieve 90 percent of the control strength at 90% confidence whereas 90 percent of the 3-day control strength was always met. One problem with the 3-day predictive model is that there was a lot of scatter. The standard error of the strength prediction was almost 10 percent.

Table 6.1 Prediction Accuracy for 3-day Acceptance Model.

pH	Cond	85% Confidence	90% Confidence
9.98	200	Positive	Positive
10.28	170	Positive	Positive
10.84	200	Positive	Positive
11.08	2,150	Positive	Positive
11.14	680	Positive	False Negative
11.27	1,184	False Negative	False Negative
11.68	5,350	Positive	False Negative
11.82	2,990	Positive	False Negative
12.11	240	Positive	Positive
12.38	3,800	Positive	False Negative
12.45	4,360	Positive	False Negative
12.57	7,710	Positive	False Negative
12.59	5,620	Positive	False Negative
12.67	8,440	Positive	False Negative

6.2 Strengths at 28 Days

The predictive accuracy of the model for achieving at least 90 percent of the 28-day compressive strength is illustrated in Table 6.2. Ten of the 14 predictions were correct (nine predictions that the concrete would achieve at least 90 percent of the control strength and one prediction that it wouldn't). Four of the predictions were False Negatives; predicting that the concrete would not achieve 90 percent of the control strength when it actually did. All of three False Negatives occurred at the highest pH and/or conductivity values.

Table 6.2 Prediction Accuracy for 8-day Acceptance Model.

pH	Conductivity	90% Confidence Prediction
9.98	200	Positive
10.28	170	Positive
10.84	200	Positive
11.08	2,150	Positive
11.14	680	Positive
11.27	1,184	Positive
11.68	5,350	Positive
11.82	2,990	Positive
12.11	240	Positive
12.38	3,800	False Negative
12.45	4,360	False Negative
12.57	7,710	False Negative
12.59	5,620	Negative
12.67	8,440	False Negative

6.3 Limitations of Predictive Models

The predictive models presented in Chapter 3 are based on data developed in NCHRP-IDEA Project 166 [Dufalla, et al, 2014] that has a range of pH values from 9.0 to 12.1 and a range of conductivity values from 207 to 1,554 µSiemens/cm. The actual pH measurements made at the concrete batch plant ranged from 9.98 to 12.67 and the conductivity measurements ranged from 200 to 8,440 µSiemens/cm. In many cases the models were operating as extrapolations rather than interpolations. All of the False Negatives for the 28-day model occurred when pH and/or conductivity values were outside of the original data range as did most of the False Negatives for the 3-day model. Additional data at higher pH and conductivity values is needed to produce a more robust model. It should be pointed out that the 40°C drying utilized when the original data was developed may have promoted reaction of some of the ions originally dissolved in the various recycled concrete fines sources, resulting in lower conductivities and possibly lower pH values.

One positive note with respective to the predictive models is that the single mixture that failed to achieve 90 percent strength criterion (9/16/2014) sampling, a mixture made with a blend of Pond and Recycled water, was correctly predicted through the pH and conductivity readings.

Chapter 7 – Conclusions and Recommendations

The work conducted in this project has led to the following conclusions and recommendations.

7.1 Conclusions

The following conclusions can be drawn from the work described in this report:

1. Concrete can be produced at a ready-mix concrete plant using water containing recycled concrete fines at considerably higher than the optional 5% level listed in the optional provisions in ASTM C1602, Table 2 and still achieve acceptable strength. Table 7.1 lists the mixtures from this study that exceeded 5% fines in the mixing water.

Table 7.1 Mixtures Exceeding 5% Fines in the mixing Water.

Sampling Date	Percent Solids	Percent 28-day Strength
9/16/2014	9.5*	95
10/17/2014	13.0	97
11/7/2014	5.5	109
11/7/2014	11.1	101

* Estimated using Equation 6 from ASTM C 1603-10.

The only mixture to not to achieve at least 90 percent of the 28-day control strength probably had a fines content of less than 5%, as it was a blend of Recycled and Pond water from the 9/16/2014 sampling. This mixture had a fairly high pH but a significantly lower pH than the 100% Recycled water mixture from that sampling day.

2. Fines content (closely related to Specific Gravity of the recycled water according to ASTM C1603) may not be the best method to predict whether or not water containing recycled concrete fines will produce acceptable strength. As pointed out above, the blended water from the 9/16/2014 sampling did not produce acceptable strength though in all probability it was below 5% fines. This water had very high pH (second highest measured in the study). The predictive equation presented as Equation 3.2 suggests that pH has a negative influence on 28-

day strength while conductivity has a positive effect. The pH of the mixing water should be considered when evaluating the effects of water containing recycled concrete fines on concrete strength.

3. None of the mixtures sampled had 3-day compressive strengths that were less than 90 percent of the control strength. In fact, in every case but one the measured 3-day concrete strength was higher than the corresponding control strength. (the one mixture that did not exceed the corresponding control strength achieved 98 percent of the control strength). The use of recycled concrete fines in mixing water should not be a concern for early strength.

4. Conductivity and pH can be easily measured with in-line sensors in the recycled water system at ready-mix concrete plants to provide improved information which would allow greater utilization of recycled concrete fines in concrete mixtures.

7.2 Recommendations

The predictions developed in this study had higher than desirable variability – especially the prediction for the probability of achieving 90 percent control strength. Also, the range of conductivity values used to develop the predictive equations was significantly exceeded by conductivities measured at a concrete ready-mix plant. Additional data should be collected to allow better predictive models to be developed, and especially so that the amount of extrapolation in the predictive models can be reduced (or preferably eliminated).

Concrete plant operators should consider monitoring the pH of their recycled water systems, as the only under-strength results were obtained for water that had very high pH and moderate conductivity.

Agencies and designers specifiers responsible for specifying concrete mixtures should not require mixing water to meet the optional ASTM C1602 requirement of a maximum of 5%

recycled concrete fines in the mixing water, as satisfactory performance can be achieved at fines contents that significantly exceed this limit.

Concrete ready-mix plant operators should install conductivity and pH monitoring systems in their recycled-water recirculation systems in order to better predict possible detrimental effects of high-fines water, especially if the concrete truck wash-out water is augmented with recycled fines from sawcutting and/or pavement diamond-grinding operations.

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