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Highway IDEA Program

Guidelines for Use of Waste Concrete Fines

Final Report for
Highway IDEA Project 166

Prepared by:
Nicole Dufalla
Julie M. Vandenbossche, Ph.D., P.E.
Donald J. Janssen, Ph.D.
University of Pittsburg

July, 2014

TRANSPORTATION RESEARCH BOARD
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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

GUIDELINES FOR USE OF WASTE CONCRETE FINES

Final Report

University of Pittsburgh
Department of Civil and Environmental Engineering
Pittsburgh, Pennsylvania 15261

Prepared by:

Nicole Dufalla
Julie M. Vandenbossche, Ph.D., P.E.
Donald J. Janssen, Ph.D.

Prepared for:

National Cooperative Highway Research Program IDEA: Project No. 166

October 2015

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1. INTRODUCTION

Concrete production and maintenance operations produce substantial amounts of wastewater from grinding and wash out operations. Typical values acquired from pavement grinding maintenance activities are shown in Figure 1. This wastewater has the potential to be reused in new concrete production as mixing water, and experiments to date have been largely supportive of this form of recycling. Recycled wastewater used in fresh concrete production must adhere to the same guidelines for any concrete mixing water, ASTM C1602.

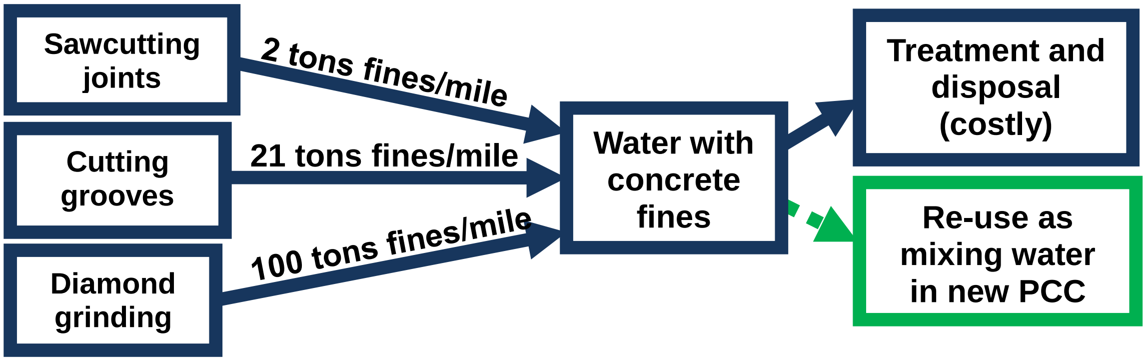

FIGURE 1 Typical production values for grinding fines maintenance activities.

An overview of experiments thus far utilize a variety of materials characterization methods and performance measurements, with set time and compressive strength testing being the most consistently measured indicators of hardened concrete performance while the wastewater itself was most often characterized by its solids content. Experimental results so far have indicated a potential increase in early strength for compressive strength values taken usually at 3 or 7 days. Explanations for this increase in early strength include improved particle packing, due to a potentially wider particle size distribution when including the recycled water. Also observed was an expedited hydration rate, potentially due to the included hydrated cement particles in the wastewater providing more nucleation sites, or to the presence of calcium hydroxide and elevated pH in the recycled water.

1.1 Production of Concrete Wastewater

A substantial amount of wastewater is produced at different stages throughout the lifespan of a concrete pavement, from standard production, maintenance, and removal practices. During production and following the placement of ready-mix concrete, concrete mixing trucks and equipment are washed out, a process which requires up to 64 gallons of water per cubic yard of waste concrete (Geem et al. 1998). After hardening, construction procedures such as joint saw cutting and diamond grooving, as well as maintenance procedures such as diamond grinding, also require water to control dust and to cool the saw blades. Likewise, at the end of a concrete pavement's useful life, additional water for dust control is needed during crushing and removal operations. Each of these actions produce water with a high pH containing hydrated cement particles and possibly chemical additives, and requires proper disposal as it is categorized as an environmentally harmful material (Shogren et al. 2009). These specific fines sources and their disposal requirements and effects on water are discussed below.

1.1.1. Grinding fines

The removal of hardened concrete, either when saw cutting joints, or grinding or grooving produces a concrete dust, which must be controlled by water and results in a wastewater product. Water is also used during these construction procedures to cool the saw blades. Each removal practice produces a different quantity of fines but they are regulated and treated in a similar manner.

Saw cutting of joints occurs as soon as the concrete is sufficiently hard to support the saw cutting operation without generating spalling. Cutting joints in jointed concrete pavements produces approximately 2 tons of concrete fines per lane mile. Joint cutting occurs earliest in the lifespan of a concrete pavement relative to other grinding fines-producing maintenance activities. Therefore, while the concrete may be sufficiently hard for joint formation, it remains in a different stage of hydration than typical grinding and grooving projects. Wastewater produced from joint saw cutting would therefore be expected to have a different chemical composition than those acquired from older concrete pavements.

Diamond grooving, both a restoration technique for aged concrete and a surface friction controlling technique for new concrete, follows a similar procedure to diamond grinding but ultimately removes less concrete from the surface and on average produces only approximately 21 tons of concrete fines per lane mile. The expectations of material properties for wastewater from diamond grooving vary based on the age of the concrete. For maintenance operations on aged pavement, a lower pH is expected due to the carbonation of the surface. Diamond grooving completed on new construction is expected to contain both unhydrated and hydrated cement particles and produce a recycled water having a higher pH.

Diamond grinding is a restoration technique used for portland cement concrete (PCC) surfaces where closely-spaced lines are cut into existing concrete pavements using diamond blades. It primarily removes a thin layer of the concrete pavement to restore the original profile or surface friction. This rehabilitation method removes joint and crack faulting, removes wheel path ruts from studded tires, corrects joint unevenness, and restores transverse drainage (AASHTO 1993). On average, diamond grinding repairs reduce the slab thickness by 3/16 to ¼ in. (Correa et al. 2001). Typically, diamond grinding produces approximately 100 tons of concrete fines per lane mile. This dust is controlled by water to produce wastewater containing hydrated cement particles as well as rock powder.

The effect of the fines on the water can vary widely and is a function of the specific concrete composition, the original quality of the wash water, and possible contaminants on the pavement surface during the maintenance operations. One of the most easily measured detrimental effects of this waste slurry is its high pH, where a value greater than 11.5 categorizes the water as an environmentally harmful substance (EPA Water Quality Act 1987). In some cases, directly disposing this waste slurry onto the roadside soil was found to raise the pH from 6.3 upwards of 9.4 (Shanmugam 2004). In a North Dakota study, the pH of concrete grinding slurry was found to fall between 11.6 and 12.5.

All three of these methods (diamond grinding, diamond grooving, and joint saw cutting) produce a wastewater infused with hydrated cement particles that requires proper disposal. In the United States, regulations for the disposal of these waste materials is specified by each state, ranging from disposal below a roadway's shoulder to offsite disposal in containment ponds and landfills (DeSutter et al. 2011).

1.1.2. Wash out fines

A second source of concrete fines occurs from washing out concrete trucks. The ready-mix concrete industry is responsible for large amounts of water consumption, specifically from concrete production, and washing out concrete mixing trucks and drums, required after each load (Tsimas et al. 2011). The estimated daily requirement for wash water for each concrete mix truck is 1,500 liters (L) (400 gallons). This wastewater contains hydrated cement particles and typically has an elevated pH, which requires it to be classified and treated as a hazardous material by both European and United States environmental regulations. Traditionally, this wash water has been disposed of in settling ponds at ready-mix concrete facilities to allow for the suspended solids to settle and the water to slowly filter. The settled suspended solids can then be dried and sent to a landfill. However, given the elevated pH of this product and recent categorization as a potentially hazardous material, requirements for disposal and treatment are becoming more stringent both within the United States and worldwide. The presence of dissolved calcium hydroxide leads to a high pH in the concrete wash water and the water has also been found to contain other dissolved solids, including sulfates, hydroxides, and chlorides, as well as traces of oil, and grease (Elchalakani et al 2012).

In the United States, the Environmental Protection Agency (EPA) 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). EPA published recommendations for the recycling of concrete wash out water suggest filtering the wastewater 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. EPA also recommends recycling concrete aggregate if separation from the mortar matrix is feasible (EPA 1987).

In the United Kingdom, wastewater has traditionally been disposed of in landfills, but recent regulations from the Environmental Agency have categorized water with a pH higher than 11.5 as hazardously alkaline and an additional tax for landfill disposal of concrete wastewater has been enforced (Sealey et al. 2001). The combination of the increasing cost of proper disposal and treatment with increasingly stringent disposal regulations has led to the reuse of concrete wash water in many countries.

1.2. Mixing Water Regulations for New Concrete Construction

One primary obstacle in using recycled wash water for concrete mixing water are the governing standards for mixing water for the production of fresh concrete. Standard specifications exist for the quality and content (including total solids, chlorides, alkalis, and sulfates) of mixing water used for fresh concrete production in both the United States (ASTM C1602) and Europe (EN 1008). Both specifications outline expectations and requirements from all water sources and provide additional quality control guidelines specifically for the reuse of water recovered from the concrete industry, which includes wash out water as well as water from grinding and cutting operations.

Both sets of standards outline two absolute requirements for any mixing water used regarding both compressive strength and time of set. Any mixing water used must meet the requirement that 7-day compressive strength is at least 90% of the mean compressive strength of the control mixture where the control concrete mixture is made with distilled or deionized water. In the ASTM C1602 specification, the time of set must not vary from the control mixture by less than 60 min or more than 90 min. The EN 1008 requirement also specifies that the time of set cannot vary by less than 60 min of the control set time but also cannot vary in either acceleration or retardation by 25% of the control mixture set time. These regulations pertaining to set time and compressive strength serve as the absolute minimum requirements for any water used for new concrete production.

The mass of solids is also governed by both specifications and is estimated in both through the water density. A water density of 1.03 g/L corresponds to a solids content of approximately 50,000 ppm. The ASTM C1602 specification lists an optional limit of total solids content of 50,000 ppm, to be specified by the purchaser or concrete mixture designer. Limits on the composition of these solids are also given with limiting values provided for chloride, sulfates, and alkalis content.

Limitations on the concentration of dissolved chloride ions are given primarily because of the possible corrosion of embedded reinforcing or prestressing steel. Variable limits are specified based on the use of the concrete and whether or not it will contain reinforcing steel. ASTM C1602 limits this value to 500 ppm for prestressed concrete and bridge decks and 1000 ppm for other reinforced concrete while the EN 1008 specification limits the chloride content to 500 mg/l for prestressed concrete, 1000 mg/l for reinforced concrete and 4500 mg/l for plain concrete.

Potentially expansive reactions and consequent deterioration by sulfate attack drives the limitations of sulfate content in mixing water. This reaction can be expedited or exacerbated from environmental conditions, such as high sulfate soils. As a result, the ASTM C1602 specification limits sulfate content to 3000, ppm while the EN 1008 specification limits sulfate content to 2000 mg/l.

Finally, alkalis such as Na_2O and K_2O must also be limited as high concentrations of alkalis have been found to reduce concrete strength while accelerating the hydration process (Kosmatka 2002). This ultimately lowers 28-day strength despite accelerating the early strength. Additionally, high alkaline water can instigate the development of alkali-silica reactions in the final concrete. The concentration of alkalis is limited to 600 ppm and 1500 mg/l for the ASTM C1602 and EN 1008 specifications, respectively. The EN 1008 provides a leniency with this limit, however, and specifies that water with alkali content higher than this specification is acceptable for use if proactive measures are taken to prevent alkali-silica reactions.

Additionally, EN 1008 provides limitations for miscellaneous other contaminants that could possibly be found in all mixing water and considered harmful, such as sugar, phosphate, nitrates, lead and zinc. Restrictions are also outlined in EN 1008 for non-harmful contaminants including oils, fats, detergents, color, suspended matter, odor, pH, and humic matter. It should be noted that only a lower limit of a pH of 4 is given for mixing water in this specification and no upper limit is specified.

The ASTM requirement offers no further requirements exclusively for the reuse of water except to suggest the use of hydration stabilizing admixtures (HA) for water with a density greater than 1.05 g/L in order to meet the two primary base requirements of mixing water: compressive strength and time set. Hydration stabilizing admixtures can reduce the rate of hydration of cement by a pre-determined amount (based on dosage) to manipulate the time of set and are frequently used for extending the time frame of concrete delivery.

In addition to the requirements outlined for all mixing water, supplementary specifications are given in the EN 1008 specification, particularly for the use of recycled concrete water as a replacement of fresh mix water. The specification assumes that no adjustments are made in the concrete mix design and any cement particles in the recycled water will be additive to the existing value of cement in the concrete mix. Based on this, a limit on these additional solids is given as less than 1% of the total mass of the aggregates in the concrete mix. Any unique requirements beyond those for standard concrete, such as architectural concrete, prestressed concrete, air entrained concrete, or concrete in extreme climate conditions, must be additionally evaluated with respect to effects of recycled concrete on the particular requirements. Additionally, the reuse of recycled water should be evenly distributed through concrete production over the course of a day.

The density specification is used to estimate total solids content in the recycled concrete mixing water, and water with a density greater than 1.01 kg/l (which would indicate a non-trivial amount of residual concrete fines in the water) requires agitation when used to maintain a homogeneous distribution of the solids. The mass of solid material in the water is a more flexible and discretionary quantity, specified only that, "for some production processes, a greater quantity of solid material may be used provided satisfactory performance in concrete can be demonstrated" (DIN-EN-1008).

The Portland Cement Association recommends total solids below 50,000 ppm, because concerns are raised when values are higher values regarding the effects on set time, concrete efflorescence, possible rebar corrosion, volume instability, reduced durability and reduced workability of the final concrete product (Geem 1998). The ASTM standard, however, holds set time and compressive strength of the final concrete product as its primary concern.

1.3. Characterization of Recycled Water and Performance Parameters

Given the broad spectrum of concentrations, materials, and degree of hydration of wastewater as well as varying sources, material characterization of wastewater is required to give some correlation to concrete performance. This can include, but is not limited to, testing pH, amounts of organic matter and electric conductivity. Previous work has included measuring varying concrete properties, to compare with specifications. These hardened properties always include compressive strength measurements. Both fresh and other hardened concrete properties have also been measured in an attempt to provide some indication of the wastewater suitability for reuse, as will be further discussed below.

As per the specification requirements, characterization of the recycled water itself included measurements of soluble salt, chloride, and sulfate content as well as the total solids content to ensure compliance with the specification limits. Other measurements taken to characterize the mix water quality included measuring mineral, salt, and miscellaneous impurities contents (Borger et al. 1994). Solids content was also used to estimate density and percentage of solids by mass based on loss on ignition measurements (Lobo et al. 2001). Dissolved solids and conductivity were also measured to provide some indication of concrete performance and solids content of both hydrated and unhydrated cement particles (Ekolu et al. 2010). Likewise, specific gravity can be measured and used through linear relationships to estimate total solids content of the slurry water (Chatveera et al. 2009).

Properties used to measure the performance of fresh concrete included the slump test for workability. Workability was a primary concern for concrete made with recycled waste materials because of the expedited increase in set time of the mortar and concrete possibly due to the expedited hydration. Consistently, it was found that increasing the quantity of waste fines in concrete both shortened the set time and decreased the workability of the mix measured either through slump testing for concrete or flow measurements for mortar (Sandrolini et al. 2001).

Sandrolini et al. (2001) focused primarily on the effect of the microstructure on concrete performance and therefore also included studying grain size distributions to quantify the fineness of the solid matter. Set time, which is also a constraint in mixture specifications, was also measured to indicate rate of hydration (Borger et al. 1994). Sulfate resistance of the mortar should also be measured if the mix water quantities have indicated that elevated sulfate levels are present.

Concrete durability can be improved by fine filler effects and a reduction of concrete capillary water absorption and porosity. Measuring the concrete’s porosity has also provided some indication of performance due to its relationship to the grain size distribution and correlation to the mortar mix density (Sandrolini et al. 2001). Similarly, an increase in the resistance of the concrete to sulfate attack, as measured through expansion mortar bar testing, provided an indication of the increased density of the mortar matrix (Borger et al. 1994).

1.4. Effects of Using Recycled Fines

Quantifying the effects of using recycled wash water and wastewater has been largely unexplored. Most projects that have tested the effects of including recycled concrete waste fines water in the production of new concrete have not established a relationship between characteristics of the water and properties of the final project. Rather, research to this point has included ensuring that recycled water falls within mixing water specifications and that the final concrete produced falls within concrete strength specifications. Considering the two primary concerns of concrete specifications being time of set and compressive strength, three trends were observed: (1) the inclusion of wastewater increased short-term concrete and mortar strength (3 or 7-day testing) and (2) the inclusion of wastewater had negligible effect on 28-day strength results and (3) time of set test results were highly varied. These differences have been primarily attributed to particle packing effects and acceleration of the concrete hydration reaction, which will be discussed at the end of this section. Both particle packing effects and acceleration of the hydration reaction have been thought to contribute to potential early strength gains but the amount that either contributes to compressive strength gain remains unknown (Jaturapitakkul 2011).

Limited work has been completed so far using recycled water as mixing water for new concrete and testing procedures have been largely inconsistent, leading to inconsistent and incomparable results. Most have maintained water requirements of either or both ASTM C94 and EN 1008 standards. Different methods of characterizing fines and fine properties were used and in some cases, a hydration stabilizing admixture was used to widen the period of time when concrete fines could be used. Studies testing plain concrete made with recycled water will be discussed first followed by studies including additives and admixtures in the concrete mix and test methodologies, parameters measured, and results for each of these studies will be discussed.

1.4.1. Plain concrete testing

Work by Sandrolini et al. (2001), which evaluated water against both ASTM and EN 1008 standards collected water at varying amounts of settling and was characterized by pH, amounts of suspended matter, and evaporation residue following testing as outlined in EN 1008. The fineness of the solid matter was calculated by allowing the volume of solids to settle and calculating evaporation residue. Sample compositions were identified through measuring soluble salts, chlorides and sulfates before testing and by using laser grain size measuring equipment to outline grain size distributions and X-ray diffraction to gain insight into chemical composition. The total solids never exceeded the 50,000 ppm specified in ASTM C94.

Following the initial characterization, both mortar prisms and concrete cubes were cast and the workability and water absorption were also measured. The *w/cm* ratio was held constant and, as a result, the workability decreased as more recycled wash water was used. The compressive strength revealed 7-day strength were higher than the control values and 28-day strength values were slightly lower than the control values, but still within both sets of requirements for mix water. No relationship was detected between characteristics of the solids content of the wash water and the final compressive strength. The result from the mortar prisms, however, showed lower strength than those for the control at 7 days but comparable or better 28-day strength. The higher 28-day strength of the mortar samples, as opposed to the lower 28-day strength of the concrete could indicate that the coarse aggregate used, a limestone, could possibly have contributed to the observed increase in strength for the concrete.

Concrete made with recycled water also exhibited lower porosity and water absorption, as estimated by the volume of water absorbed by a concrete sample submerged in water. This decrease in absorption was attributed to the fine suspended particles behaving as a filler, thus decreasing the effective pore size. This would be consistent with the lower porosity values as well.

Tsimas et al. (2011) conducted similar testing but sought to more thoroughly investigate the composition of the recycled concrete water. Wash out water samples were collected and progressively diluted to obtain a wider spectrum of concentrations of concrete fines. All water samples fulfilled both specifications for the amount of total solids and all had pH values over 11.5, thus categorizing them as hazardous materials. A high loss on ignition suggests that large amounts of calcite were present in the water, possibly from the fine fractions of the fine aggregate. An analysis of the solids content of the sludge water revealed the most common solid to be CaO followed by SiO_2 and negligible amounts of all other solids. A mineralogical analysis of the water using X-ray diffraction revealed that the fines material was comprised of mostly calcite and silicon oxide as well as $Ca(OH)_2$. $Ca(OH)_2$, more commonly known as portlandite, is a product of cement hydration, implying that some of the cement particles in the recycled water were already hydrated. It was found that most 7- and 28-day strength exhibited a slight improvement over the strength of the control mix. Due to the fineness of the particles in the recycled water, this slight strength gain was attributed to improvements in the packing index. The packing index is defined as the ratio of volumes of an individual particle and the unit cell. Contrary to other studies, no impact on workability of the concrete was found and the slump was affected only by the addition of admixtures. Also, no significant change to set time was observed.

Similar work performed by Su et al. (2002) also focused on more thoroughly categorizing the properties of the recycled water and tested water with a variety of total solids concentrations and measured pH, turbidity, total solids, chloride ion content, and sulfate content. Wash water was taken from varying depth of sedimentation pools to obtain a wider spectrum of particle concentrations. All pH values were found to exceed 11.0, and both turbidity and total solids were found to increase with increasing particle concentration. All measures of performance fell within the limits as outlined by the specifications. Chloride and sulfate levels fell within the ASTM C1602 and EN 1008 standards. The mortar time of set fell within -10 min and +30 min of the control mixture, well within the specification limits. Both the 7-day and 28-day compressive strength were above the base requirement of 90% of the control strength. While 28-day compressive strength fell below control values, but still within limit, the 7-day compressive strength (early strength) exceeded the control strength. Additionally, the measured compressive strength of the concrete samples increased as the concentration of the solids in the water increased.

1.4.2. Concrete containing additives and admixtures

Given the increased set time and decreased workability sometimes found when using recycled water in concrete mixtures, some research work has evaluated chemical admixtures and cementitious replacement materials to counter some of these undesirable effects. Hydration stabilizing admixtures were used to counter the issue of decreased effectiveness of the inclusion of concrete wash water as a function of time. Hydration stabilizing admixtures first stabilize the hydration reaction for a period of time (depending on dosage) and then activating hydration. This two-step process results in the slowing of cement hydration followed by a sudden activation of the hydration process.

Work performed by Ekolu et al. (2010) included experimenting with mortars and concrete mixtures made with recycled concrete wash water and mixing samples with and without slag as a replacement for cementitious materials. Tests completed on the mortar and concrete included slump and flow, unit weight, set time, total heat of hydration, compressive strength, and permeability. The total dissolved solids of the recycled water fell within the EN 1008 specification and were approximately 20 times greater than the control mix water. Total dissolved solids, conductivity, and pH were measured for each water sample and chemical impurities were measured (chlorides and sulfates) to compare with the EN 1008 requirement. All recycled water used fell within the requirements for total solids, chlorides, and sulfates.

Set time decreased when recycled water was used but still fell within the limits outlined in EN 1008. This trend fluctuated when slag was used as a replacement for cementitious materials, while the set time was higher than that for the control mixture. Slump was also found to steadily decrease with increasing concentrations of solids in the wash water. Strength values for the concrete, however, fluctuated, whereas strength values for mortar did not, indicating a possible adverse reaction with the coarse aggregate. The mortar strength values consistently increased with recycled fines water and 28-day strength values increased 8% over the control. Overall, concrete prepared with the recycled concrete water showed a decrease in workability and an increase in unit weight, indicating a denser mortar matrix.

Research performed by Borger et al. (1994) used stabilizing admixtures to control the rate of hydration. The compressive strength, set time, workability and sulfate resistance of mortars were investigated. Rather than keep a constantly agitated supply of wastewater with a stabilizing admixture, this effect was approximated by controlling the time since the cement comes in contact with the water for the wash water. This time ranged from 2 h to 48 h. The stiffest mortar was produced using wash water between 2 and 4 h old, likely due to the heightened reactivity of the cement particles at this point. The mortars became equally stiff to that of the control mixture after the wash water had aged 8 h.

The greatest strength gain for the mortar mixes was observed with the 2-h old wash water and the lowest strength gain was found with the 24 and 48-h old wash water. This was attributed to the reduction of the water-cementitious materials ratio (*w/cm*) by the inclusion of the fines water (cement amounts were not adjusted to reflect solids content of the water), which ultimately increased the cement content. Without the inclusion of a stabilizing agent, the set time for the control mixtures varied up to 25% from that of the control mixture. The stabilizers allowed for control of the accelerating affects from the wash water. The 2-h old water also best resisted sulfate attack. The age of the wash water had the greatest impact on the concrete strength. The 28-day strength increased by 20% and an increase in strength was generally observed for ages of wash water 8 h old or less. Overall, the expansion of the cement, as determined by mortar bar expansion testing, increased with the increasing age of the wash water. This was likely because the overall cement content of the mix increased as the wash water aged, thereby increasing mortar matrix density and reducing expansion.

Lobo et al. (2001) simulated continuously agitated slurry tanks with a laboratory set up including a motorized paddle and varied the solids content with time of day to better simulate truck wash out variability conditions. The total solids content varied between 25 and 40 percent solids by mass. Unlike other previous work, Lobo included a solids content up to four times more than the ASTM total solids limit. Density and percentage of solids by mass were measured as well as loss on ignition and insoluble residue.

Concrete samples were mixed to a target slump value rather than *w/cm* ratio, therefore mix compositions were more highly varied than other previous work. Density and temperature were measured as well as initial set time using both the Vicat test and a thermocouple so readings could be matched to a heat signature curve. The amount of mix water required to obtain the desired slump increased as higher concentrations of solid particles were found in the slurry water. This increased need was proportional to the amount of solids as well as the age of the slurry, with slurry water aged past one day requiring significantly higher amounts of water.

The initial set time of the control was 4.9 h while the largest variation occurred for recycled water with the highest concentration of solids with a set time of 4 h. This accelerated hydration rate was attributed to the existing hydrated cement and calcium hydroxide (hydrated lime). There was a noticeable reduction in 28-day concrete strength; however, which is most likely due to the addition of extra water needed to obtain the 5 in slump required. The weakest concrete samples were also those which required the highest levels of additional water and therefore also had the highest *w/cm* ratio. Younger slurries, those aged less than 4 h, had higher strength possibly due to the additional cement provided by the unhydrated cement particles. Mixes with high water contents had higher levels of drying shrinkage and permeability, also likely due to the increased water content itself rather than the composition of the recycled water.

Following this first phase of testing, Lobo et al then included HAS into a second phase of testing. By controlling the dosage of the HAS, compressive strength results for the control mix was similar to the HA treated concrete made with 7-day old slurry water. Without inclusion of the HA, concrete made with the 7-day old slurry water performed worst relative to the control mixture. Therefore, while 7-day slurry water, and water outside of the ASTM/EN requirements was found to be the most detrimental to concrete performance when left untreated, treatment with HA was able to rectify these effects. It should be noted that 4-h old slurries did not require treatment with HA to fall within these testing limits and most closely aligned with control mix values.

A more comprehensive study by Chini et al. (2000), included both standard (Class I) and bridge deck (Class II) concrete mixtures made with hydration stabilizing admixtures coupled with water reducing admixtures. Concrete mixtures were also made to check dosage effects on air-entraining and water reducing admixtures when hydration stabilized wash water was used. Class II concrete for bridge deck use was also prepared. For all testing, fly ash was used as a cementitious replacement material in the control mixture. The test concrete was mixed to a standard slump, and consequently had different *w/cm* ratios varying from 0.48 to 0.55. Three different limestone coarse aggregates were used from three different local sources. Properties measured for each concrete mixture included temperature, slump, unit weight, air content, set time, compressive strength, flexural strength, drying shrinkage, resistance to chloride-ion penetration, and sulfate expansion. It was found that for concrete mixes made with a chemical stabilizer for re-used wash water, the two primary differences were increased drying shrinkage and reduced set times as a result of the activating agent.

Work by Elchalakani and Ehgaahi (2012) sought to test the effects of using completely recycled concrete, that is, concrete made using both recycled concrete wash water as well as recycled concrete aggregates. The recycled water was obtained from the wet recycling process during concrete production. The mechanical properties of the finished concrete were found to depend most highly on the quality of the recycled aggregate and water used. Most specimens tested fell within the quality standards described from the ASTM C1602 and EN 1008 standards. It was found that when slag was used as a replacement for the cementitious materials that strength and durability of the concrete increased. The highest strengths were achieved from fully recycled concrete (with 100% of both recycled aggregate and recycled water) with 80% slag replacement.

Chatveera and Lertwattanaruk (2009) conducted a similar experiment but included concrete admixtures coupled with additives. The recycled water used did not satisfy ASTM C1602 because it contained a total solids content of 56,000 ppm, exceeding the 50,000 ppm limit imposed by ASTM C1602. A linear relationship between the total solids content and the specific gravity of the recycled water was obtained. The recycled water also contained a high pH and a high loss on ignition was measured. The particle size distribution was measured for each concrete component and while the distributions were close, the overall average size distributions ranged from coarsest to finest for the recycled fines, fly ash, and Portland cement, respectively.

The concrete mixtures were mixed to obtain a specified slump measurement, therefore each sample had a variable *w/cm*. Samples having a total solids content of less than 5% had a compressive strength most comparable to that of the control. However, the set times increased substantially (by more than 90 min), an increase outside of the allowable change specified in the ASTM C1602. Through experimentation, it was found that the optimal recycled water content that fell within the ASTM specification for strength and set time contained between 5.4% and 6.1% solids. It is interesting to note that this optimal percentage of total solids content for achieving ASTM specifications falls outside of the 50,000 ppm limit of total solids suggested by the ASTM C1602 specification.

The concrete made with recycled water without any additives or admixtures was ultimately found to have a longer set time than the plain control concrete. Concrete made with super plasticizers and recycled water was found to have a noticeably reduced set time and slump. Concrete made with recycled water had compressive strength lower than plain concrete but higher than plain concrete made with either super plasticizer, an admixture, or fly ash, an additive. Concrete made with recycled water and either a super plasticizer or fly ash obtained compressive strength higher than the control. Plain concrete made with recycled water only showed a negative effect on acid resistance but increased the durability as measured through permeability and sulfate resistance. Without admixtures or additives, cement paste with increased total solids content reduced the compressive strength and shortened the total set time by 20 min.

Improvements in concrete durability were attributed to fine filler effects and the consequent reduced capillary water absorption and porosity found in the denser cement matrix. The possibly accelerated hydration reaction was attributed to the high alkalinity of the recycled water.

1.5. Particle Packing Effects

A possible reason as to the increased strength properties observed in cement and concrete made with recycled water could be particle packing effects. For a case where all cement particles are of uniform size and shape, the ideal packing configuration of its crystalline structure is a close-packed structure. Even for this ideal packing configuration, however, gaps are still present between the particles. In this simple and homogeneous example, introducing a secondary particle size small enough to fill the voids created would create an overall denser matrix and higher packing factor of the overall structure (Allen 1999). In reality, however, cement particles contain a distribution of particle sizes, which further complicates the packing scheme. A supplementary cementitious material with a wide and varying particle size distribution can exhibit similar particle packing effects on concrete strength properties by increasing the density of the mortar matrix. Likewise, supplementary cementitious materials substantially finer than cement particles are capable of increasing mortar matrix density by filling gaps created in the mortar matrix.

Supplementary cementitious materials have been known to reduce the overall porosity of mortar, sometimes upwards of 35% (Brooks et al. 2011) as well as reduce both the mean and average pore size of the mortars to upwards of 80%. Metakaolin, however, proved to be a more effective pore filler than both fly ash and blast furnace slag. Supplementary cementitious materials with a smaller median and average pore diameter lead to an overall reduction in mortar pore size. The inclusion of supplementary cementitious materials was also found to significantly reduce macropores (>50 nm) and increase the number of mesopores (<50 nm). Smaller sized supplementary cementitious particles more easily fill larger macropores and decrease the pore size distribution. Likewise, supplementary cementitious materials can contribute filler effects, which increase concrete strength. As described before, filler effects occur when the supplementary material has a smaller average particle size than the cement particles and more easily fills voids within the paste to create an overall denser matrix. The increase in compressive strength contributed by filler effects was found to increase as the particle size of the supplementary materials decreased, thus increasing the overall particle size distribution.

Particle packing effects have been reported with other concrete additives, such as rice husk ash. In a study by Bui et al., the effects of rice husk ash on concrete properties were investigated. It was concluded that relative strength of the concrete increased when rice husk ash was used, if the cement particle size was coarser. This led to the conclusion that the larger size discrepancy between the cement particles and the rice husk ash particles increased the strength by decreasing porosity and improved the particle packing of the structure (Siddique 2008).

1.6. Effects of the Hydration

Hydration is a key mechanism in the strength gain, hardening and setting of portland cement. Hydration is, by definition, the combination of water with an anhydrous material to produce a hydrate. This process is complicated in cement hydration by the fact that there are several compounds and hydration processes occur both in series and parallel. Initial hydration occurs when the two calcium silicate compounds in Portland cement (primarily C_3S) are hydrated by water and form calcium hydroxide and calcium silicate hydrate (C-S-H). It is this calcium silicate hydrate that hardens the mortar matrix by bonding to other unhydrated cement particles, fine aggregate, and coarse aggregates (Kosmatka 2002). The rate of Portland cement hydration most directly depends on the rate of dissolution of the materials, the rate of nucleation and crystal growth of the hydrates to be formed, and the rate of the diffusion of water and ions through the hydrated material already formed.

The short-term strength of the concrete is more directly dependent on the fineness of the cement and increases as the amount of fine particles increases while long-term strength is more highly dependent on cement composition. More fine particles increase the specific surface of the cement and as the specific surface area of the cement increases; the hydration reaction rate also increases. The cement hydration progress and kinematics are affected by the phase composition of cement and foreign particles within crystalline lattices, the particle size distribution of the cement (and overall fineness), the water-cement ratio, the curing temperature, the presence of chemical admixtures, and additives such as fly ash or slag (Lea 1998).

Expedited hydration could provide an explanation to the early strength gain observed thus far in concrete made with recycled water. This expedited hydration could occur as a result of the composition of the hydrated cement particles present in the recycled water because the presence of hydrated cement particles could accelerate hydration effects. The primary reaction of cement hydration occurs from the conversion of C_3S into C-S-H. Thomas et al. (2009) tested whether the inclusion of C-S-H particles into concrete would expedite the hydration reaction by providing nucleation sites for subsequent C_3S reactions. They theorized there would be three primary effects of including fully hydrated cement particles. First, the initial nucleation period would be completely reduced because the C-S-H particles would provide nucleation sites for further reactions beginning immediately. Secondly, the acceleration of the entire hydration reaction would increase and occur with a higher rate peak. Third, the total hydration during early nucleation and growth should increase because of the increased nucleation sites.

While the experimentation confirmed these three effects, testing also revealed that the location of hydration sites changed depending on whether or not C-S-H was initially included.

When cement is left to hydrate without the seeding of C-S-H particles, nucleation was found to initiate near particle surfaces whereas the inclusion of C-S-H shifted this hydration location to include between the C_3S particles as well in the pore space. By expanding the possible locations of nucleation, this inclusion of C-S-H particles heavily increased the initial rate of hydration. Increasing the number of nucleation sites also resulted in a more homogeneous final microstructure of the hardened concrete with less capillary porosity. Therefore, the inclusion of recycled water (and consequently C-S-H) would be expected to both increase the rate of hydration as well as the overall mortar matrix density.

1.7. Conclusions

Despite the limited scope of work and highly variable experiments conducted, several trends can be identified from the present work completed thus far. Generally, material parameters measured to give an indication of performance or to categorize the wastewater included pH measurements, total solids contents, and chloride and sulfate contents. Most of the time the measured performance was compared against either ASTM C1602 or EN 1008 requirements, thus the solids, chloride, and sulfate contents fulfilled the criteria outlined. Wash water was found to be highly alkaline with pH measurements exceeding 11.0.

In the experiments conducted, wash water was used as a replacement for mixing water. The use of wash water usually decreased set time and increased the rate of hydration. Increasing the amount of wash water used exacerbated this effect while decreasing workability. If the *w/cm* was held constant, it was found that workability severely decreased with increasing concentrations of wash water. If more water was added to improve workability, strength decreased as expected from the increasing *w/cm*.

Introducing stabilizers to control the workability as a result of the increased wash water further increased the variability in the performance. Admixtures can be used to control the set time and workability but the strength results are inconsistent. Without the use of admixtures, early strength usually increased. This can be attributed to either the increased rate of hydration or particle packing affects. However, 28-day strength results were much more inconsistent without significant trends present. Most of the concrete produced using wash water, excluding those with extreme replacement levels, fell within the strength requirements outlined in ASTM C1602 (compressive strength must be at least 90% of the control mixture compressive strength).

There is clearly a need for quantifying wastewater material parameters and correlating these measurements with concrete performance, given the wide variability of water sources and composition. Results thus far indicate that a correlation should exist between these parameters if it is possible to reduce the scatter historically found in the data. Likewise, there is a need for additional work to account for the fines in the wash water as additional cementitious materials, which could ultimately indicate that a solids content exceeding the value outlined in the ASTM C1602 specification can still produce consistent, acceptable results.

2. EXPERIMENTAL INVESTIGATION

The experimental investigation of the recycled fines was divided into two primary sections: an initial materials characterization of the recycled fines and the mortar mixture properties, which included 3- and 28-day compressive strength testing and set time testing. The results of this experimental investigation were ultimately used to build prediction models for the performance of concrete. First, the sources of the recycled fines will be discussed followed by the testing procedures.

2.1. Selection of Recycled Fines Sources

The behavior and quality of recycled concrete fines as a cementitious replacement material varies widely based on many variables relating to material source. A preliminary division for characterizing fines is based directly on the source of the wastewater: wash out water from ready-mix concrete trucks (wash-out fines, or WOF) or grinding fines from pavement maintenance operations (grinding fines, or GF). Wash out fines were produced from water used to wash out ready-mix concrete trucks and were collected from settling ponds or recirculation systems found at ready-mix concrete plants. Grinding fines were produced from a variety of pavement maintenance and construction activities that include sawcutting joints in freshly placed pavement, and diamond grinding and grooving, which can occur in freshly hardened pavement or as a maintenance procedure for aged pavements.

Because the reaction accelerating potential of this recycled water is hypothesized to be related to the unhydrated cement particles, the age of the fines is an important factor for performance predictions. In total, six recycled fines sources were identified for initial testing and model development: three grinding fines and three wash out fines sources. Details of each recycled fines type are given in Table 1. Washout fines were taken from ready mix concrete plants both near Pittsburgh, Pennsylvania, and Seattle, Washington. The concrete plant source in Pittsburgh utilizes a three settling pond system wherein all wash-out water is emptied into the first settling pond. After a set amount of time when the largest fines have settled, the water was moved to the second settling pond and the process repeated for this and the third settling pond as well. This project utilized fines from the third settling pond; therefore, of the wash out water available, the sample used should contain the highest amount of small particles. The Seattle wash out fines were obtained from recycled water recirculation systems so the particle size distribution of this material was expected to be greater than that from the Pittsburgh area wash out fines.

Grinding fines sources were identified based on location, including sources from both the Pittsburgh and Seattle areas, and the age of pavement when the sample was taken. The age of the pavement when the diamond grinding was performed could possibly have an effect on the reactivity of the fines. An older pavement would be expected to be more highly carbonated, which could decrease the reactivity of the fines. This could potentially affect whether the fines will expedite the early strength gain through reactivity, or if any strength effects may be a result of filler effects and improved particle packing, as might be seen with a less reactive particle. In addition, the grinding fines would be expected to contain a higher percentage of rock dust from the grinding operation.

TABLE 1 Summary of recycled fines used for initial experimental testing

	Stoneway	**Fairchild**	**I-79**	**Stoneway Hauser**	**Bryan 3**	**Miles–Auburn**
Type	Grinding	Grinding	Grinding	Wash out	Wash out	Wash out
Fines number	GF 1	GF 2	GF 3	WOF 1	WOF 2	WOF 3
Source	I-405	Fairchild Air Force base	I-79	Stoneway Concrete ready mix plant	Bryan Concrete ready mix plant, settling pond 3	Miles Concrete ready mix plant
Location	Seattle, WA	Seattle, WA	Pittsburgh, PA	Renton, WA	Pittsburgh, PA	Near Seattle, WA
Pavement age	>10 years	new	~10 years	N/A	N/A	N/A
Date collected		Fall 2011	Fall 2011	2009	Summer 2012	Fall 2012
Additional notes		Grinding occurred within days of construction				

N/A = not available.

2.2. Preparation of Recycled Fines

To prepare for testing, each recycled fines source was collected as wastewater and then dried at 40°C. This drying was necessary to control the amount of recycled fines used in later material characterizations and mortar testing as a percentage of the mass of cementitious materials. The implementation plan and guidelines, however, will be developed for wastewater with unknown concentrations. The samples were considered sufficiently dry when the change in mass did not vary by more than 1% daily. Once dried, the samples were mechanically sieved in a No. 40 sieve for 8 min. This was to ensure that there were no large agglomerates of fines, which would affect mortar consistency, as well as to remove any pebbles or similar debris.

Following the drying and sieving of a complete source of recycled fines, the entire dried and sieved sample was then mixed and divided to ensure uniformity. This mixing was done through quartering and followed the procedure outlined in ASTM C702: Standard Practice for Reducing Samples of Aggregate to Testing Size.

Once a sample had been dried, sieved, and mixed, it was considered ready to be tested by the procedure discussed in the following sections.

2.3. Materials Characterization

A material characterization testing procedure was developed to build characterization curves based on easily measured parameters in order to quickly describe the wastewater. This ensured the applicability of the testing procedure to a water recycling recirculation system with in-line sensors that could be adopted by ready-mix concrete plants. These measured parameters were used to define the fines sources with parameters to be included in the final predictive models. Three material parameters were initially identified to fulfill the criteria of quickly describing possible sources of reactivity of the recycled fines. The index of refraction (IR) was measured to indicate the approximate level of both the suspended solids and dissolved ions. A Brix reading was taken and then used to calculate an IR value since it allowed the measurement to be easily made with a handheld instrument. Conductivity was also measured because of its sensitivity to only dissolved ions and not suspended solids. The combination of the IR and conductivity measurements could then be used to discern between dissolved ions and suspended solids. Finally, pH was measured because of its sensitivity to hydroxyl ions and therefore could provide an approximate indication of the rate of reaction of the fines. While some of the hydroxyl ions could be associated with alkalis (Na and K) from un-hydrated cement in the recycled fines, the relatively low alkali content in most cements (typically less than 1%) suggest that most of the hydroxyl ions in the recycled fines are instead associated with calcium ions. Calcium ions would contribute to accelerated hydration reactions. Ultimately, the three of these parameters combined should provide an indication of the total reactivity of the fines. All three of these parameters can both be measured quickly and using in-line sensors adaptable for plant use, as will be required in further experimental testing to be described later.

Finally, to investigate the possibility of particle size effects, all specimens were scanned in a Microtrac particle size diffraction laser. This equipment provided average size and distribution values for each recycled fines sample.

2.3.1. Materials characterization testing equipment

The equipment used for the material characterization testing is shown in Figure 2 (a) and includes the three handheld sensors for measurement of Brix (to be correlated to Index of

Refraction), conductivity, and pH. A milkshake-style mixing stand, typically used in soil testing laboratories, was also used and is shown in Figure 2 (b).

(a) Hand held material characterization meters (b) Stand mixer

FIGURE 2 Equipment used for material characterization.

The specifications for the handheld equipment used for material characterization are described in Table 2. The index of refraction and conductivity measurements required approximately 2 to 3 drops of solution each while the pH meter was a probe-type meter.

TABLE 2   Hand held meters for fines characterization

Property measured	Sampling	Precision
Brix	2–3 drops in sensor well	0.01%
Conductivity	2–3 drops in sensor well	2% full scale: 4 µS/cm up to 199 µS/cm 40 µS/cm, 200–1,999 µS/cm
pH	Immersion in solution	0.1 pH

It is important to note that the measurements taken from the Brix meter were Brix measurements and required conversion into IR for full material characterization. The relationship given as Equation 1 was used for this purpose.

$$IR = 1.33302 + 0.001427193\, Brix + 0.000005791157\, Brix^2 \qquad (1)$$

A Microtrac diffraction laser was used to gather particle-size effect information for each fines type. The data given by the equipment included a particle size distribution for the scanned particles with average diameters given for each particle size increment. The particle size distribution used was based on the number of particles rather than the mass or volume of the particles, also given as output by the scanning equipment. Given the large amount of data produced for each fines type, it became apparent that a single parameter that could be used to describe the relation of the average particle size as well as the range of particle sizes would be beneficial. Therefore, the span parameter was employed to quantify the relationship between the entire particle range and the median particle size. The span parameter is defined by Equation 2 below.

Where,

$$Span = \frac{d_{90} - d_{10}}{d_{50}} \tag{2}$$

d_{90} = the diameter based on the 90th percentile of the tested particles

d_{50} = the diameter based on the 50th percentile of the tested particles

d_{10} = the diameter based on the 10th percentile of the tested particles.

2.3.2. Materials characterization testing procedure

To establish a materials characterization database, six different recycled fines sources were tested. The dried recycled fines were characterized by first placing 518.2 g of room temperature, de-ionized water with 12.25 g of recycled fines, representing 1% of the total mass of cementitious material based on the mortar cube mix design to be described in Section 2.4. This mixture was then mixed in a milkshake-style mixing stand shown in Figure 2 (b).

This mixture was then mixed on low speed for four min, which was found to be the minimum time required for full mixing and to achieve stabilized material parameter measurements in a preliminary study (Janssen et al. 2010). After four min of mixing, measurements of the index of refraction, conductivity, and PH were taken using the hand-held meters.

Once measurements were taken, 12.25 g of fines were added to the mixture and the process was repeated incrementally until a total of 122.5 g of fines were used, representing a 10% level of the total mass of cementitious materials based on the quantities for each batch of mortar. The quantities of fines used for each cycle are given in Table 3. This process was repeated at least three times for each recycled fines type until repeatable results were achieved.

TABLE 3 Recycled fines quantities required for materials characterization

Test increment	**Mass of cementitious material, percent**	**Total de-ionized water, g**	**Total fines, g**
1	1	518.2	12.25
2	2	518.2	24.50
3	3	518.2	36.75
4	4	518.2	49.00
5	5	518.2	61.25
6	6	518.2	73.50
7	7	518.2	85.75
8	8	518.2	98.00
9	9	518.2	110.25
10	10	518.2	122.50

A small sample (approximately 20 g) of each recycled fines source was mixed with deionized water and placed in the Microtrac diffraction laser for particle size characterization. The particle size analysis obtained for each sample was recorded. This process was repeated until three consistent trials between any single fines source was obtained.

2.4. Mortar Testing

Mortar mixtures were then prepared to determine both early-age and long-term compressive strength as well as initial set times. A series of mortar mixtures were proportioned and prepared with a constant fines content (by mass), which included portland cement and dried recycled fines, and in some cases, a cementitious replacement material. A total of seven mortar mixtures were tested for each set of recycled fines. Both slag and Class F fly ash were used as cementitious replacement materials in the mixtures at three different replacement levels for each. The mill sheets for both materials are included in Appendix A. Slag mixtures contained 25%, 37.5%, and 50% slag as a percentage of total cementitious materials and fly ash mixtures contained 10%, 20%, and 30% fly ash as a percentage of total cementitious materials by mass. A control mixture, containing no recycled fines, was also made for each replacement type.

Four different mixtures were then cast for each of the seven mortar mixture designs with different percentages of recycled fines as a percentage of mass of total cementitious replacement material: 0%, 2.5%, 5%, and 7.5%. It is important to note that the recycled concrete fines were measured as a replacement of the cementitious materials by mass and were included in the mixtures as a dried powder as opposed to inclusion as wastewater. This ensured a consistent water to powder (defined as cementitious materials plus the recycled powder) ratio of 0.42 for all mixtures. An outline of the mixture designs by mass is given in Table 4.

TABLE 4 Mortar mixture designs, mass for each component in g

		Percent fines			
		0	**2.5**	**5**	**7.5**
Control	Cement	1,225.0	1,194.4	1,163.8	1,133.1
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9
50% Slag	Cement	612.5	597.2	581.9	566.6
	Slag	612.5	597.2	581.9	566.6
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9
37.5% Slag	Cement	765.6	746.5	727.3	708.2
	Slag	459.4	447.9	436.4	424.9
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9
25% Slag	Cement	918.8	895.8	872.8	849.8
	Slag	306.3	298.6	290.9	283.3
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9
30% Fly ash	Cement	857.5	836.1	814.6	793.2
	Fly Ash	367.5	358.3	349.1	339.9
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9
20% Fly ash	Cement	980.0	955.5	931.0	906.5
	Fly Ash	245.0	238.9	232.8	226.6
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9
10% Fly ash	Cement	1,102.5	1,074.9	1,047.4	1,019.8
	Fly Ash	122.5	119.4	116.4	113.3
	Sand	1,947.0	1,947.0	1,947.0	1,947.0
	Water	518.2	518.2	518.2	518.2
	Fines	0.0	30.6	61.3	91.9

On each mixing day, four mixtures with a single type of waste fines at the four replacement levels were cast using a single percentage of the cementitious replacement type. Six 2 in. × 2. in mortar cubes were made from each batch according to the specification ASTM C109: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. The short-term (3-days) compressive strength was measured for three specimens and the long-term (28-days) compressive strength were measured for the remaining three. The compressive strength were measured, as shown in Figure 3 below, and load was continuously applied until failure, as specified in ASTM C109.

FIGURE 3 Compression machine used for mortar cube samples.

Mortar set time was measured with a Vicat testing apparatus, as shown in Figure 4 and in accordance with ASTM C807-08: Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle. This included casting a cylindrical mortar sample in two lifts and using the penetration needle to measure depth of penetration every 30 min, increasing readings to every 10 min when penetrations were less than 40 mm. The mortar sample was considered to have reached initial set once the penetration measurements were less than 10 mm.

FIGURE 4 Vicat apparatus for mortar set time testing.

3. RESULTS

3.1. Materials Characterization Results

The materials characterization procedure was repeated for each fines type until consistent results from three trials were obtained. Results from these three trials were then averaged to obtain a representative value for each of the three material parameter measurements. The complete set of results for all six sets of fines is given in Appendix B. Only the results and calculations for wash out fines sample number 2 (WOF 2) are presented here for the sake of brevity but the calculations for the other five fines types were completed in the same manner. Results from the three replicated trials for the three material characterization parameter measurements are given in Figure 5 for all six recycled fines samples.

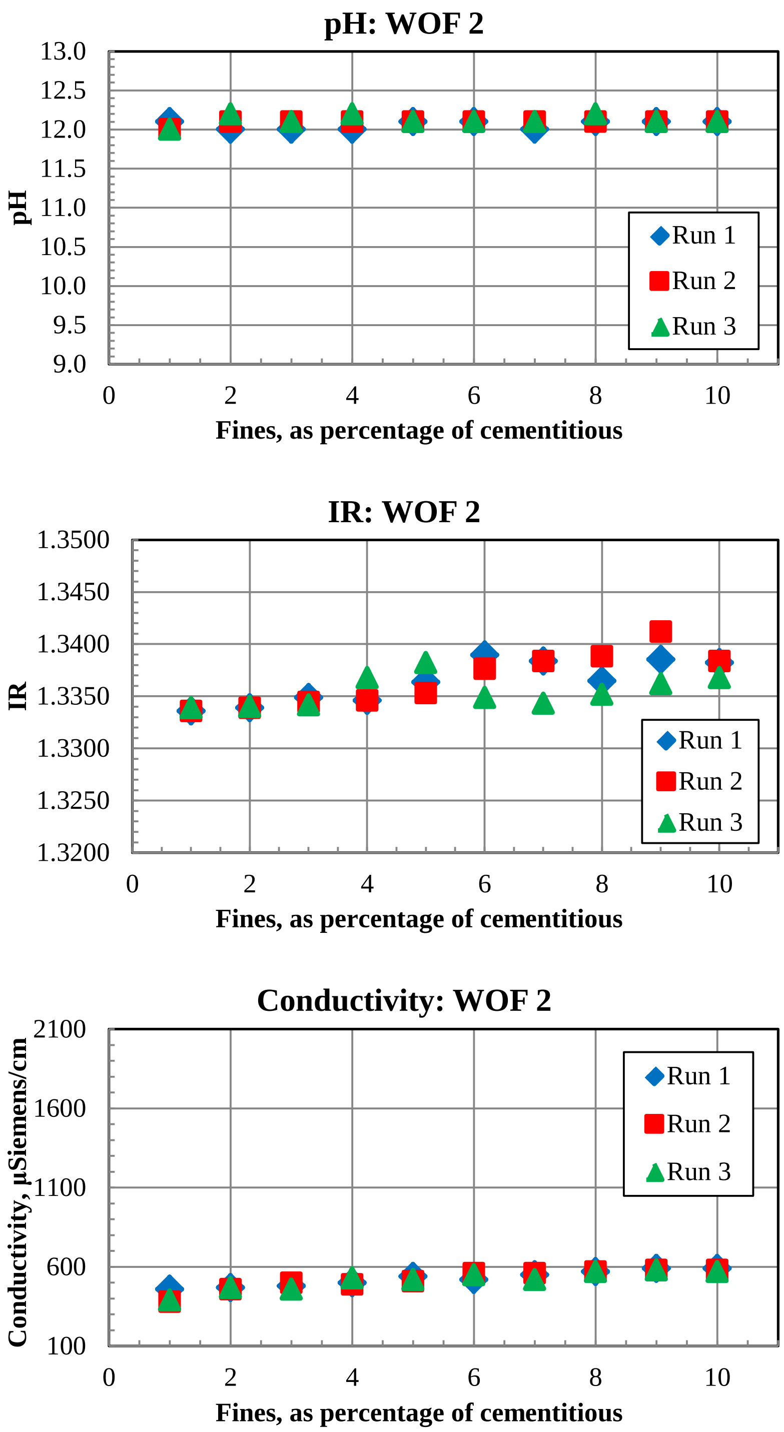

FIGURE 5 Materials characterization parameter plots for WOF 2.

Several trends can be observed from the plots of these material parameters for WOF 2. The pH value is relatively constant and does not vary with concentration. The conductivity increases slightly with increasing fines content and the index of refraction value appears to be most directly related to the concentration of recycled fines. Overall, the values appear to be repeatable and consistent; therefore, the values obtained from these three trials are then averaged to create a single representative trial for the specific set of fines. The average values for WOF 2 are given for pH, conductivity, and IR (calculated from measured Brix values) in Table 5.

TABLE 5 Average material characterization measurements for WOF 2

Test	**Fines, g**	**Average from Three Trials**		
		pH	IR	Conductivity, μS/cm
1	12.25	12.0	1.33369	410.00
2	24.50	12.1	1.33393	466.67
3	36.75	12.1	1.33450	480.00
4	49.00	12.1	1.33532	506.67
5	61.25	12.1	1.33662	523.33
6	73.50	12.1	1.33716	543.33
7	85.75	12.1	1.33701	543.33
8	98.00	12.1	1.33682	570.00
9	110.25	12.1	1.33863	583.33
10	122.50	12.1	1.33779	580.00

All relationships were assumed to be roughly linear based on observed trends. The slope and intercept from a linear fit for each material parameter is then calculated along with a corresponding R^2 value and are given for the WOF 2 parameters in Table 6.

TABLE 6 Linear fit results for WOF 2 fines

	pH	**IR**	**Conductivity, μS/cm**
Slope	0.00505	0.000528	17.74
Intercept	12.06	1.333245	423.11
Standard Error	0.0241	0.0006	15.71
$\boldsymbol{R^2}$	0.31	0.89	0.93

It can be seen from the R^2 values that the correlation for pH does not fit well. This is attributed to the relatively constant values with low variation, as evidenced by the low standard error. These slope and intercept values are then used to define linear plots for each parameter. This procedure is then repeated for each of the six sets of recycled fines to obtain representative linear plots for the six fines samples between the range of 1% and 10% of total cementitious material by mass. These percentages correspond to the inclusion of between 12.25 g of fines and 122.5 g of fines. The trends between the different types of fines can now be compared, as shown in the plots given in Figures 6–8. All wash out fines are shown with dashed lines and hollow markers while grinding fines are designated with solid lines and markers.

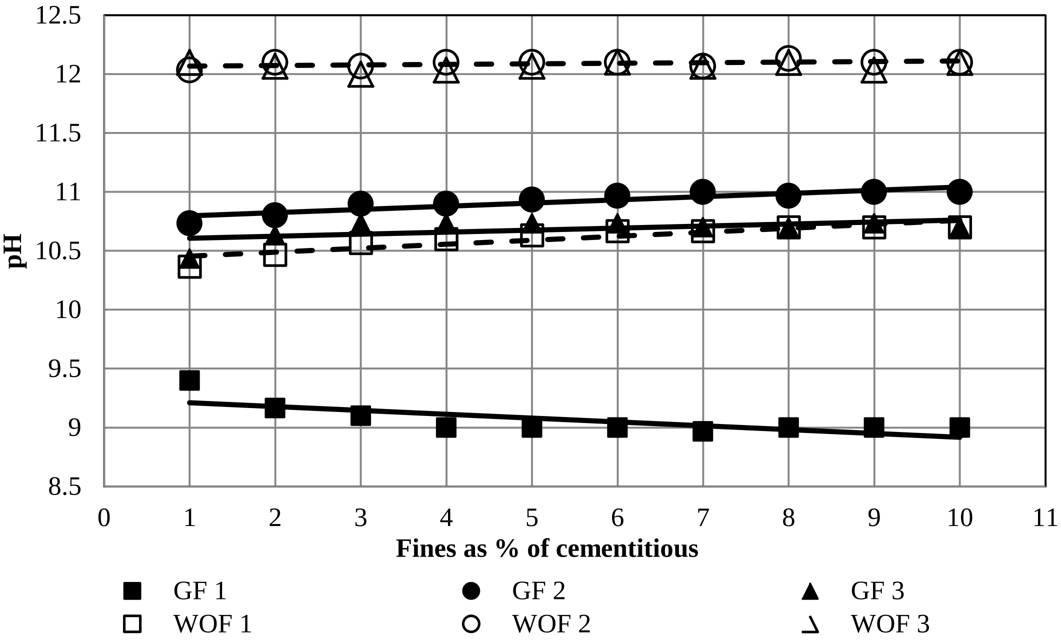

FIGURE 6 pH readings as a function of fines concentration.

Certain trends can be observed from these plots. The pH, which is expected to provide an indication of reactivity, appears to be quite linear with a relatively small slope. The largest differentiation between the different fines types is the magnitude of the pH rather than the degree of slope. This is evidenced from the data presented in Table 7 where the slopes for the pH lines are all close to zero. Both WOF 2 and WOF 3 have a similar pH reading close to 12.0 and that is relatively constant regardless of concentration. These two fines sources are both young wash out fines (from 2011 and 2012, respectively). Additionally, the pH readings of WOF 1 and both GF 2 and GF 3 are similar. However, the sources of these three fines are less similar. WOF 1 was the oldest wash out fines (from 2009) and therefore possibly affected by carbonation. GF 2 was produced from grinding a new concrete pavement immediately following construction and GF 3 was produced from maintenance diamond grinding a 10-year old pavement. Finally, GF 1 behaved completely differently. The pH decreased with increasing concentration and was the lowest in magnitude of all of the fines sources.

The pH is expected to be related to the ability of the fines to increase the rate of hydration. From this materials characterization, it would be expected that WOF 3 and WOF 2, which are the two youngest wash out fines, would increase the rate of hydration the most, thus leading to the highest decrease in set time and possibly the highest increase in short-term compressive strength.

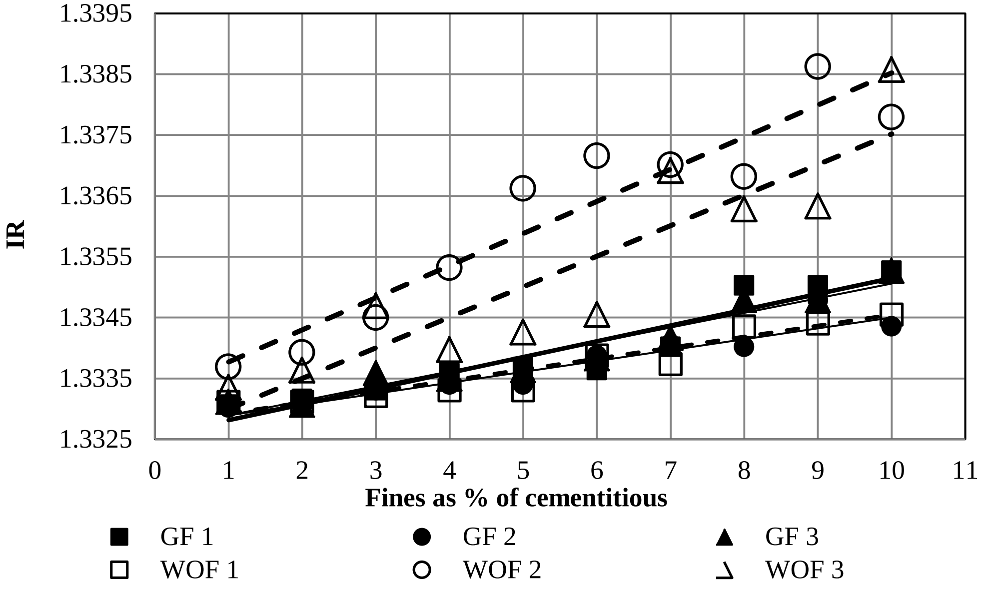

FIGURE 7 IR measurements as a function of fines concentration.

The index of refraction readings all increased with increasing concentration as expected, because the index of refraction will approximately indicate both the dissolved and suspended solids content. Again, the WOF 2 and the WOF 3 have similar trends but different magnitudes. WOF 2 overall had a higher index of refraction than WOF 3 but both had nearly identical slopes. GF 1 and GF 3 were nearly identical in their behavior as well; however, the index of refraction was significantly lower than WOF 3 and WOF 2. WOF 1 and the GF 2 had the lowest index of refraction and also had nearly identical results.

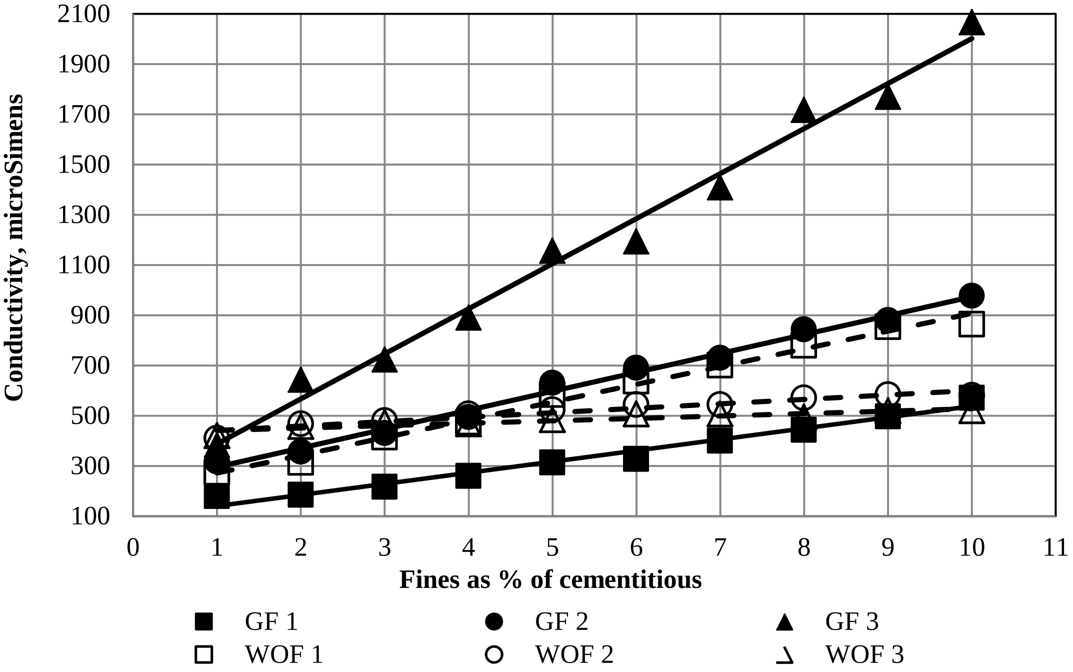

FIGURE 8 Conductivity readings as a function of fines concentration.

The conductivity readings are expected to give an indication of dissolved ions only. Again, the two youngest wash out fines, the WOF 2 and the WOF 3, behave similarly with a relatively small slope and an overall low conductivity ranging only between 450 and 600 µS/cm. Similar to the pH readings, GF 2 and WOF 1 again behaved similarly for this parameter, with a steeper slope than the other two wash out fines. The approximate range for WOF 1 and GF 2 conductivity readings falls between 300 and 900 µS/cm. GF 3, acquired from the older pavement, has extremely high conductivity readings with a very steep slope: increasing substantially with increasing concentration. The range for the conductivity falls between 400 and 2,000 µS/cm. The primary difference between GF 3 and GF 2 is the age of the pavement, which could explain the difference in dissolved ions. Of the six fines types tested, GF 3 is from a 10 year old pavement. GF 1, however, which was from the oldest pavement but had a similar trend to GF 2 and WOF 1 results but lower in magnitude. The dissolved ions content would be expected to be similar to GF 2.

Since the index of refraction measurements provide an indication of total solids content while the conductivity measurements indicate dissolved solids only (not suspended solids), the two measurements must be considered together. From the measurements, it appears that the two youngest washout fines, WOF 2 and WOF 3, have the highest number of total solids, which increases with concentration. However, the conductivity measurements indicate a moderate amount of dissolved solids, which increased very little with increasing concentration. Therefore, for the young wash out fines, the amount of suspended solids increases with increasing concentration but the dissolved ions does not. GF 2 and WOF 1 exhibited similar and consistent behavior: both the dissolved and total solids increased moderately with increasing fines concentration. GF 1 had a similar increasing trend but was less gradual and would therefore overall contain fewer solids than the other fines types. Finally, GF 3 overall contained a moderate amount of total solids but by far the highest number of dissolved solids. This discrepancy indicates that GF 3 had a relatively low number of suspended solids.

Table 7 gives a summary of the trends and similarities discussed above between the three material parameters.

TABLE 7 Summary of trends and similarities between recycled fines samples.

	pH	**Conductivity**	**Index of refraction**
Low	GF 1	GF 1	GF 2 WOF 1
Medium low	GF 2 WOF 1 GF 3	WOF 2 WOF 3	GF 1 GF 3
Medium high		GF 2 WOF 1	
High	WOF 2 WOF 3	GF 3	WOF 2 WOF 3

Average values for each of the three materials characterization measurements previously discussed were then calculated for each fines type and are provided in Table 8.

TABLE 8 Materials characterization results for recycled fines

		Slope	**Intercept**	**Standard error**	**R^2**
GF 1	pH	-0.033	9.24	0.0945	0.55
	Conductivity	44.06	96.67	22.85	0.97
	IR	0.0003	1.33	0.00028	0.90
GF 2	pH	0.027	10.77	0.0408	0.82
	Conductivity	75.39	220	22.88	0.99
	IR	0.000181	1.33	0.0002	0.89
GF 3	pH	0.0172	10.59	0.082	0.31
	Conductivity	179.4	208.7	65.24	0.99
	IR	0.00024	1.332	0.0002	0.93
WOF 1	pH	0.034	10.42	0.0501	0.82
	Conductivity	70.65	200.4	23.35	0.99
	IR	0.00018	1.33	0.0002	0.91
WOF 2	pH	0.0051	12.06	0.0241	0.31
	Conductivity	17.74	423.1	15.71	0.93
	IR	0.0005	1.33	0.0006	0.89
WOF 3	pH	0.0024	12.05	0.0368	0.043
	Conductivity	9.62	431.8	12.90	0.85
	IR	0.0005	1.33	0.0008	0.81

From these data, it can be seen that linear trends fit the relationships quite well. The low R^2 value seen for pH relationships can be attributed to the relatively constant readings, as shown by the relatively low slope (near zero). Otherwise, the linear trends fit quite well, as evidenced by the high R^2 values and the relatively low standard error for each case.

The particle size distribution was then plotted for each of the six fines type investigated with and is shown in Figure 9.

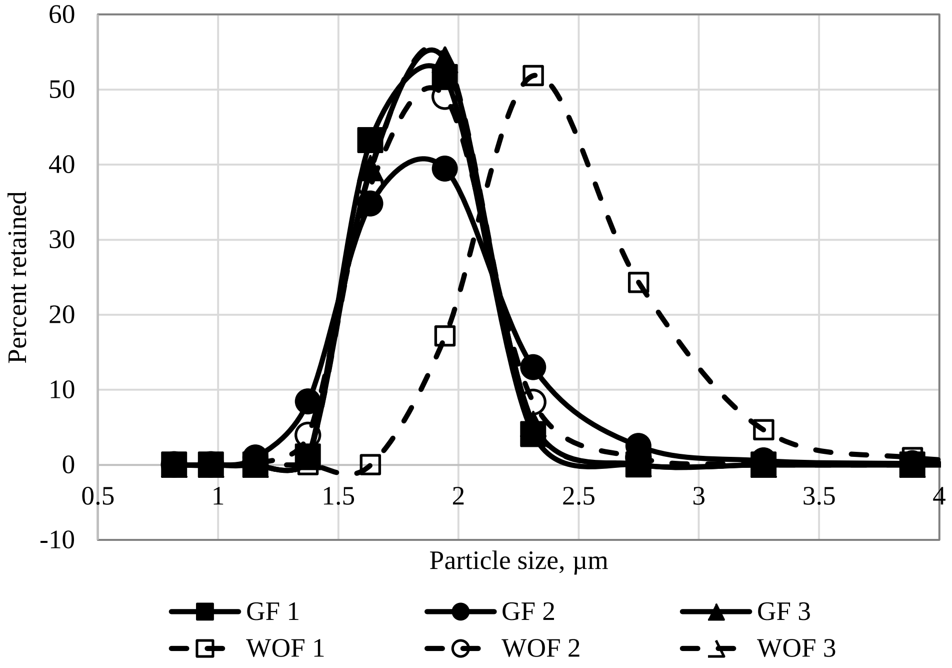

FIGURE 9 Particle size measurements as a function of fines concentration.

From the plot, it can be seen that the particles have similar, but slightly different, distributions. Most notably, the WOF 3 sample has a slightly larger average particle size. The GF 2 sample has a wider distribution than the other fines types and WOF 2 has a slightly wider distribution than the other fines samples. The particle size distribution of GF 1, WOF 3, and GF 3 is very similar.

3.2. Mortar Mixture Results

Mortar mixtures were prepared to test three criteria: 3-day compressive strength, 28-day compressive strength, and set time. Compressive strength data was obtained using mortar cubes which were tested in accordance with ASTM C109 to obtain both early (3-day) and long-term (28-day) compressive strength. Both were reported as an absolute strength (psi) and as a percentage of the control strength. The control strength used for percentage calculations was the strength obtained by plain portland cement mortar mixtures without supplementary cementitious replacement material and without recycled fines. Thus, all subsequent mixtures could be reported as a percentage of these values for both 3-day and 28-day compressive strength.

The intent of testing these mortar properties is to obtain data to construct three predictive models: one for the change in set time from the control mixture, one for 3-day strength as a percentage of the control strength, and one for 28-day strength as a percentage of the control strength. These three parameters were selected because they are the stated criteria in ASTM C1602: Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete. This specification states that any mortar made with a different water source cannot have a strength value less than 90% of the control strength or the water cannot be used. Therefore, these three parameters must be evaluated when considering the use of a different water source. During this proposed initial testing, the solids in the recycled water are treated as a supplementary cementitious material; however, this approach was primarily taken to control workability in order to develop a robust predictive model. For implementation guidelines, the recycled fines will be treated as mixing water; therefore, the ASTM C1602 guidelines would be appropriate.

3.2.1. Set time

The mortar set time was tested through a modified Vicat testing apparatus as detailed in ASTM C807: Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle resulting in data for an initial set time in min. In ASTM C1602: Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete, acceptable limits for different water sources are measured as a difference from the set time of a control mix. The specification gives an acceptable range of set times as neither 60 min shorter nor 90 min longer than the control mixture. Throughout this project, the difference in set time will be defined as the revised mortar mixture set time subtracted from the control mixture set time. Because in most cases, the revised mix set time was shorter than the control mixture, these values are presented as negative values.

Therefore, to compare all data and ultimately be able to build a model incorporating data from all seven types of mixtures, including the cementitious replacement materials, the final data set used was the difference from each of the three recycled fines replacement percentages (2.5%, 5%, and 7.5%) from the control mix, thus “normalizing” all results by supplementary cementitious material. This allowed for comparison across all data types and the inclusion of all data into an eventual model.

First, the difference in set time will be considered. Therefore, plots can be presented from the three material characterization parameters: pH, conductivity, and IR against the difference in set time and are shown in Figure 10 to Figure 12 below. The CaO content, given as a percentage and calculated based on known values for the cement, fly ash, and slag, was also considered in the predictions and is plotted against the difference in set time in Figure 13. Finally, the diameter of the 50th percentile particle size is plotted against the difference in set time in Figure 14 below.

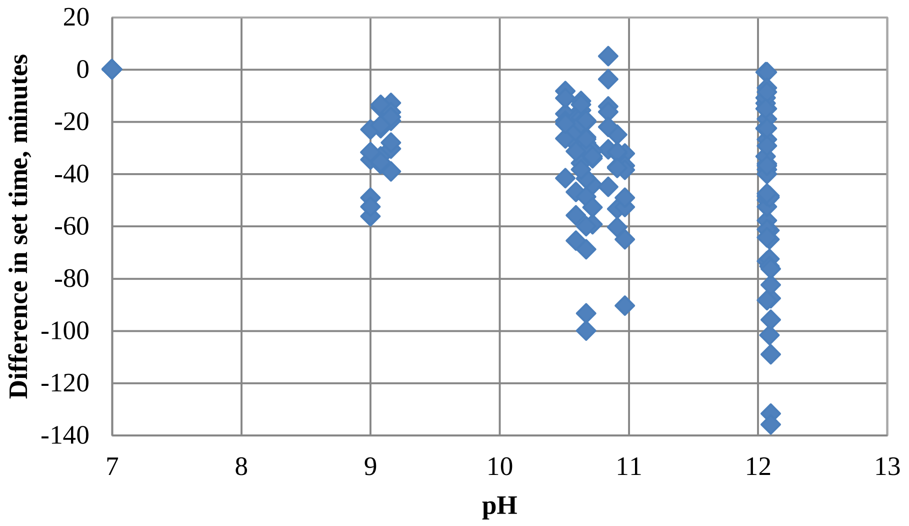

FIGURE 10 pH versus difference in set time.

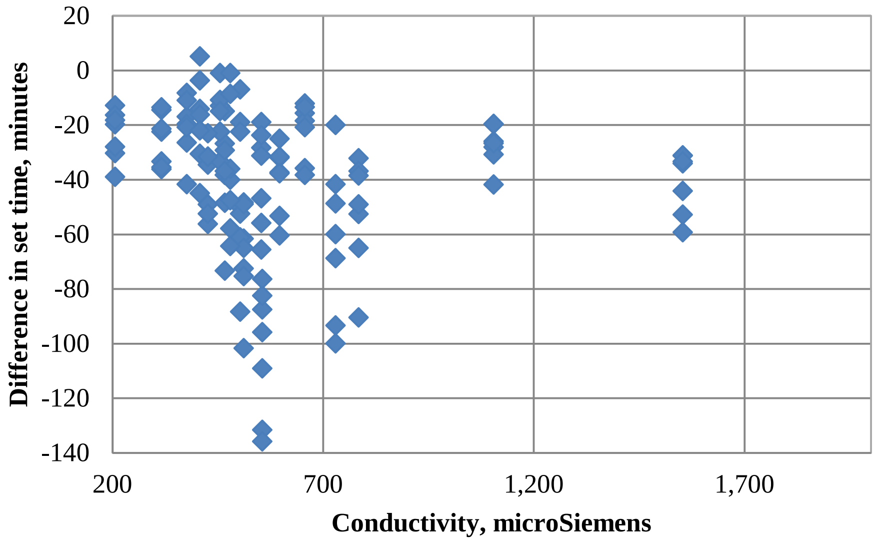

FIGURE 11 Conductivity versus difference in set time.

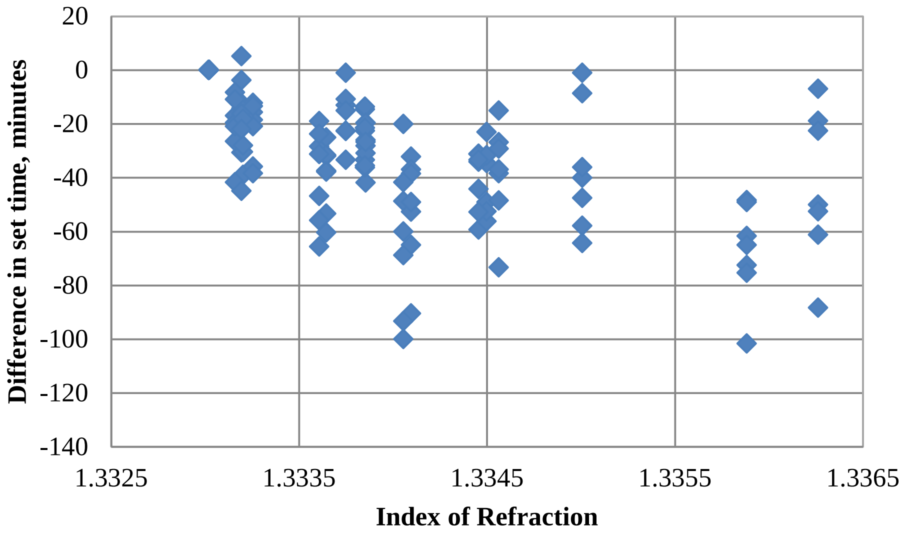

FIGURE 12 Index of refraction versus difference in set time.

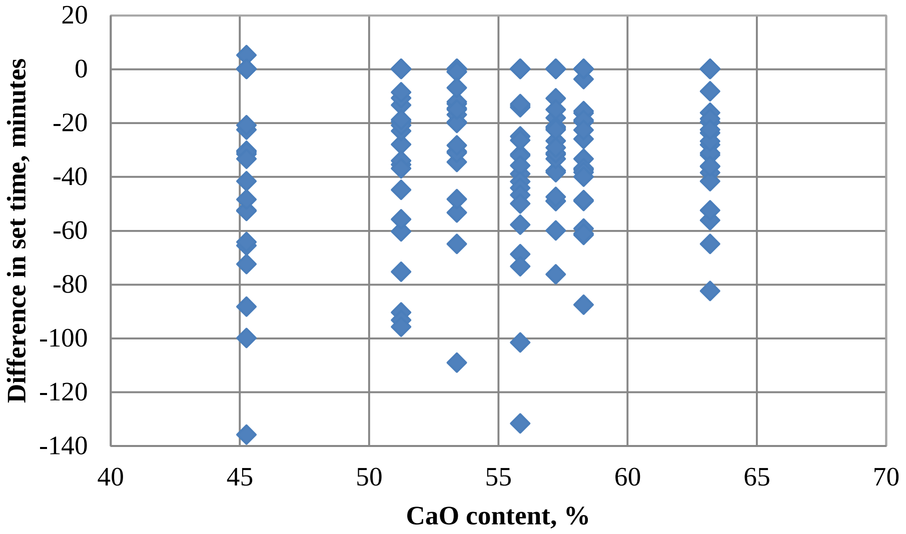

FIGURE 13 CaO content versus difference in set time.

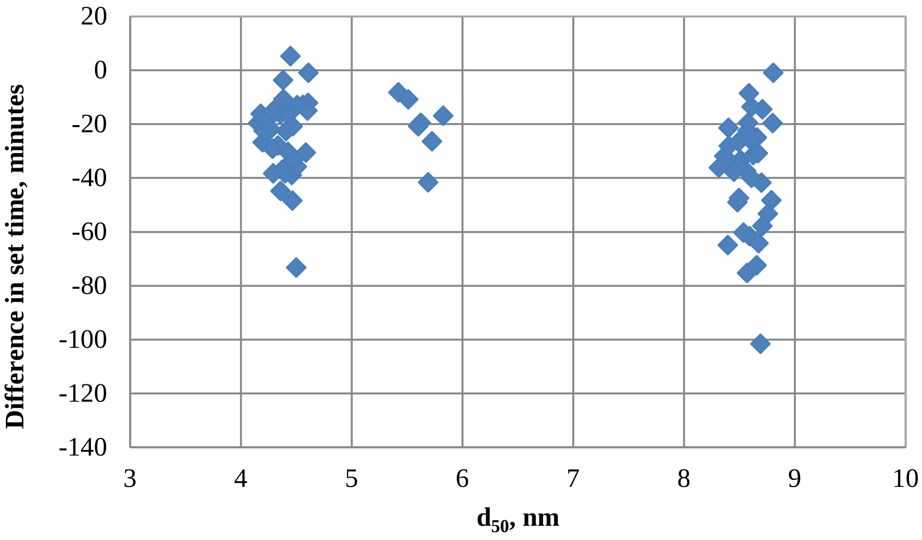

FIGURE 14 Diameter of 50th percentile particle, d_{50}, versus difference in set time.

While strong trends are not immediately obvious from these relationships, all factors will be considered in building a multiple linear regression, as will be described later.

3.2.2. Compressive strength

The next phase of the laboratory consisted of measuring the 3-day and 28-day compressive strength of mortar cubes. Six cubes were cast for each mix design (see Table 4), three of which were used for measuring 3-day compressive strength and the remaining three for 28-day compressive strength. The mix water used in each of the mortar cube batches was tested for pH, conductivity, and Brix (for IR). The strength, as a percentage of the control, are shown with respect to these factors in Figures 15 to 17. For additional particle size considerations, the span, as defined in Equation 2, is plotted against the percentage of the control 3-day compressive strength in Figure 18. While compressive strength were measured for ages of both 3- and 28-days, the focus of the results remains on early mortar properties. This is consistent with the initial speculation that using the recycled fines as a cementitious replacement material would more greatly affect the 3-day strength and the effect would be greatly lessened for 28-day compressive strength.

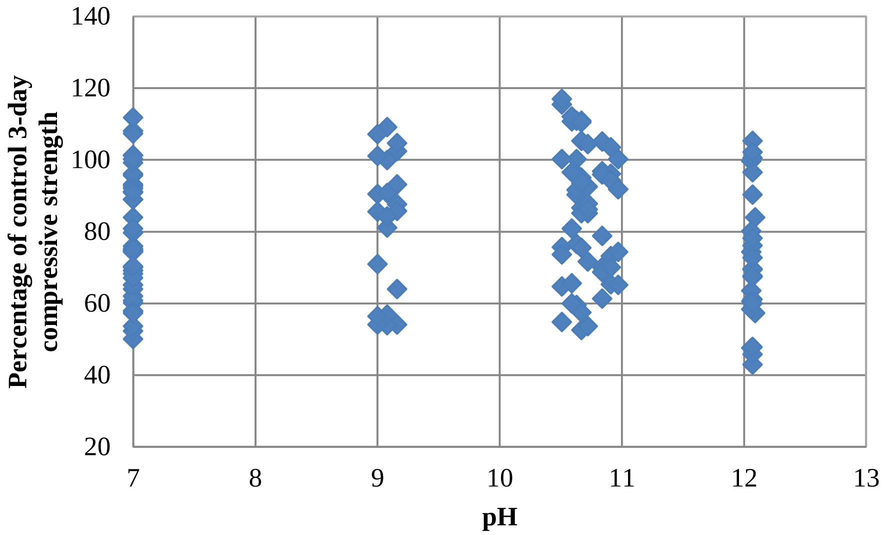

FIGURE 15 pH versus percentage of control 3-day compressive strength.

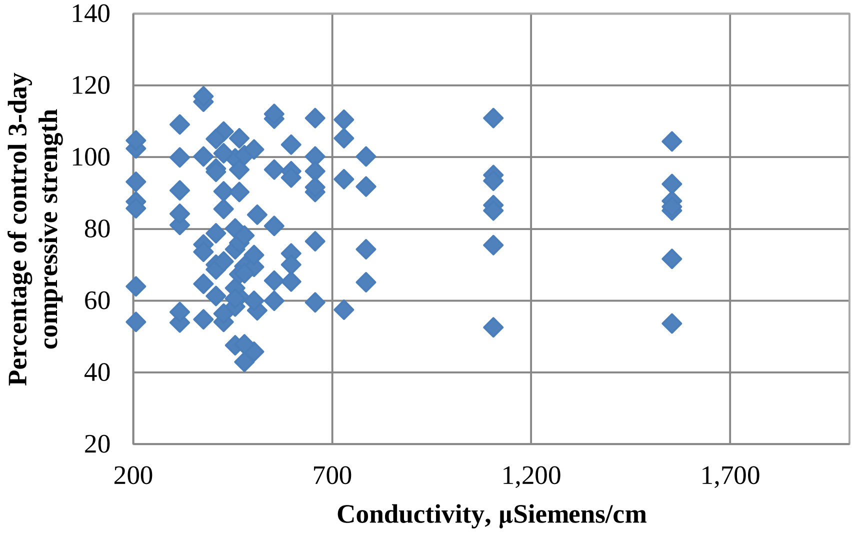

FIGURE 16 Conductivity versus percentage of control 3-day compressive strength.

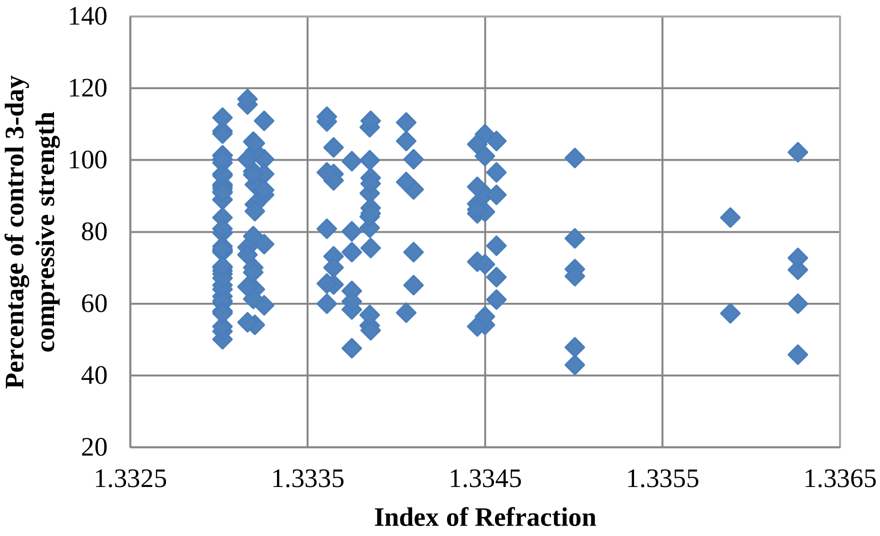

FIGURE 17 **Index of refraction versus percentage of control 3-day compressive strength.**

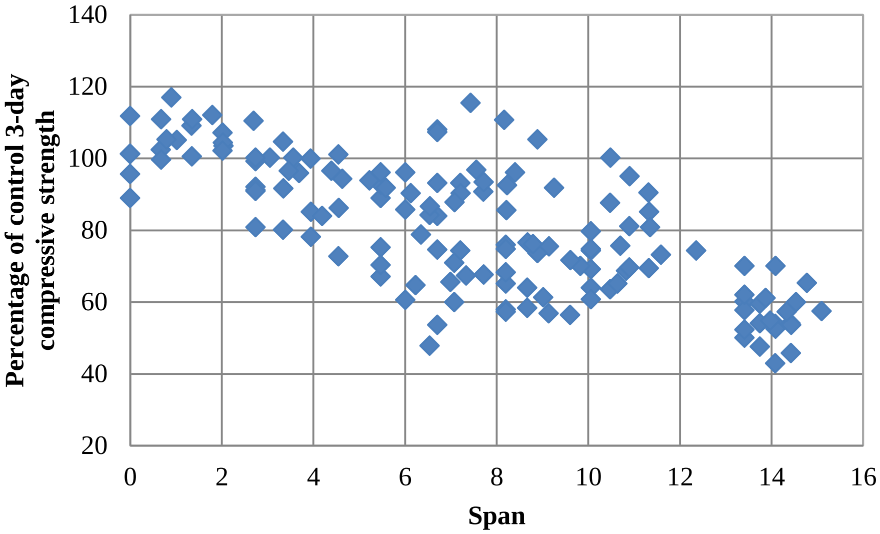

FIGURE 18 **Span versus percentage of control 3-day compressive strength.**

The compressive strength as a percentage of the control are plotted against pH, conductivity, and IR in Figures 19 to 21. Additional particle size effects are also considered and the percentage of control strength is plotted against the span, as defined in Equation 2, in Figure 22.

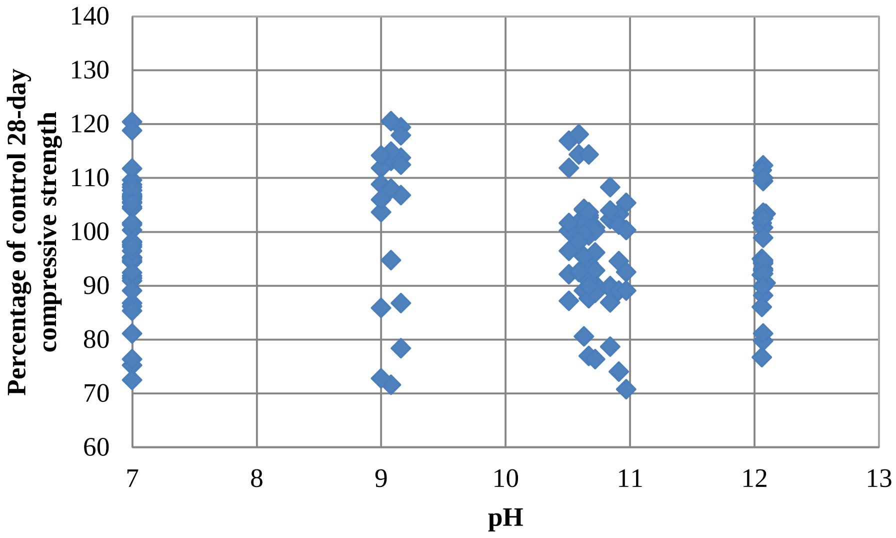

FIGURE 19 pH versus percentage of control 28-day compressive strength.

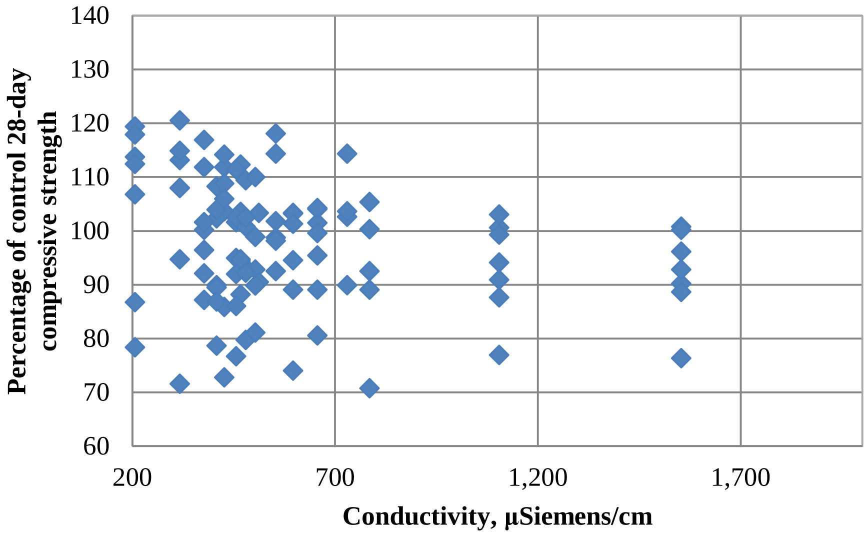

FIGURE 20 Conductivity versus percentage of control 28-day compressive strength.

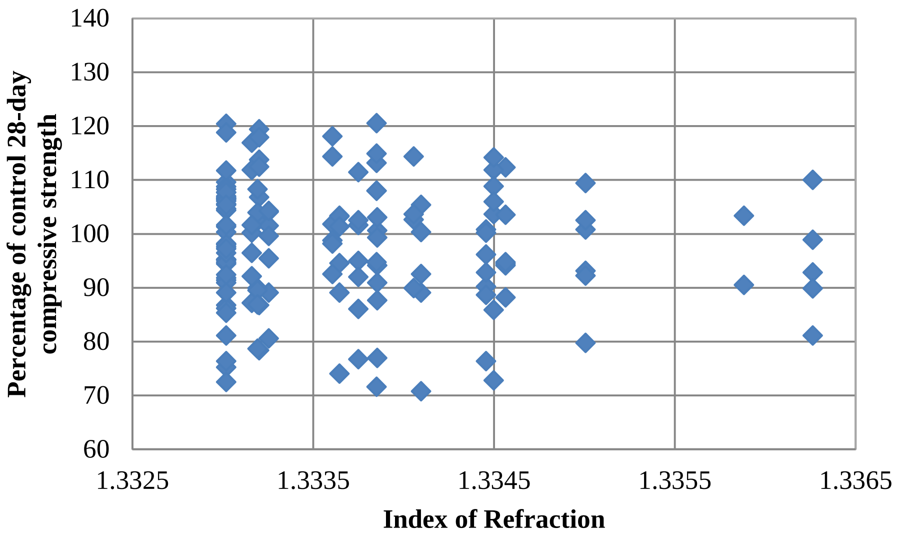

FIGURE 21 Index of refraction versus percentage of control 28-day compressive strength.

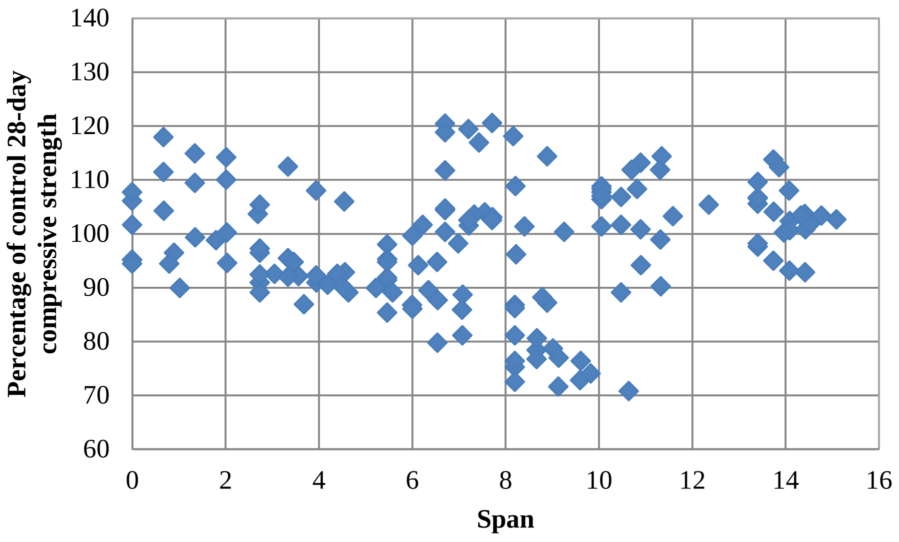

FIGURE 22 Span versus percentage of control 28-day compressive strength.

Additionally, the mortar samples were normalized to account for the varying levels of different supplementary cementitious materials used in the mix designs. In order to account for this variation, two material-based parameters were considered to normalize the supplementary cementitious material content. First, the CaO content, given as a percentage, was considered. Second, a CaO ratio, defined in Equation 3, was also used to account for differences in the results based on the supplementary cementitious material used.

$$CaO\ Ratio = \frac{CaO}{Al_2O_3 + SiO_2} \tag{3}$$

Where,

CaO = percentage content of calcium oxide in the cement or cementitious material

Al_2O_3 = percentage content of aluminum oxide in the cement or cementitious material

SiO_2 = percentage content of silicon dioxide in the cement or cementitious material.

The total number used in the analysis, however, incorporated the varying percentages of cementitious replacement material as well such that the final value of CaO ratio considered for each mix was calculated as given in Equation 4.

$$Mix\ CaO\ Ratio = (F_c)(CaO\ Ratio_c) + (F_{scm})(CaO\ Ratio_{scm}) \tag{4}$$

Where,

F_c = fraction of the total cementitious materials comprised of cement

$CaO\ Ratio_c$ = CaO ratio of cement

F_{scm} = fraction of the total cementitious materials comprised of supplementary cementitious material (either slag or fly ash)

$CaO\ Ratio_{scm}$ = CaO ratio of the supplementary cementitious material.

To justify this normalization procedure, the compressive strength must have a linear relationship with the CaO ratio, implying that strength predictions can be made based on the amount and type of supplementary cementitious material. Therefore, the 3-day control strength can be plotted against the CaO ratio, as shown in Figure 23. It was found that a linear relationship fit the data well with an R^2 of 0.89 and a standard error of 250 psi.

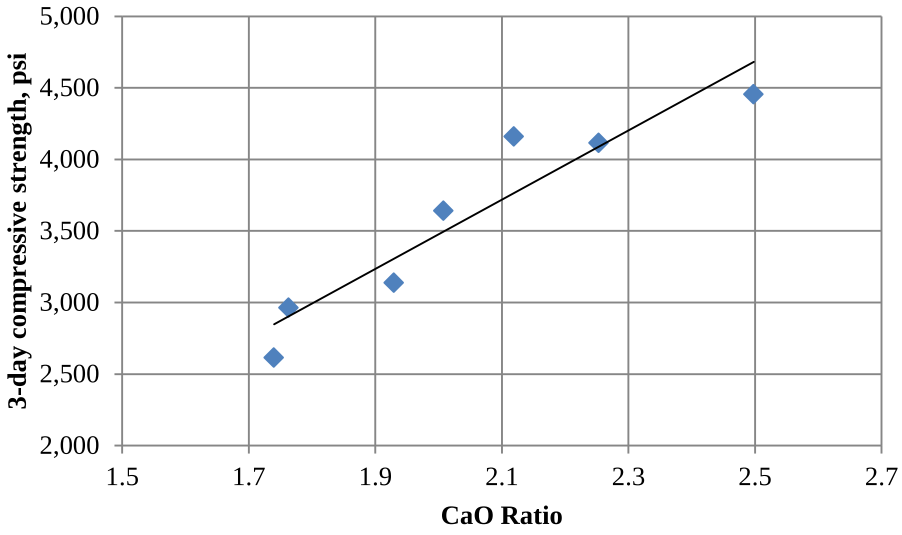

FIGURE 23 CaO ratio versus control 3-day compressive strength.

The 28-day control strength were then plotted against the CaO content given as a percentage and shown in Figure 24. This relationship was not as strong as the relationship with early strength and resulted in an R^2 value of 0.50 and a standard error of 550 psi. This relationship is expected to be weaker considering that the expected effects from the inclusion of the recycled fines have a greater effect on early strength.

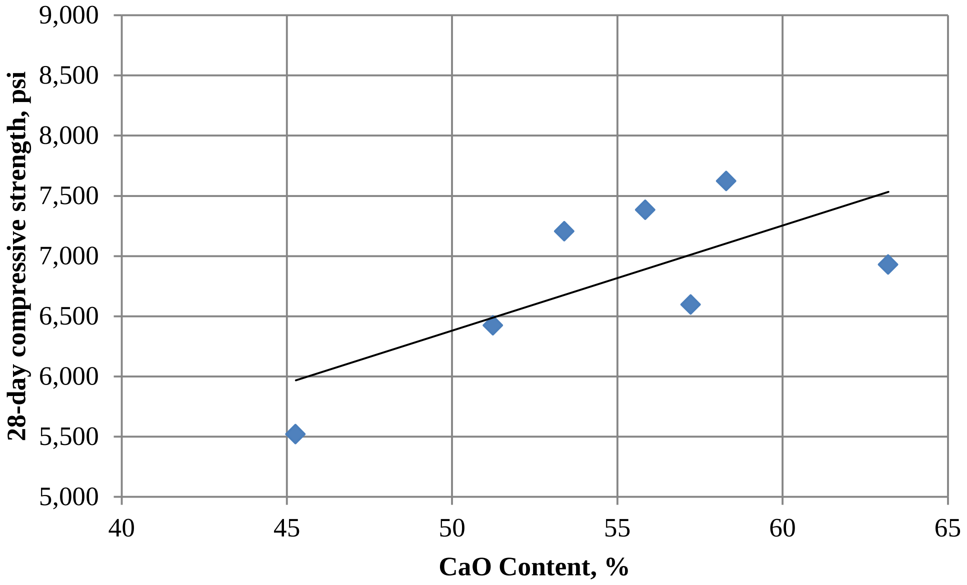

FIGURE 24 CaO content versus control 28-day compressive strength.

Given that this normalization procedure is valid, both the CaO ratio and the CaO percentage were proportioned, as described by Equation 4. The relationship between the CaO ratio and the percentage of the control 3-day compressive strength is given in Figure 25 and the relationship between the percentage of the 28-day control compressive strength is given in Figure 26.

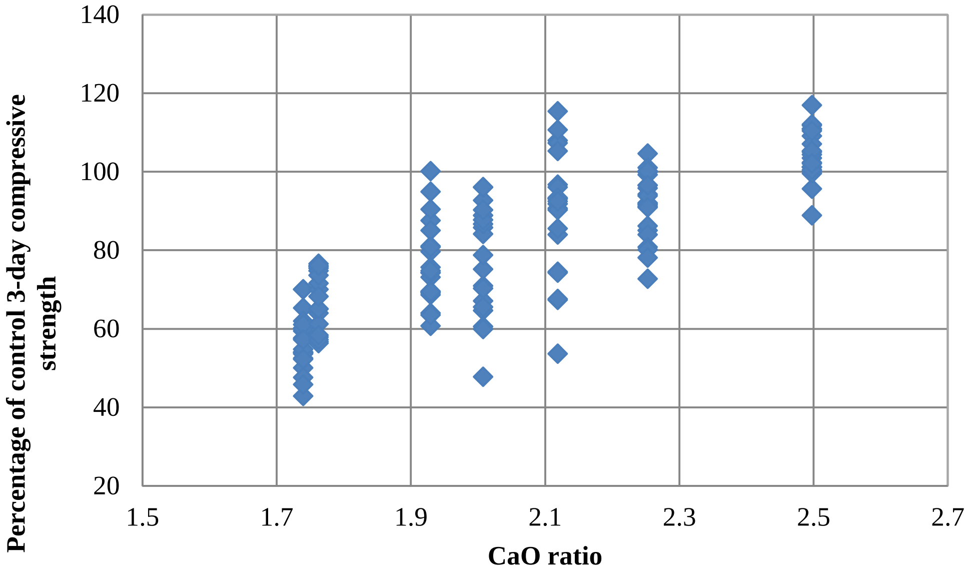

FIGURE 25 CaO ratio versus percentage of control 3-day compressive strength.

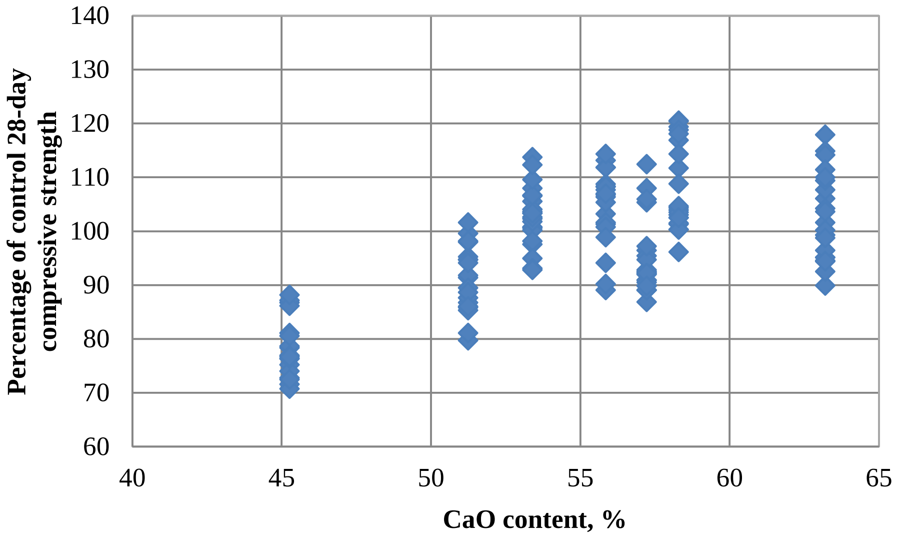

FIGURE 26 CaO content versus percentage of control 28-day compressive strength.

4 DATA ANALYSIS

The laboratory work completed and previously discussed was then used as a database in order to build the intended predictive equations. Because the intent of the project was to predict performance of the mortar using initial measurements of the wastewater, the data was organized for regression modeling. Therefore, the predicted performance factor (either the difference in set time or 3-day or 28-day strength as a percentage of control strength) would be described as a function of the input parameters selected from the wastewater. The process of developing these regression equations will be discussed in this chapter, beginning with sorting the initial data to check for possible outliers and required transformations, and into the development of the final models.

4.1 Data Transformations

An initial check for outliers was performed when calculating average compressive strength from three cubes for each batch, in accordance with the requirements outlined in the ASTM C109 specification. This specification states that outlier specimens should not be considered and of three cubes cast in the same mortar batch, no result should vary by more than 8.7% from the average compressive strength for the three cubes. If one outlier is identified and removed, then neither of the two remaining results should vary by more than 7.6% from the average of the two specimens. This specification requirement provided the first method of outlier removal. Because of the relatively unknown nature of this topic, all data points were used in initial model development. When plotted, no substantial outliers were observed, and the requirement from the mortar cube specification was the only method of outlier removal that was employed.

Initially, the raw compressive strength were plotted against each for the three material parameter predictors (pH, IR, and conductivity) individually for each of the seven mix designs to look for approximate trends. The lack of linearity of the data indicated that a linear regression model would not fit the data well. Two options emerged: either a multiple nonlinear regression model could be used or the raw data could be transformed using nonlinear functions and the transformed data could then be used in a linear regression model.

This second option of transforming the data, is a more simple and practical approach and was therefore tried first.

First, a single-factor regression analysis for each of the three parameters for each of the seven individual mix designs across all six fines types was completed. This was done in order to observe trends across the similar mix designs or fines types. Standard transformations were all attempted for all three parameters and are listed in Table 9.

TABLE 9 Data transformations

Transformation	
1	exp(x)
2	ln(x)
3	1/x
4	1/exp(x)
5	1/ln(x)
6	x^2
7	$1/x^2$

Several trends emerged across all seven mix designs (regardless of percentage or type of cementitious replacement material), which indicated the presence of some kind of trend across the data. After the evaluation of each prediction variable using all transformations (and all combinations of the transformations given in Table 5), best fit transformed parameters were selected. The parameters which best fit the mix designs in single-factor linear regressions were exp(pH), conductivity and IR^2. This transformed data was then used for the remainder of the model analysis.

Original pilot testing (Janssen 2010) indicated that an optimal fines replacement percentage might exist. The optimal fines replacement percentage was defined as a replacement percentage, which produced maximum performance. All data were analyzed for statistical significance based on Dunnett's testing to evaluate if a statistically optimal fines percentage existed. This testing revealed that an optimal fines percentage did not exist.

Here it should be noted that all data was included for the development of the set time testing prediction models. However, it was determined that water that would not fulfill the set time requirements outlined in the ASTM requirement would not be used for concrete production. Therefore, the predictive models for the strength prediction only included data that fulfilled the set time requirements. This selection criteria was justified based on the intention of the prediction equations, which would be to predict concrete performance using recycled concrete water. Recycled water outside of the range of set time test requirements outlined by ASTM C1602 was not be used for concrete production and these was therefore not included in developing prediction equations for compressive strength.

4.2 Model Development

The six models were developed using the results from the laboratory testing. Two of the models predict set time, two predict 3-day compressive strength and two predict 28-day compressive strength. A practitioner's model, which does not include particle size information, was developed for each of the three parameters. Additional, comprehensive models were then developed and require particle size information. The additional particle size information was found to strengthen models but this information is not readily available, especially for the practical application of this work. The three models at each level predict the difference in set time, in min, from the control mixture, and both 3- and 28-day compressive strength, given as a percentage of the control mixture. For each model, the equation describing the prediction is given, as well as the coefficient of determination, R^2, which describes the fit of a model to the data. The adjusted R^2 is also reported for each model, which accounts for possible size effects of the model (such that more predictor terms would produce a better fit, regardless of actual, significant relationship). The standard error of each model is also given. Finally, a plot of the measured values from the data set versus predicted values using the models will be given to display the fit of the model.

4.3.1. Practitioner's models

The first practitioner's model predicts the difference in set time, in min, from the control mixture. All data, including data which did not fulfill ASTM requirements, was used for the development of this model. The final regression equation is given as Equation 5.

$$difference\ in\ set\ time = 18{,}159.11 + 1.062\ CaO - 10{,}246\ IR^2 - 0.03\ Cond \qquad (5)$$

Where,

CaO = percentage of CaO in the cementitious materials, including all supplementary cementitious materials

IR = index of refraction

$Cond$ = Conductivity in μSiemens/cm.

This model had an R^2 of 0.61 and an adjusted R^2 of 0.60 with a standard error of 18.0 min. The plot of measured versus predicted values is given in Figure 27.

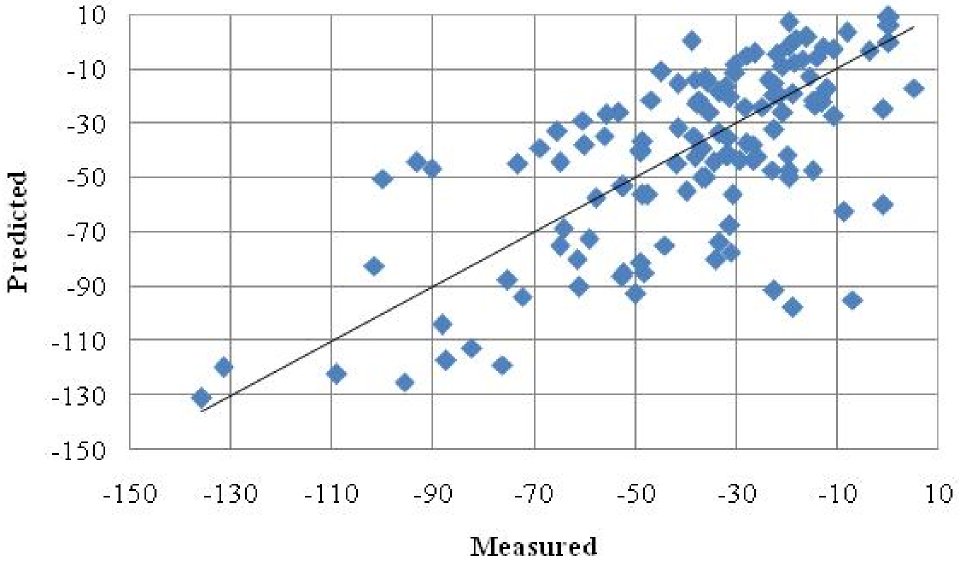

FIGURE 27 Measured versus predicted for the difference in set time practitioner's model.

The next practitioner's model predicts 3-day compressive strength as a percentage of the total control strength. The final regression equation for the second model is given as Equation 6.

$$3\ day\ f_c\ percentage = -85.83 - 9.7 \times 10^{-5} \exp(pH) + 8.93 \times 10^{-3} Cond + 78.02\ CaO\ Ratio \qquad (6)$$

Where,

pH = pH of the recycled water

$Cond$ = Conductivity of the recycled water, measured in μSiemens/cm

$CaO\ Ratio$ = ratio of CaO to SiO_2 and Al_2O_3 in the cementitious materials, as described in Equations 3 and 4, including all supplementary cementitious materials.

This model had an R^2 of 0.70 and an adjusted R^2 of 0.70 with a standard error of 10%. The plot of measured versus predicted values is given in Figure 28.

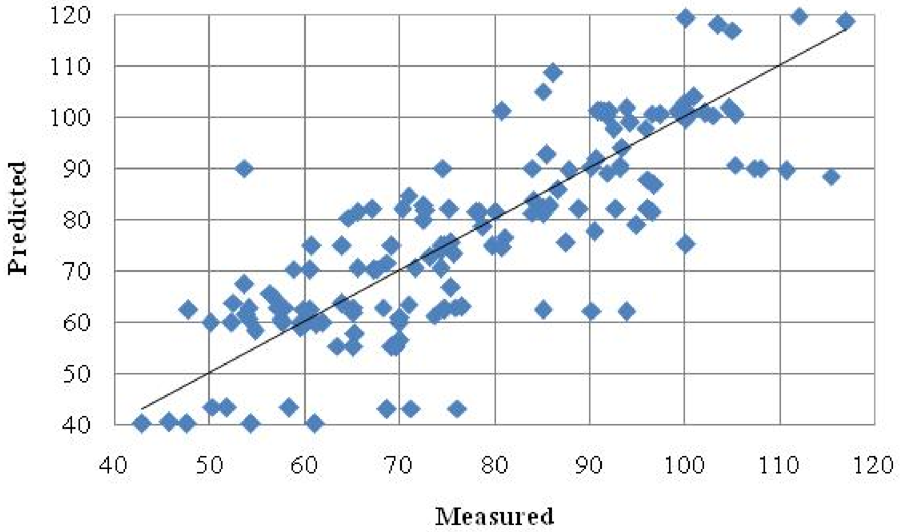

FIGURE 28 Measured versus predicted for the percentage of 3-day compressive strength practitioner's model.

The final practitioner's model predicts 28-day compressive strength as a percentage of the total control strength. The final regression equation for the second model is given as Equation 7.

$$28\ day\ f_c\ percentage = -62.02 - 5.5 \times 10^{-5} \exp(pH) - 0.00851\ Cond + 3.083\ CaO \qquad (7)$$

Where,

pH = pH of the recycled water

$Cond$ = Conductivity of the recycled water, measured in µSiemens/cm

CaO = percentage of CaO in the cementitious materials, including all supplementary cementitious materials.

This model had an R^2 of 0.46 and an adjusted R^2 of 0.45 with a standard error of 8.5%. The plot of measured versus predicted values is given in Figure 29.

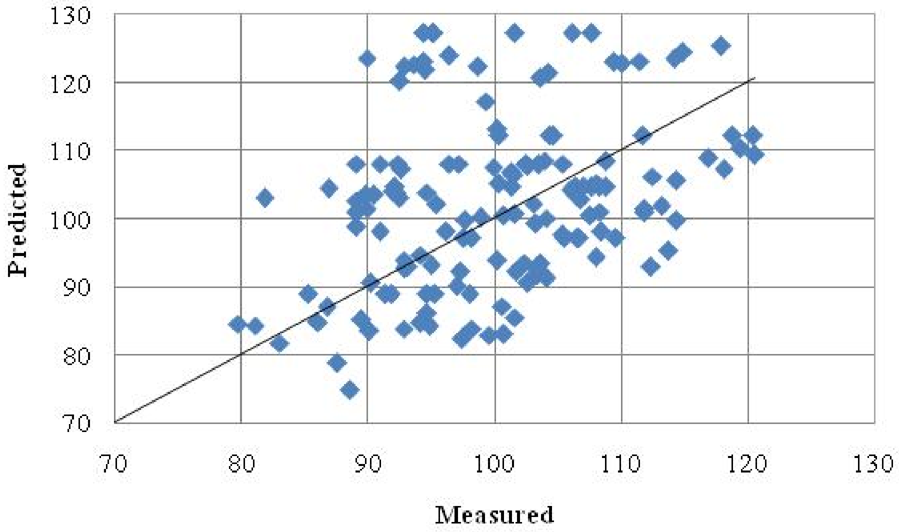

FIGURE 29 Measured versus predicted for the percentage of 28-day compressive strength practitioner's model.

4.4.2. Comprehensive models

The comprehensive models all require additional particle size information. The first comprehensive model predicts the difference in set time, in min, from a control mixture. All data, including data which did not fulfill ASTM requirements, was used for the development of this model. The final regression equation is given as Equation 8.

$$difference\ in\ set\ time = 16196.14 - 16.99(d_{50}) + 1.047\ CaO - 9137.32\ IR^2 - 0.00832\ Cond \qquad (8)$$

Where,

d_{50} = the diameter based on the 50th percentile of the tested particles

CaO = percentage of CaO in the cementitious materials, including all supplementary cementitious materials

IR = index of refraction.

This model had an R^2 of 0.65 and an adjusted R^2 value of 0.64 with a standard error of 17 min. The plot of measured versus predicted values is given in Figure 30.

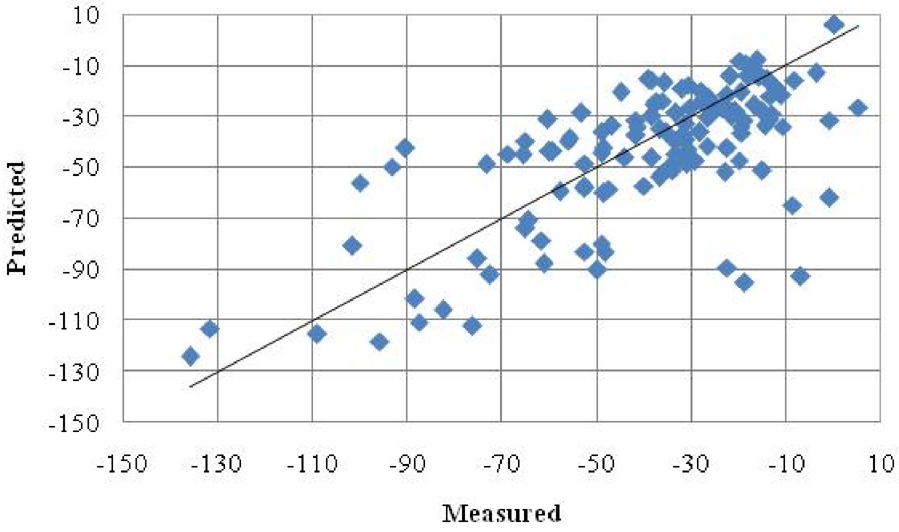

FIGURE 30 Measured versus predicted for the difference in set time comprehensive model.

The 3-day compressive strength as percentages of the control strength can be obtained using Equation 9 if the particle size characterization information is available.

$$3\ day\ f_c\ percentage = -83.79 - 1.09 \times 10^{-4}\exp(pH) - 0.00321 Cond + 77.27\ CaO\ Ratio + 28.57\ Span \quad (9)$$

Where,

$Cond$ = Conductivity of the recycled water, measured in µSiemens/cm

$CaO\ Ratio$ = ratio of CaO to Al_2O_3 and SiO_2 in the cementitious materials, including all supplementary cementitious.

$Span$ = Boundary to describe the size distribution of the particles using the diameters of different percentiles of particles: d_{90}, d_{50}, and d_{10}.

This model had an R^2 of 71and an adjusted R^2 value of 0.70 with a standard error of 9.9 %. The plot of measured versus predicted values is given in Figure 31.

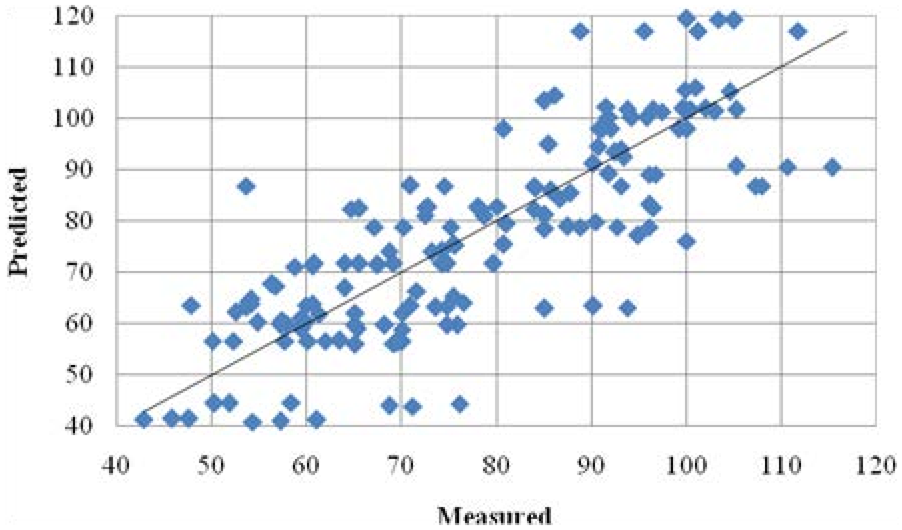

FIGURE 31 Measured versus predicted for the percentage of 3-day compressive strength comprehensive model.

The next two model predicts 28-day strength as percentages of the control strength. The final regression equation for is given as Equation 10.

$$28\ day\ f_c\ percentage = -72.3 - 0.0176Cond - 7.32 \times 10^{-5}\exp(pH) + 2.941\ CaO + 47.85\ Span \qquad (10)$$

Where,

pH = pH of the recycled water

$Cond$ = Conductivity of the recycled water, measured in μSiemens/cm

CaO = percentage of CaO in the cementitious materials, including all supplementary cementitious materials

$Span$ = Boundary to describe the size distribution of the particles using the diameters of different percentiles of particles: d_{90}, d_{50}, and d_{10} for the 90^{th}, 50^{th}, and 10^{th} percentiles, respectively.

This model had an R^2 value of 0.48 and an adjusted R^2 value of 0.47 with a standard error of 8.4%. The plot of measured versus predicted values is given in Figure 32 below.

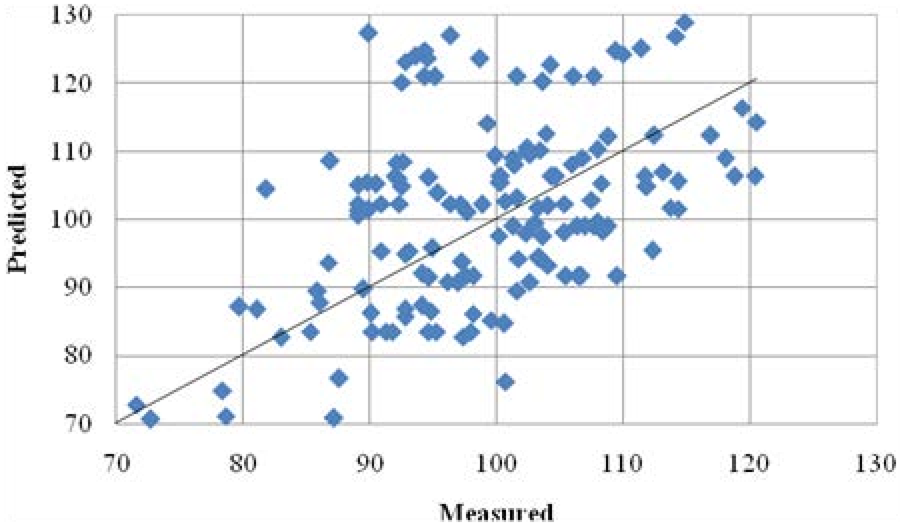

FIGURE 32 Measured versus predicted for the percentage of 28-day compressive strength comprehensive model.

5 IMPLEMENTATION

5.1 Model Validation

An established model, even a well-fitting model, is not guaranteed to fulfill its intended function. Therefore, model validation is necessary. There are several limitations to the model that was developed. First, it was developed only using mortar cube compression strength data rather than full concrete cylinders. Many tests were run and cost and time efficiency dictated casting small mortar cubes since it was assumed they would provide a close approximation to the performance of concrete. The final intention of the model, however, is to predict the behavior of concrete rather than mortar. Additionally, the regression model used material characterization data from multiple recycled fines sources under extremely controlled conditions, where the fines sources were dried, sieved, mixed, and measured carefully by mass. In reality, however, these fines sources will be included as wastewater with only the three in-line measurements as an indication of the material properties. These differences could potentially have an impact on the prediction capabilities of the regression model and therefore model validation is necessary.

Generally, three validation techniques can be used: (1) analysis of the model coefficients by comparing with experience, theory, or simulation; (2) collection of new data, and (3) data splitting.

For this specific data set, option one was not feasible as there is extremely limited, scattered and unreliable previous work and no simulations were run. Option three was possible, but given the unknown behavior of this experiment, it seemed a more robust model would be possible if all data was included. Therefore, the regression model will be validated using option two of collecting new data.

5.2 Mock-up Water Supply System

To validate the model, a mockup water supply system simulating those typically used in a batch plant was used to make concrete. Again, despite the fact that the initial model was developed for mortar samples only the ultimate application is concrete strength prediction. The water supply system was instrumented with in-line sensors for monitoring pH, conductivity, and percent solids as shown in Figure 33. The sensor output devices are shown in Figure 34.

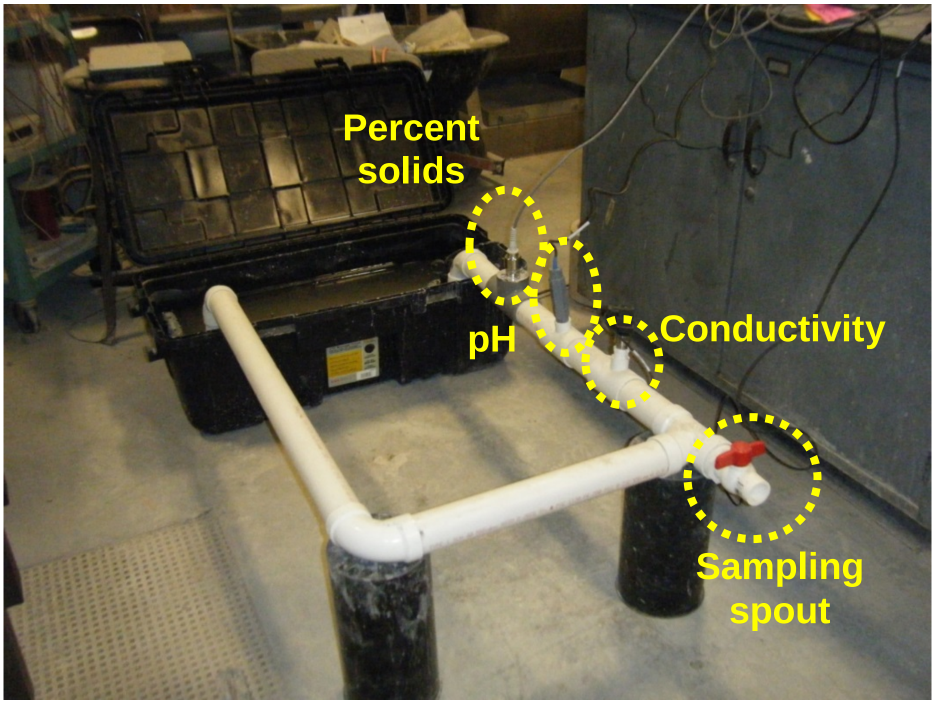

FIGURE 33 Water recirculation system with in-line sensors.

FIGURE 34 Sensor output devices.

The sensors used in this laboratory study along with their sensitivities and accuracies are given in Table 10 below.

Table 10 Equipment accuracy and resolution for water recirculation system

Property measured	Accuracy	Resolution
Percent solids	±5% of range 0.0006 (for IR)	0.01%
Conductivity	±1%	1 µS/cm
pH	0.01	0.01

It is important to note that the equipment used to measure IR was a percent solids meter, which is converted into IR. The percent solids meter was deemed to be more appropriate for this application. In order to convert between percent solids and index of refraction, an initial material characterization using the original six types of fines was completed with the percent solids meter. Then, a linear regression between the two measurements was completed in order to convert between the two types of measurements. A plot of the materials characterization of the six fines types is given in Figure 35.

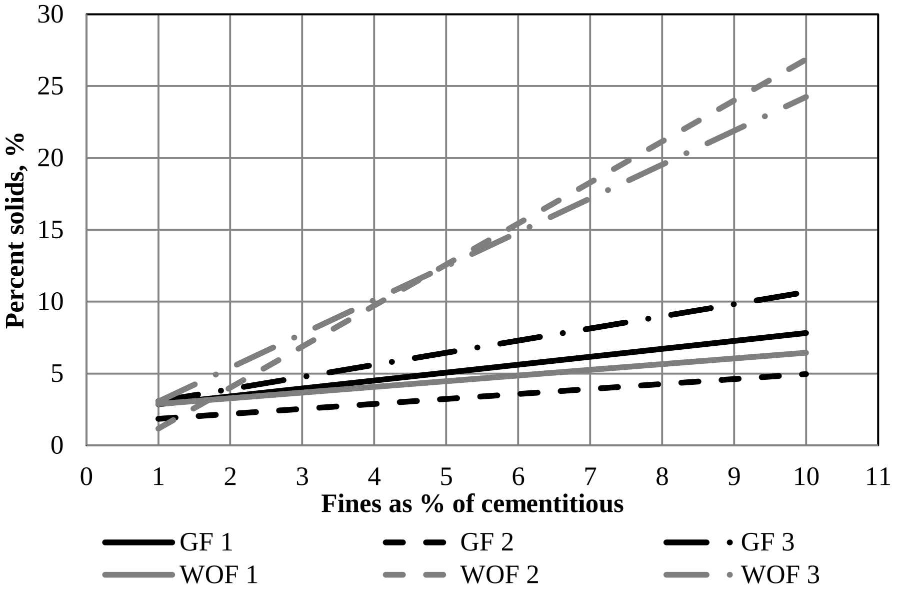

FIGURE 35 Particle content as a function of fines concentration.

The linear regression relationship developed for predicting IR based on the particle content is described by Equation 11 given below.

$$IR = 1.33289 + 0.00019857\,PS \tag{11}$$

Where,

PS = percent solids, %.

This relationship had an R^2 of 0.92. The standard error for the estimate was 0.000312.

5.2.1. Results

To validate the predictive models, three concrete mixtures were cast: one control and two batches with different wastewater used. All three concrete mixtures had a supplementary cementitious replacement material of 15% Class F fly ash. The same fly ash from the original mortar testing was used. From each batch, slump, set time, and 3-day and 28-day testing was completed. Material details are given for the coarse and fine aggregate, and the cement and fly ash in Table 11 below.

TABLE 11 Detail of materials used in validation concrete mixtures

Coarse aggregate	
Type	River gravel
Top size	1.0 in.
Bulk specific gravity (SSD)	2.50
Absorption capacity	2.07 %
Los Angeles abrasion value	34%
Fine aggregate	
Fineness modulus	2.86
Absorption capacity	1.24%
Bulk specific gravity (SSD)	2.62
Cementitious materials	
Cement type	ASTM Type I Portland
Fly ash type	Class F

The mixture design for all three mixtures was then constructed based on the concrete mixture requirements outlined in Table 12. The target mixture characteristics are provided in Table 13. Additionally, quantities are provided for a standard cubic yard.

TABLE 12 Mix design criteria used to design concrete mixtures

Criteria	**Value**
w/cm ratio	0.42
Slump, in.	4
Min. 28-day compressive strength	4500 psi
Target 28-day compressive strength	5500 psi
Min. cement requirements	520 lb/CY
Approximate air content (not entrained)	1.5%

TABLE 13 Concrete mixture proportions

Component	**Proportion (lbs/cyd)**
Cement	587
Fly ash	104
Fine aggregate	1,218
Coarse aggregate	1,816
Water	281

Concrete was mixed in a standing drum mixer in accordance with ASTM C 192: Practice for Making and Curing Concrete Test Specimens in the Laboratory. Slump was then measured for each mixture and was tested according to ASTM C 143: Test Method for Slump of Hydraulic-Cement Concrete. Following slump testing, cylinders were cast according to

ASTM C 39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. A total of eight cylinders were cast with four allocated towards 3-day and four for 28-day compressive strength measurements. Finally, mortar was separated from the concrete mixture (by sieving the coarse aggregate out of the concrete with a No. 4 screen) to use for Vicat testing of mortar samples. It was determined that despite penetration testing is the standard for concrete testing, the Vicat testing would better simulate the predicted models, because Vicat testing was used for data for model development.

Two of the three concrete mixes contained recycled wastewater as the mix water in the concrete. Randomized mixtures of dried fines were blended into the water in order to make a completely new wastewater mixture. The mixture was intended to be a completely unknown, randomized mixture in order to simulate conditions that would be experienced in an in-line water supply system in a ready-mix concrete plant. Therefore, only the readings taken from the in-line sensors were used and no quantification of the behavior of the fines was otherwise considered. Readings from the three in-line sensors were then taken while the water was being pumped through the system such that sufficient agitation was present to keep the solids suspended and thoroughly mixed in the water. Water was then pulled from the sampling spout and used as mixing water for making the concrete. The in-line sensor measurements for the water used in the concrete are provided in Table 14.

TABLE 14 In-line sensor measurements for two validation mixtures

Concrete mixture	**pH**	**Conductivity, µSiemens/cm**	**Percent solids**	**IR[1]**
Mixture 1	11.27	1184	8.75	1.33465311
Mixture 2	11.14	680	14.3	1.33603868

[1] IR was calculated from the percent solids using Equation 11.

The results from this testing for all three batches are given in Table 15 below. Fresh water without the addition of recycled fines was used for the control mix.

TABLE 15 Measured raw data for the two validation mixtures

Concrete mixture	Slump, in	Set time, min	3-day compressive strength, psi	28-day compressive strength, psi
Control	5	210	4020	6060
Mixture 1	3	229	4280	6370
Mixture 2	3	251	4390	6210

5.2.2. Predictions

To validate the models, the data from the testing described in the previous section will now be used with the practitioner's predictive models given in Equations 5-7. First, the raw data given in Table 15 was converted into the prediction values: difference in set time, and the percentages of strength with respect to a control and are provided in Table 16.

TABLE 16 Measured concrete properties

Concrete mixture	Difference in set time, min	Percentage of 3-day compressive strength	Percentage of 28-day compressive strength
Mixture 1	-19	106	105
Mixture 2	-41	109	102

It can be seen from the results in Table 16 that both mixtures fulfilled the requirements outlined in ASTM C 1602 for mixing water in fresh concrete production. Both 3-day and 28-day compressive strength met and exceeded the requirement that they have at least 90% of the compression strength of the control mixture. Likewise, the difference in set time from the control mixture did not exceed the 60 minute threshold outlined in the specification. Both mixtures fell well within these limitations despite containing a percent solids value (from Table 14) that far exceeded the 5% set as a limitation in the specification. The practitioner's models (Equations 5 through 7 were then used to calculate the predictions given in Table 17 below. The standard errors calculated for each prediction model are given in parenthesis next to the corresponding prediction model.

TABLE 17 Predicted concrete properties

Concrete mixture	Difference in set time, min	Percentage of 3-day compressive strength	Percentage of 28-day compressive strength
Mixture 1	-71 (18.0)	91 (8.62)	87 (8.24)
Mixture 2	-93 (18.0)	88 (8.62)	91 (8.24)

These results indicate several discrepancies with the prediction equations. First, the difference in set time, was not close to the intended values. However, the difference between the two measured values was close to the difference for the predicted values for the two batches. The predicted range, based on the standard error of the prediction equation, exceeds the measured difference between the two predictions indicating that the problem may exist between the absolute accuracy of the model rather than the relative accuracy. Additionally, this accuracy discrepancy could be attributed to using the Vicat testing apparatus for the set time testing of the mortar extracted from the concrete rather than using the standard penetration testing device. The predictions for percentage of 3-day compressive strength indicate close predictions. However, the percentage of 28-day strength does not indicate a close prediction. This model had the worst fit of the three separate parameters being modeled and therefore the prediction, even with the mortar cubes, was not very accurate. The predictions for both of the 28-day strength mixtures far exceeded the predicted value and its standard error. In both cases, however, the measured strength exceeded the predicted strength and exceeded the limit established by the ASTM C 1602 specification.

Despite these initial reasons explaining the discrepancy between the predicted and measured values, several other factors may contribute to the variation between the measured and predicted values. First, it must be noted that all prediction models were built using mortar strength data. Fortunately, the prediction is based on difference in strength from a control rather than absolute strength, but it should be noted that concrete and mortar strength are inherently different. ASTM C 109, which specifies the testing procedure for mortar cube strength, states, “Caution must be exercised in using the results of this test method to predict the strength of concretes.” Similarly, the mix design for the concrete contained a higher sand to cement ratio than the mortar mixture. This would decrease the overall set time and possibly affect the other parameters as well.

Other discrepancies between the concrete behavior and mortar behavior could be attributed to the inclusion of coarse aggregates in the concrete mixtures (a smooth river gravel was used for all mixtures) and a river sand was used for the concrete mixtures, whereas a much more uniformly graded Ottawa sand was used for the mortar mixtures.

However, the most pronounced difference in results would most likely be attributed to the use of the fines in the wastewater as a replacement material during the prediction of the models rather than an additional material as was used in the concrete mixtures. The fines were initially treated as a replacement for the cementitious materials. However, the wastewater as a whole was used in the concrete mixture strictly as water and not as a replacement for cementitious materials. This different treatment of the recycled fines probably had the greatest effect on the discrepancy between the predicted results and the measured results.

6 USER GUIDELINES

The previous prediction models have shown that measurements of several key parameters can be used in order to predict performance. These prediction models can be used to predict concrete behavior based on the in-line measurements taken from the wastewater. To provide guidelines for the use of these prediction models, plots were created to present the sensitivity to certain parameters of the basic level predictions. Because the final output is a combination of three input variables, the output can vary greatly based on the combination of these parameters. Plots describing the relationship between the predicted percentage of 3-day compression strength and the conductivity measured in μSiemens/cm are given below. Four plots are presented from Figures 36 to 39 with pH levels of 9, 10, 11, and 12, respectively. Five different curves are plotted on each graph for different levels of the CaO ratio, which helps account for the effects of supplementary cementitious materials.

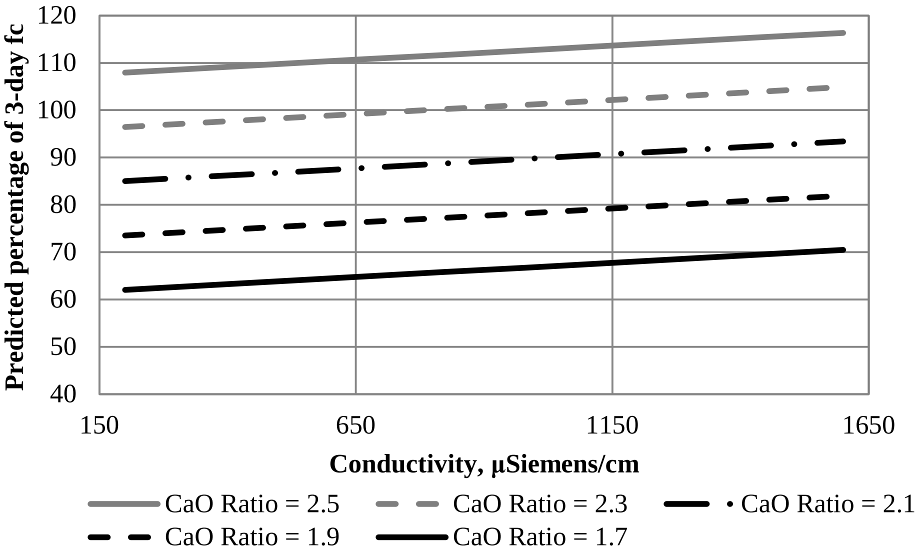

FIGURE 36 Predicted percentage of 3-day strength vs. conductivity for pH = 9.

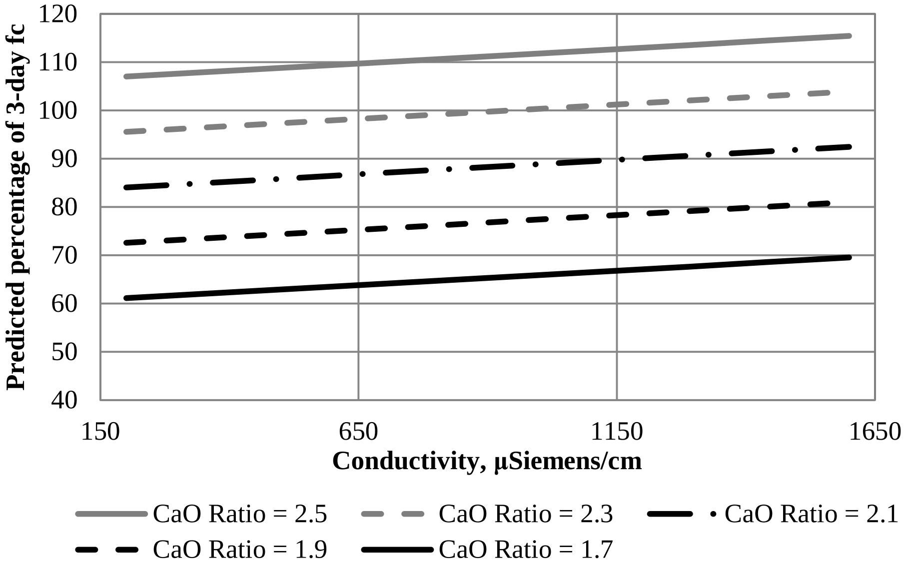

FIGURE 37 Predicted percentage of 3-day strength vs. conductivity for pH = 10.

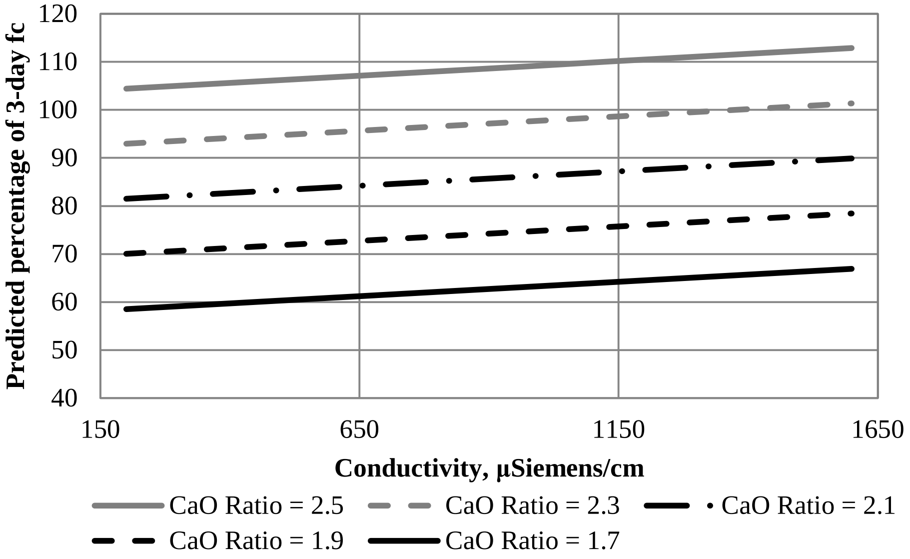

FIGURE 38 Predicted percentage of 3-day strength vs. conductivity for pH = 11.

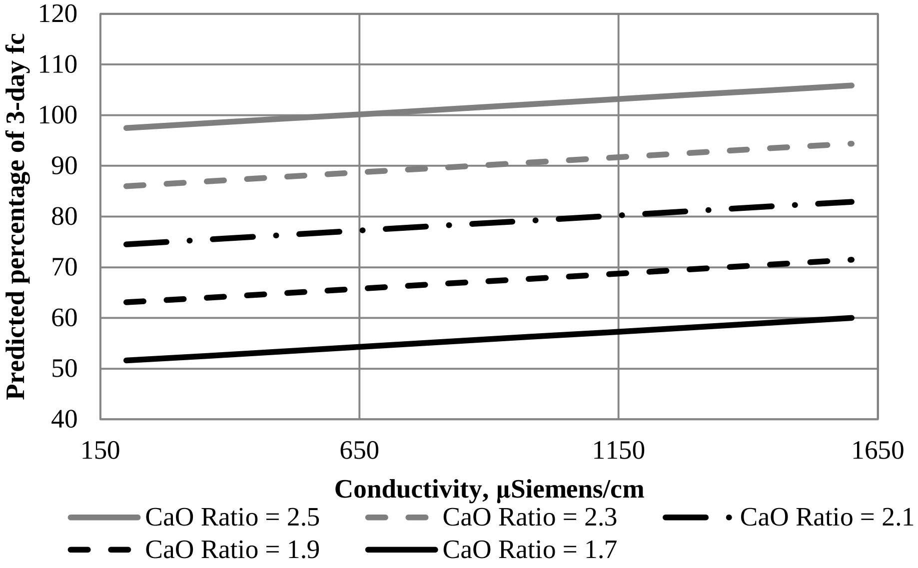

FIGURE 39 Predicted percentage of 3-day strength vs. conductivity for pH = 12.

Plots describing the relationship between the predicted percentage of 28-day compressive strength and the conductivity measured in µSiemens/cm are given below. Four plots are presented from Figures 40 to 43 with pH levels of 9, 10, 11, and 12, respectively. Five different curves are plotted on each graph for different levels of the CaO content.

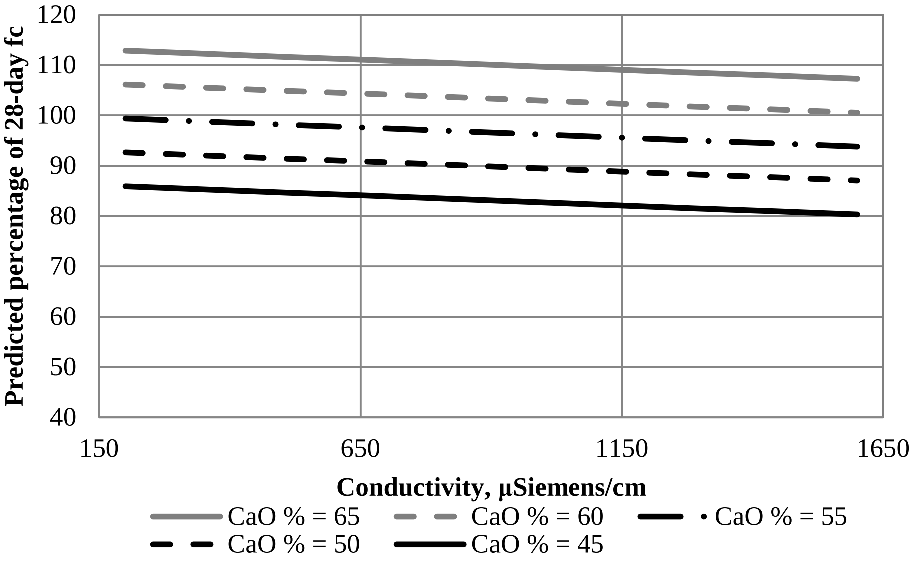

FIGURE 40 Predicted percentage of 28-day strength vs. conductivity for pH = 9.

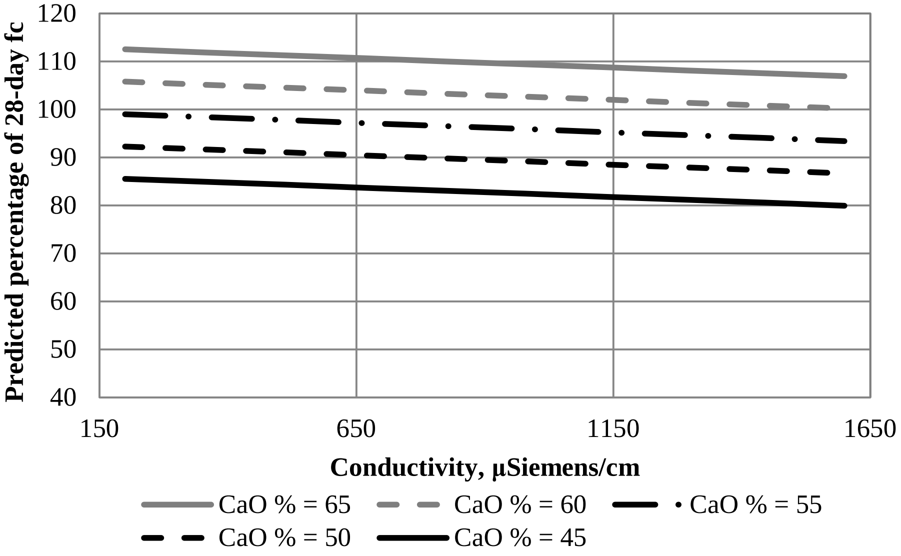

FIGURE 41 Predicted percentage of 28-day strength vs. conductivity for pH = 10.

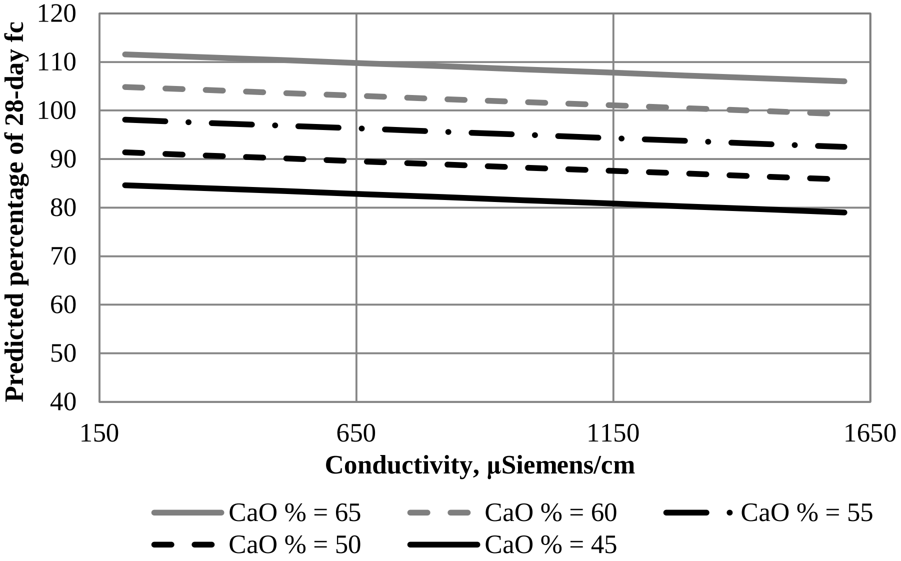

FIGURE 42 Predicted percentage of 28-day strength vs. conductivity for pH = 11.

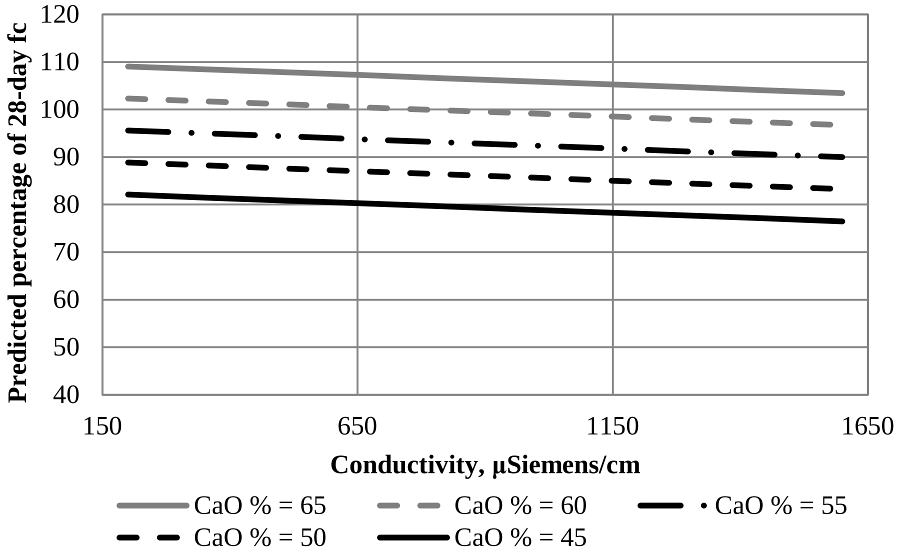

FIGURE 43 Predicted percentage of 28-day strength vs. conductivity for pH = 12.

Plots which describe the relationship between the predicted difference in set time and the index of refraction are given below. Four plots are presented from Figure 44 to Figure 47 with different conductivity levels of 200, 500, 1000, and 1500 µSiemens/cm, respectively. Five different curves are plotted on each graph for different levels of the CaO content.

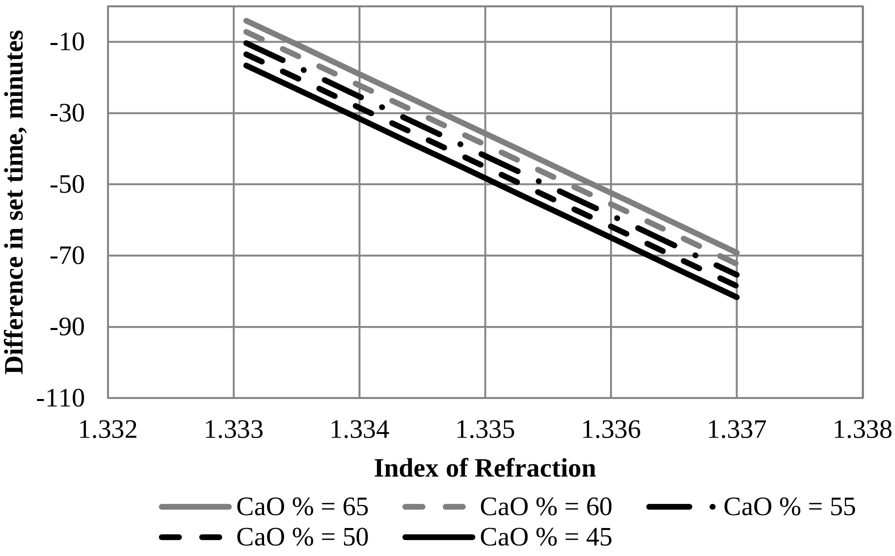

FIGURE 44 Predicted difference in set time vs. IR for conductivity = 200 µSiemens/cm.

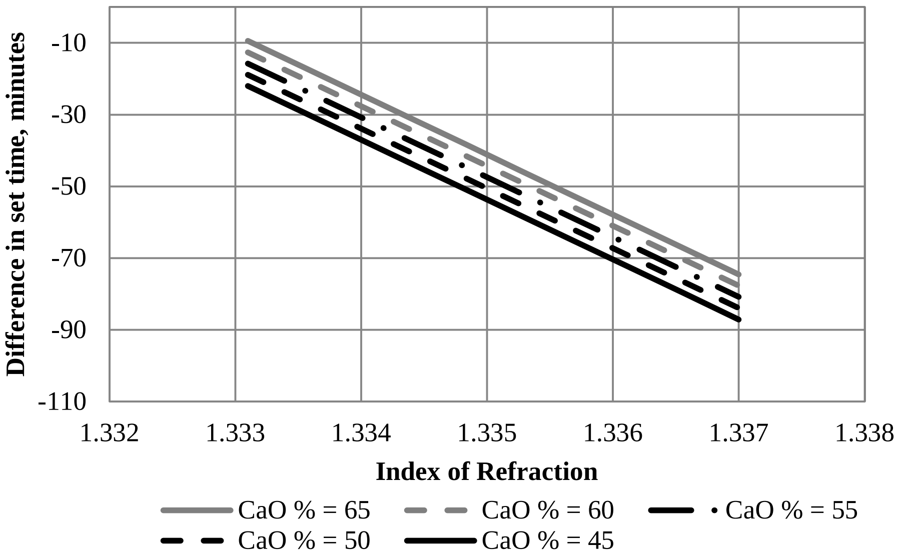

FIGURE 45 Predicted difference in set time vs. IR for conductivity = 500 µSiemens/cm.

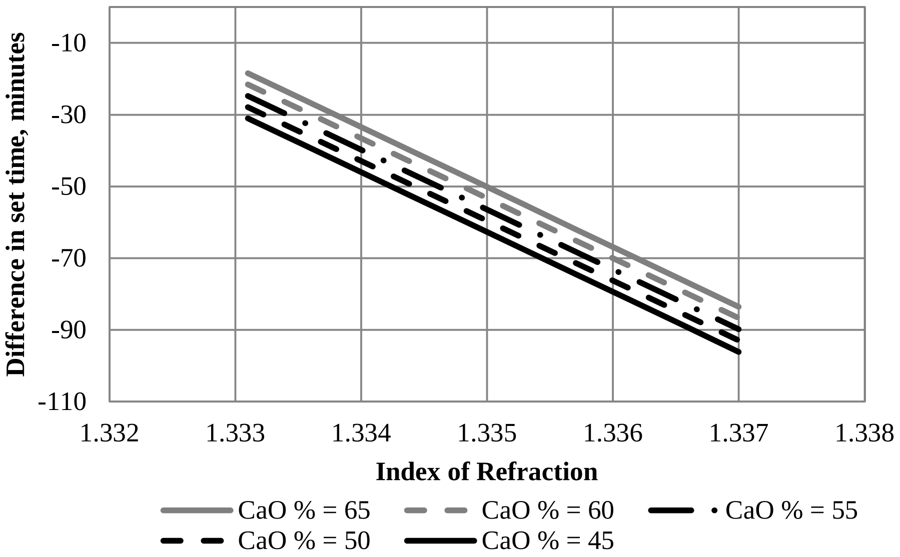

FIGURE 46 Predicted difference in set time vs. IR for conductivity = 1000 µSiemens/cm.

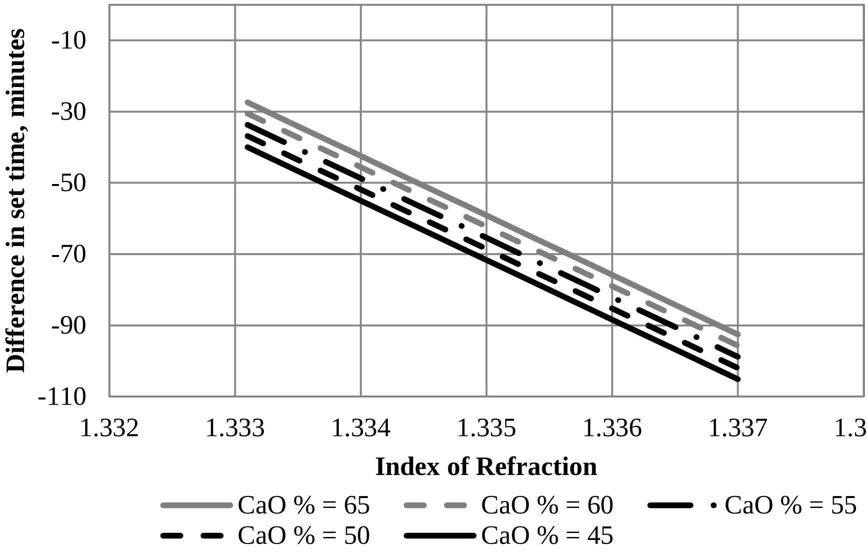

FIGURE 47 Predicted difference in set time vs. IR for conductivity = 1500 µSiemens/cm.

These plots provide a resource to users of the prediction models to help in visualizing the relationship between the relevant variables in each equation and to provide insight into the performance of the mixture.

7 SUMMARY

Mortar mixtures were used to investigate the effects of a wide range of recycled concrete fines, both sources and amounts, on set time as well as early and long-term strength. The recycled concrete fines were evaluated by measuring the index of refraction, conductivity and pH so that results could be applied to other sources and amounts of recycled concrete fines in concrete mix water.

A variety of cementitious materials combinations were also investigated in conjunction with these fines sources. These cementitious materials were characterized as to their calcium content and calcium-ratio so that the results could be applied to cementitious materials not used in this study.

Chemical analysis of the different fines sources was not conducted, both because it was beyond the scope of the research and because such analysis would not be done at a ready-mix concrete plant (the eventual implementation target for this research). Though chemical analysis was not conducted, it can be assumed that alkalis (Na and K) would not be expected to be increased significantly by using recycled concrete fines since the alkalis from cement in the recycled fines would be less than 1% and the recycled fines would be significantly less than a tenth of the new cementitious material in a concrete mixture.

Models relating set time as well as percentage of the control strength (both 3- and 28-day) were developed. These models predicted that two concrete mixtures produced in the laboratory with unknown (but characterized by conductivity and pH measurements) would meet ASTM C 1602 set time and strength requirements at significantly above the optional Table 2, Part D limits.

A follow-up field implementation study in which temporary instrumentation was installed in the mix-water weigh tank at a commercial ready-mix plant. Details are provided in Appendix C. Model refinement performed as a part of this study produced predictive equations, based on pH and conductivity measurements of the mix water, that include the variability of the prediction (standard error) for 3- and 28-day compressive strength. These predictive equations correctly identified a mixture prepared at a ready-mix concrete plant that did not achieve 90% of the 28-day control strength even though the amount of fines in the mix water met the ASTM C 1602 Table 2, Part D limits. The variability of the 3-day strength model was unacceptably high. However, all mixtures in the follow-up field implementation study described in Appendix C achieved at least 90% of the control strength; even the mixture that failed to achieve 90% of the 28-day control strength.

The model refinement identified a need for additional data (either mortar or concrete mixtures) with recycled concrete fines at higher pH and conductivity values. All four of the ‘false negative predictions in encountered in the work summarized in Appendix C were for mixtures that had pH values measured in the mix water that were above the range used in the dataset to develop the equations.

8 CONCLUSIONS AND RECOMMENDATIONS

The wastewater from a variety of sources, including grinding operations and ready mix truck wash out, can be characterized through several key parameters in order to predict set time and compression strength, as required in ASTM C1602. Concrete mix water containing a higher solids content than allowed under ASTM C1602 might be suitable for use in new concrete. The hydrated and unhydrated cement particles can serve as nucleation sites, thus expediting the hydration reaction. Improved particle packing is another positive effect that can be achieved through the presence of the cement particles in the wastewater. Characterization of the wastewater for use requires additional parameters along with the IR, specific gravity, or fines content, that has been traditionally used. This work has shown that a combination of conductivity, IR, and CaO are sufficient for water characterization in order to predict the performance parameters of a concrete mixture.

This work included the development of six predictive models based on mortar testing in order to predict the difference in set time from a control mixture, and the 3-day and 28-day compression strength as a percentage of the control strength of the mixture. These three models were computed over two separate levels: (1) a practitioner's level, which does not include particle size information and therefore is more applicable for immediate implementation in a ready-mix concrete plant, and (2) a comprehensive level, which includes particle size information and ultimately produced more accurate models. Finally, a mock-up water supply system was constructed in the lab to be used in making concrete. Comparisons were then made between the predicted values, based on equations developed with the mortar test results, to that of actual concrete samples. The agreement between the performance of the concrete samples and the prediction models varied, but sufficient evidence was provided to validate the concept and provide guidance on the direction of future work needed to further refine the process.

Future work needed includes the development of a database for concrete mixtures, similar to the database developed for mortar mixtures. The field implementation study described in Appendix C clearly showed the potential for using pH and conductivity measurements rather than total fines content for limiting recycled fines in the concrete mix water. However, additional field data are needed before this approach can be adopted by either ASTM or ready-mix concrete producers. The implementation of an in-line, full scale system in a concrete ready mix plant so that the in-line sensor readings could be monitored and the resulting concrete performance measured would be greatly beneficial. The concrete mixture-performance data would be used to populate a database. This would facilitate further exploration of the relationships between the recycled water and full-scale concrete production.

Acknowledgments

The authors would like to express their sincerest gratitude to the Innovations Deserving Exploratory Analysis (IDEA) program sponsored by the National Cooperative Highway Research Program (NCHRP) who provided the funding under which this work was performed. The authors would also like to thank Dr. Inam Jawed of NCHRP and Dr. Tommy Nantung of the Indiana Department of Transportation for their assistance. Finally, the authors would also like to thank industry collaborators who donated time, materials, and assistance to the completion of this project including Mr. Robert Shogren of Lafarge North America, Tom Bryan of Bryan Concrete, and John Depman of Safety Grooving and Grinding.

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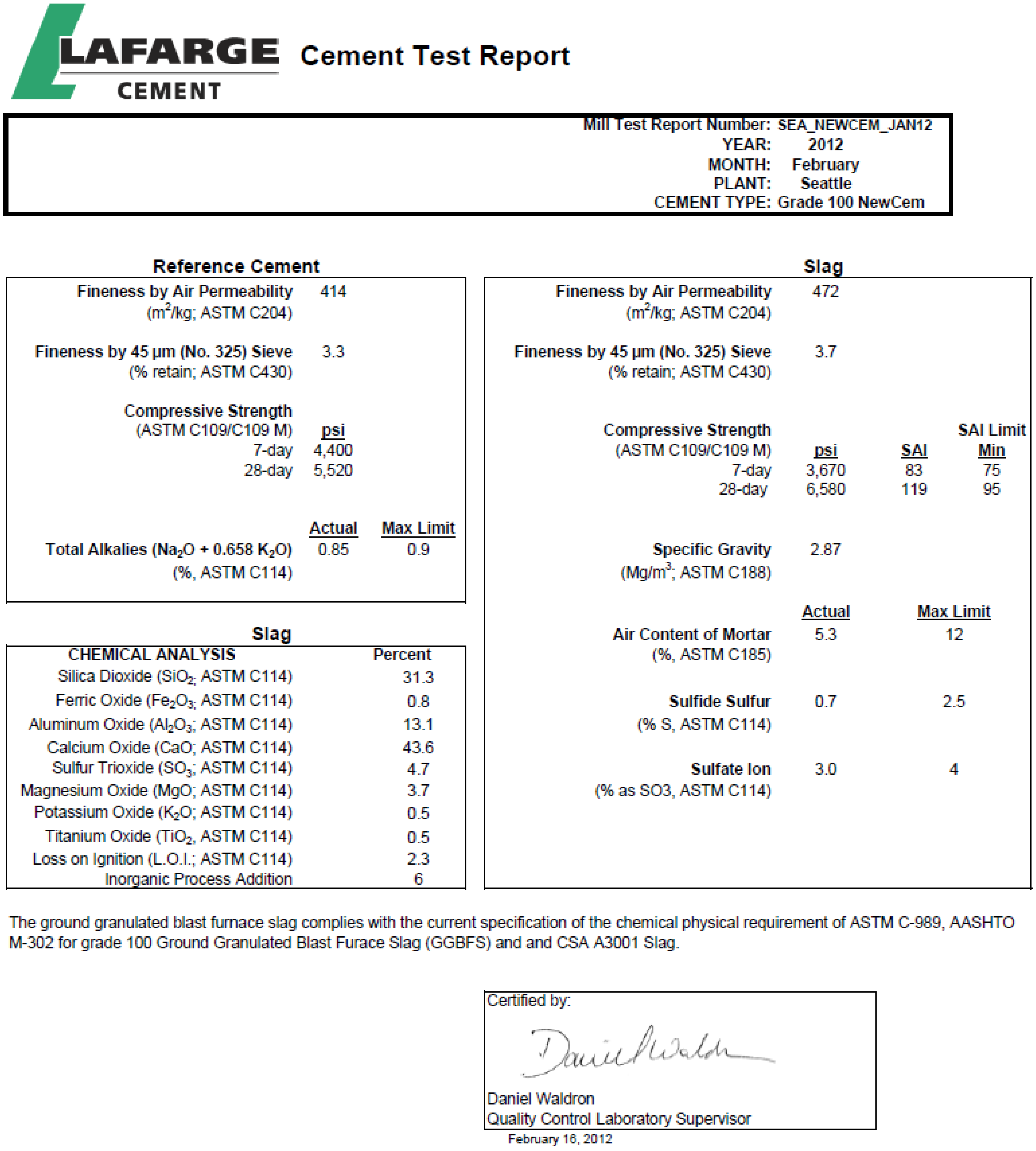
Appendix A

Supplementary Cementitious Material Mill Sheets



LAFARGE CEMENT

Cement Test Report

Mill Test Report Number: SEA_NEWCEM_JAN12
YEAR: 2012
MONTH: February
PLANT: Seattle
CEMENT TYPE: Grade 100 NewCem

Reference Cement

Fineness by Air Permeability (m^2/kg; ASTM C204)	414	
Fineness by 45 µm (No. 325) Sieve (% retain; ASTM C430)	3.3	
Compressive Strength (ASTM C109/C109 M)	psi	
7-day	4,400	
28-day	5,520	
	Actual	Max Limit
Total Alkalies (Na_2O + 0.658 K_2O) (%, ASTM C114)	0.85	0.9

Slag

CHEMICAL ANALYSIS	Percent
Silica Dioxide (SiO_2, ASTM C114)	31.3
Ferric Oxide (Fe_2O_3, ASTM C114)	0.8
Aluminum Oxide (Al_2O_3; ASTM C114)	13.1
Calcium Oxide (CaO; ASTM C114)	43.6
Sulfur Trioxide (SO_3; ASTM C114)	4.7
Magnesium Oxide (MgO; ASTM C114)	3.7
Potassium Oxide (K_2O; ASTM C114)	0.5
Titanium Oxide (TiO_2, ASTM C114)	0.5
Loss on Ignition (L.O.I.; ASTM C114)	2.3
Inorganic Process Addition	6

Slag

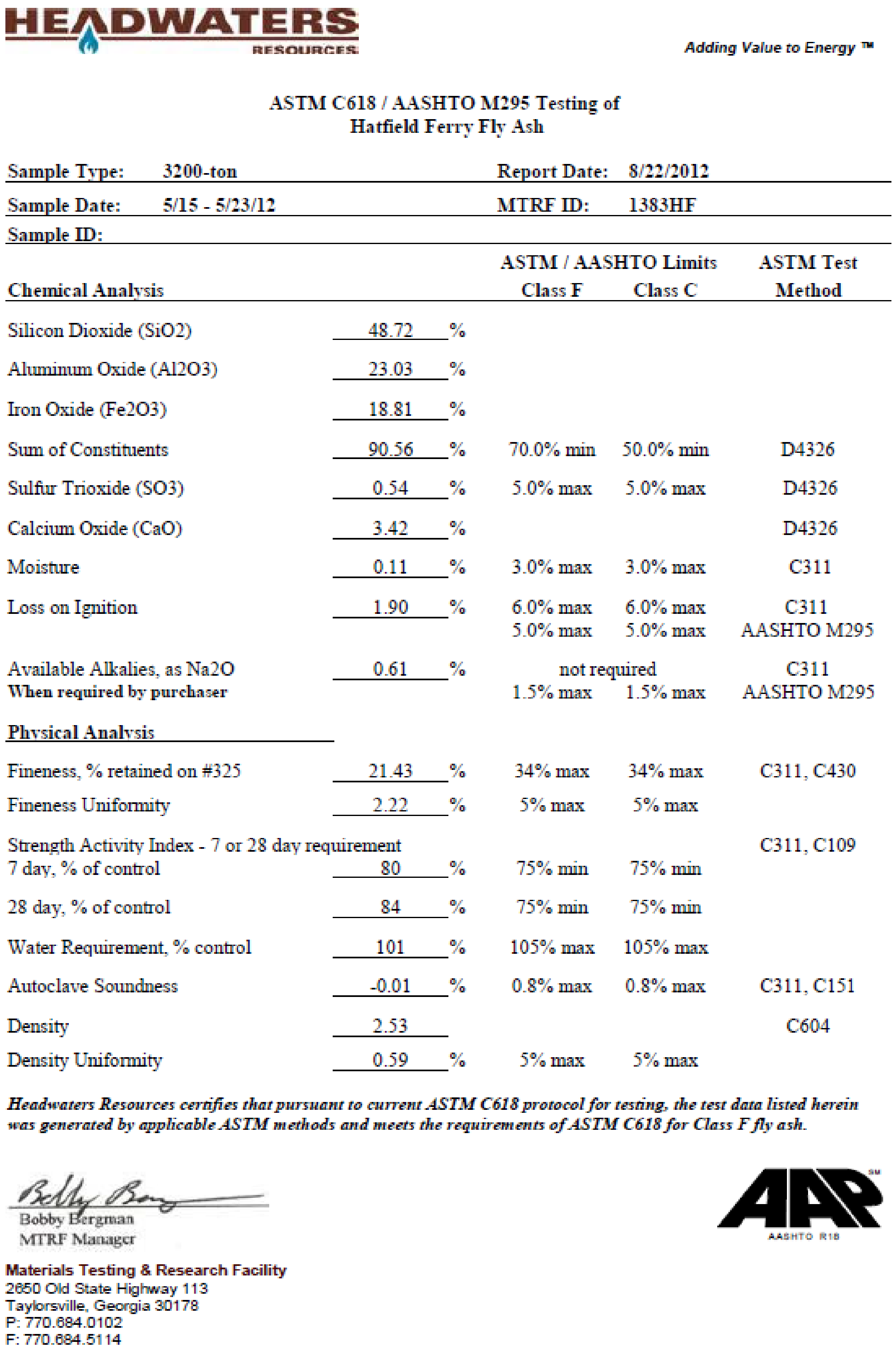
Fineness by Air Permeability (m^2/kg; ASTM C204)	472		
Fineness by 45 µm (No. 325) Sieve (% retain; ASTM C430)	3.7		
Compressive Strength (ASTM C109/C109 M)	psi	SAI	SAI Limit Min
7-day	3,670	83	75
28-day	6,580	119	95
Specific Gravity (Mg/m^3; ASTM C188)	2.87		
	Actual	Max Limit	
Air Content of Mortar (%, ASTM C185)	5.3	12	
Sulfide Sulfur (% S, ASTM C114)	0.7	2.5	
Sulfate Ion (% as SO3, ASTM C114)	3.0	4	

The ground granulated blast furnace slag complies with the current specification of the chemical physical requirement of ASTM C-989, AASHTO M-302 for grade 100 Ground Granulated Blast Furace Slag (GGBFS) and and CSA A3001 Slag.

Certified by:

Daniel Waldron
Quality Control Laboratory Supervisor
February 16, 2012

FIGURE A1 Mill testing information for slag used in laboratory.



HEADWATERS RESOURCES

Adding Value to Energy ™

ASTM C618 / AASHTO M295 Testing of
Hatfield Ferry Fly Ash

Sample Type:	3200-ton	**Report Date:**	8/22/2012
Sample Date:	5/15 - 5/23/12	**MTRF ID:**	1383HF
Sample ID:			

Chemical Analysis			**ASTM / AASHTO Limits** **Class F**	 **Class C**	**ASTM Test Method**
Silicon Dioxide (SiO_2)	48.72	%			
Aluminum Oxide (Al_2O_3)	23.03	%			
Iron Oxide (Fe_2O_3)	18.81	%			
Sum of Constituents	90.56	%	70.0% min	50.0% min	D4326
Sulfur Trioxide (SO_3)	0.54	%	5.0% max	5.0% max	D4326
Calcium Oxide (CaO)	3.42	%			D4326
Moisture	0.11	%	3.0% max	3.0% max	C311
Loss on Ignition	1.90	%	6.0% max 5.0% max	6.0% max 5.0% max	C311 AASHTO M295
Available Alkalies, as Na_2O **When required by purchaser**	0.61	%	not required 1.5% max	 1.5% max	C311 AASHTO M295
Physical Analysis					
Fineness, % retained on #325	21.43	%	34% max	34% max	C311, C430
Fineness Uniformity	2.22	%	5% max	5% max	
Strength Activity Index - 7 or 28 day requirement					C311, C109
7 day, % of control	80	%	75% min	75% min	
28 day, % of control	84	%	75% min	75% min	
Water Requirement, % control	101	%	105% max	105% max	
Autoclave Soundness	-0.01	%	0.8% max	0.8% max	C311, C151
Density	2.53				C604
Density Uniformity	0.59	%	5% max	5% max	

Headwaters Resources certifies that pursuant to current ASTM C618 protocol for testing, the test data listed herein was generated by applicable ASTM methods and meets the requirements of ASTM C618 for Class F fly ash.

Bobby Bergman
MTRF Manager

AASHTO R18

Materials Testing & Research Facility
2650 Old State Highway 113
Taylorsville, Georgia 30178
P: 770.684.0102
F: 770.684.5114

FIGURE A2 Mill testing information for Class F fly ash used in laboratory.

Appendix B

Complete Materials Characterization Plots

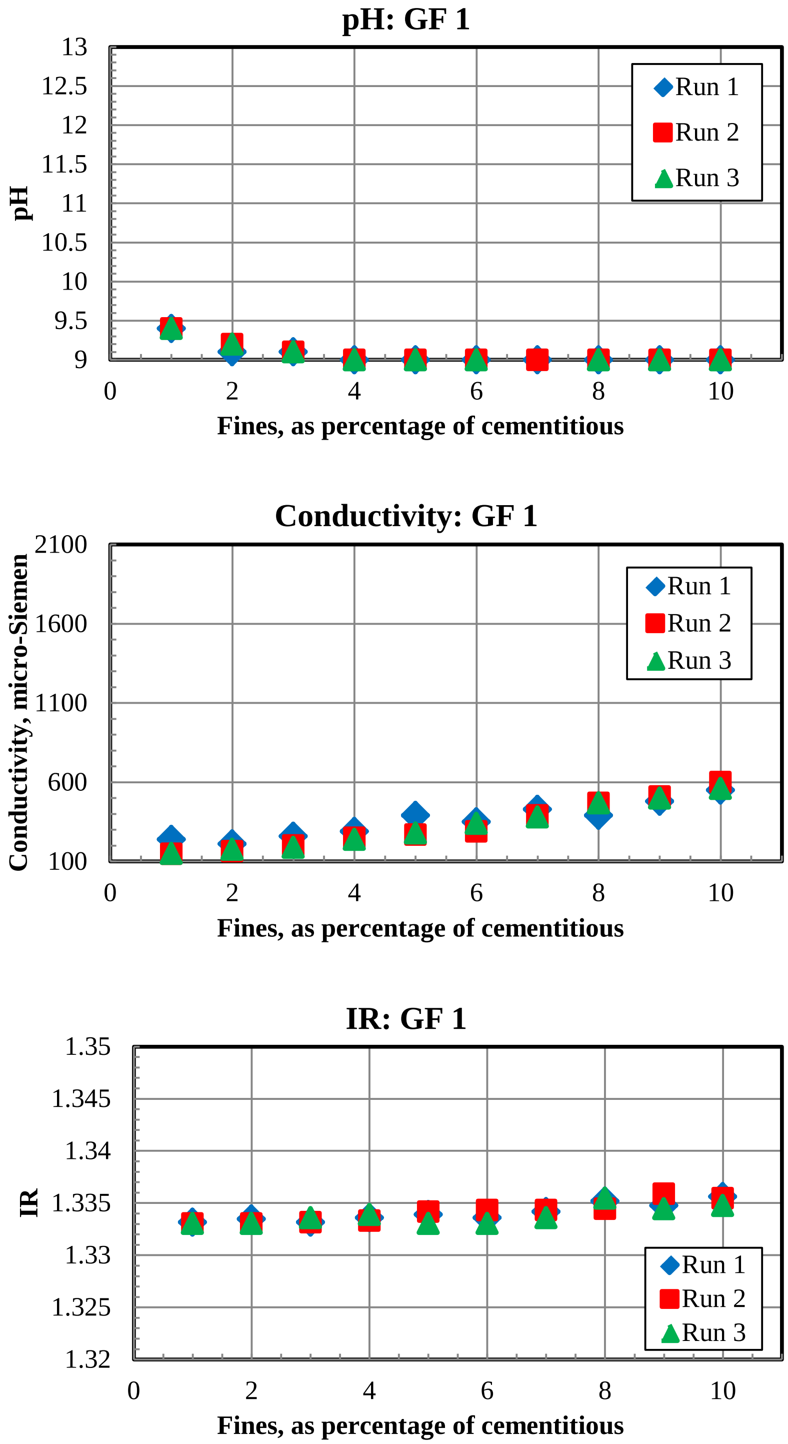


FIGURE B1 Materials characterization parameter plots for GF 1.

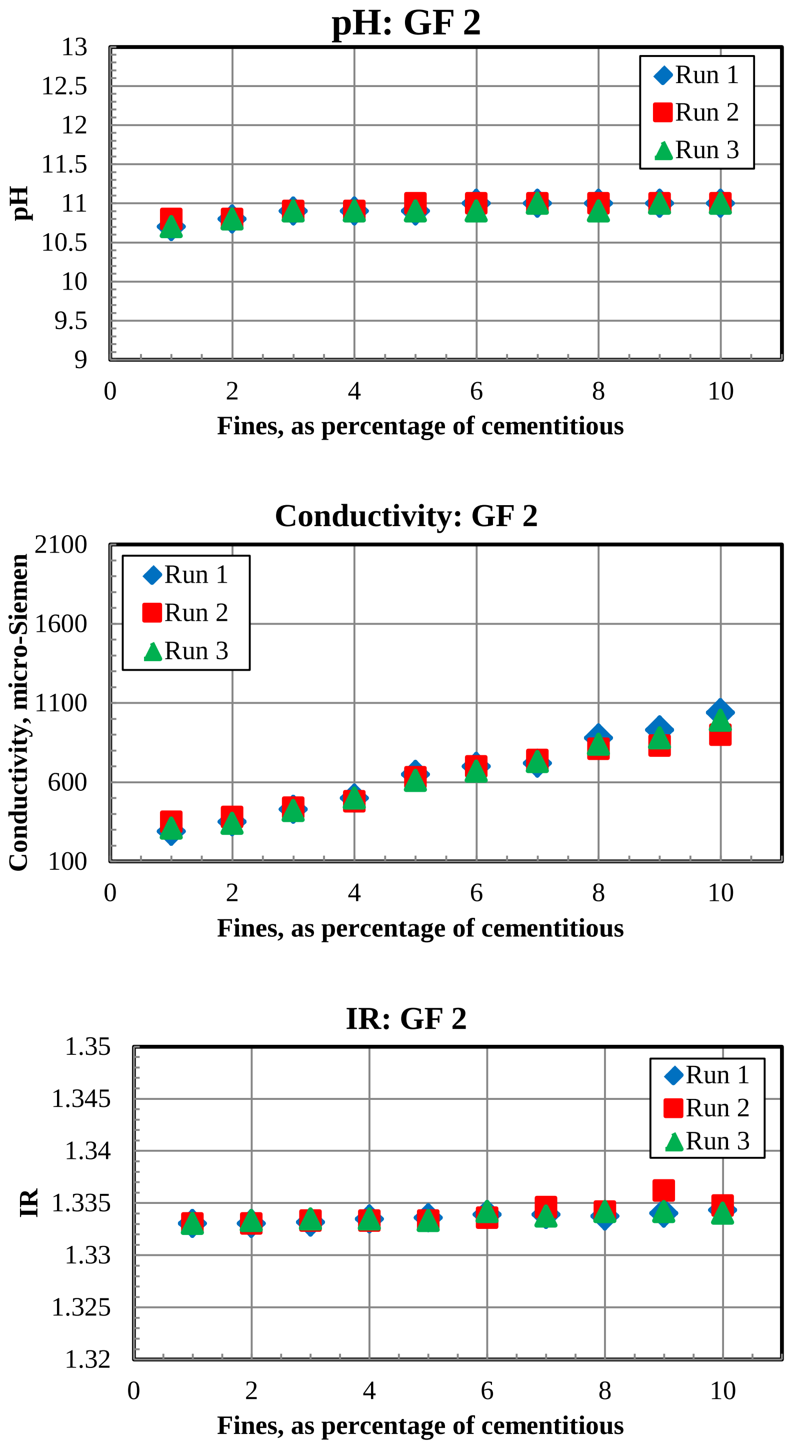


FIGURE B2 Materials characterization parameter plots for GF 2.

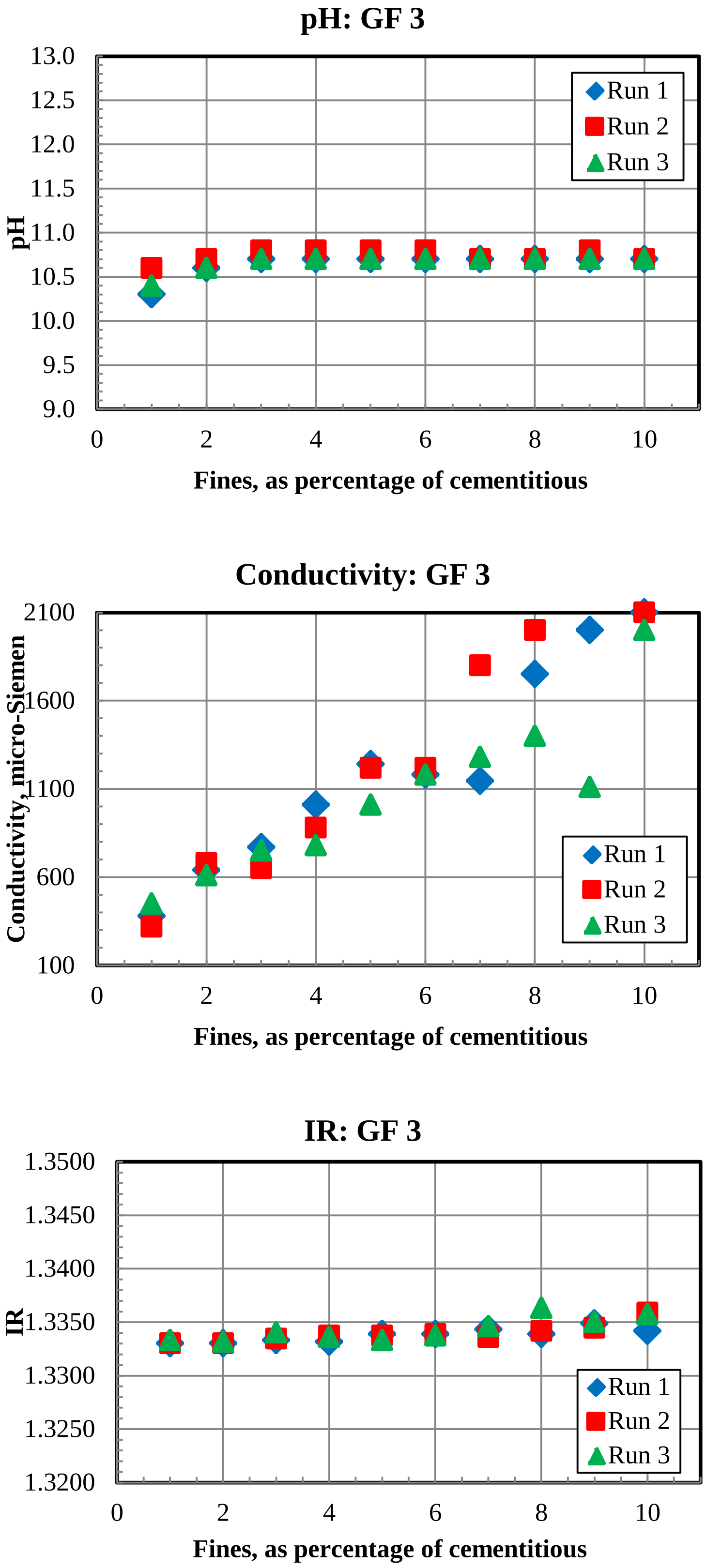


FIGURE B3 Materials characterization parameter plots for GF 3.

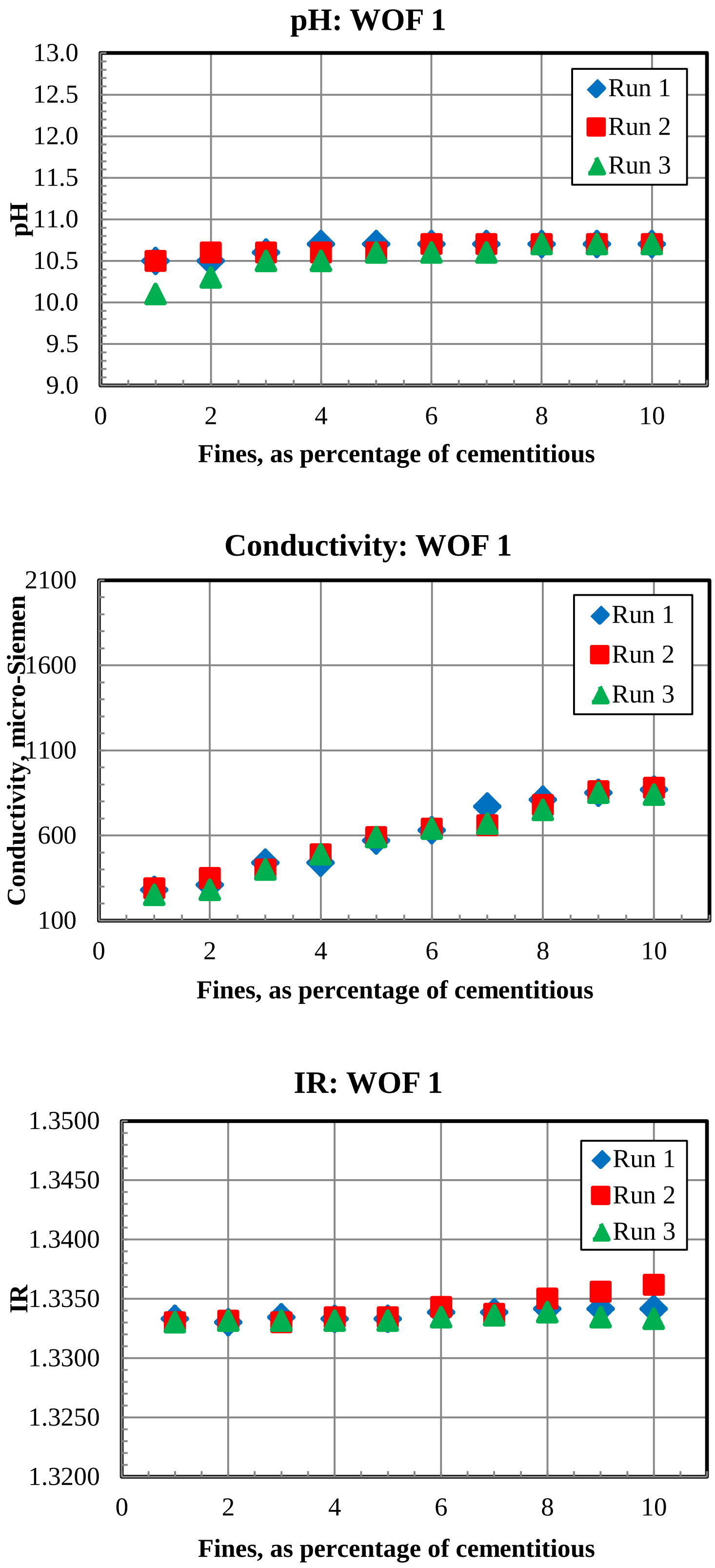


FIGURE B4 Materials characterization parameter plots for WOF 1.

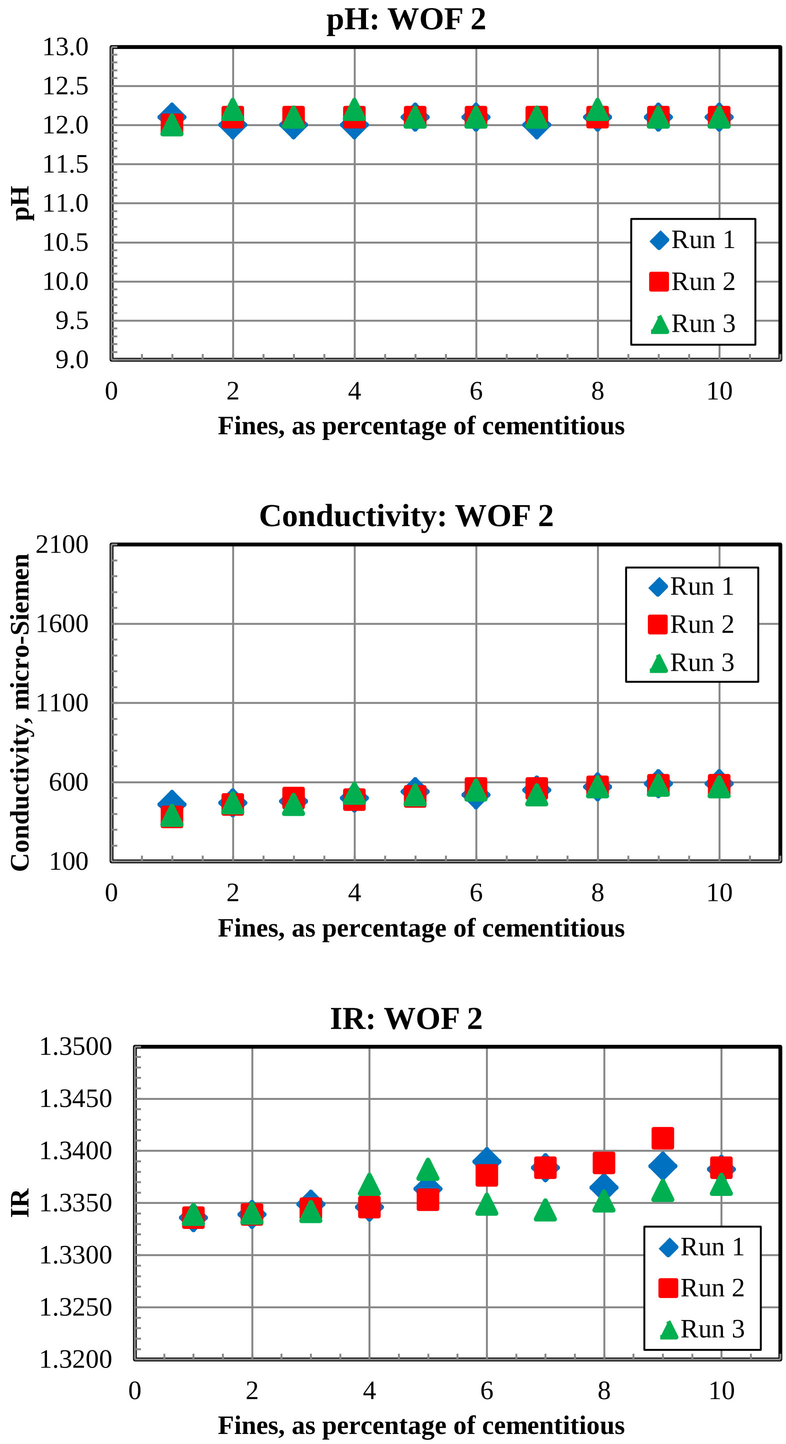


FIGURE B5 Materials characterization parameter plots for WOF 2.

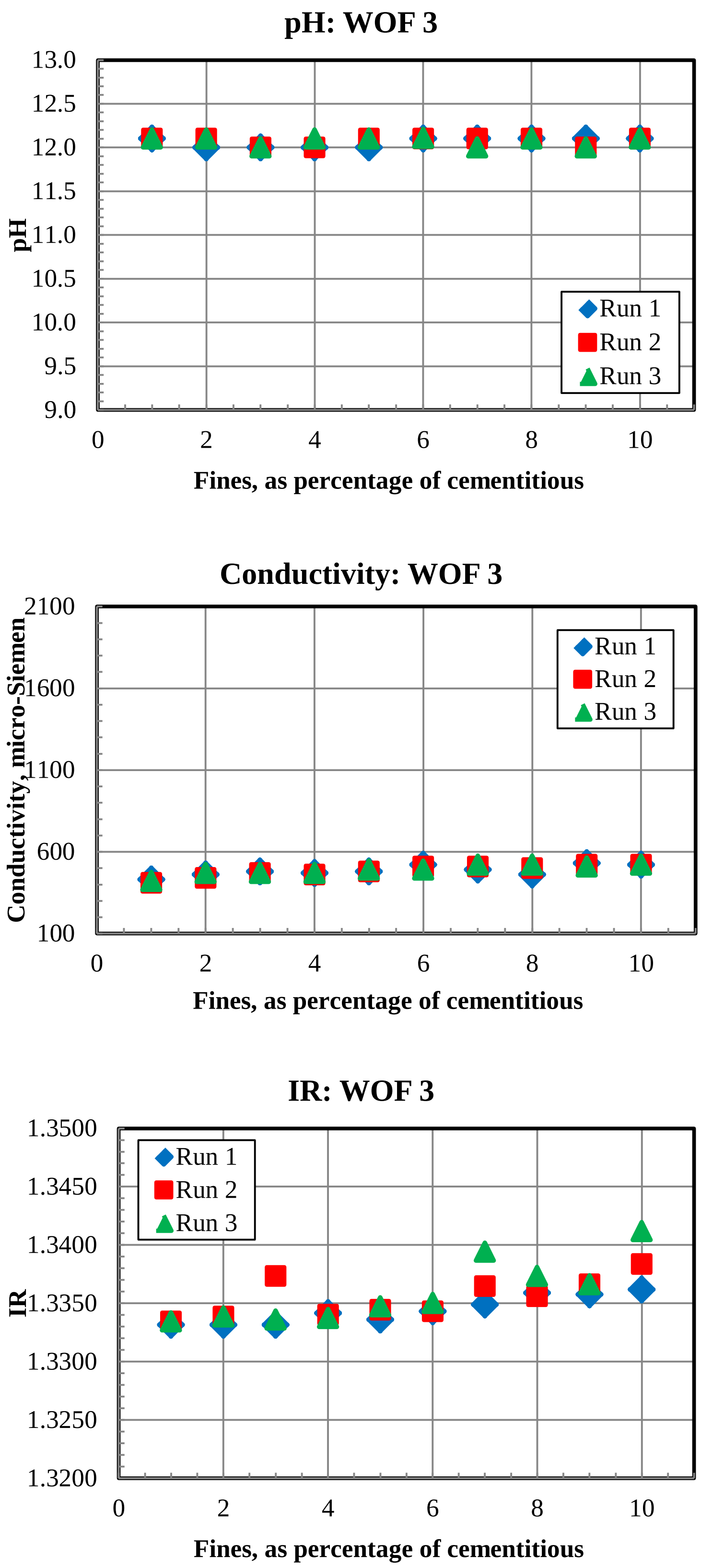


FIGURE B6 Materials characterization parameter plots for WOF 3.

Appendix C

Field Validation of Recycled Concrete Fines Usage

Field Validation of Recycled Concrete Fines Usage

Supplement to
GUIDELINES FOR THE USE OF WASTE CONCRETE FINES
NCHRP-IDEA Project 145

by

Donald J. Janssen
Lily B. Grimshaw
University of Washington

with assistance from
Dr. Julie Vandenbossche, University of Pittsburgh

This work was made possible with supplemental funding from
Pacific Northwest Transportation Consortium
University Transportation Center for Federal Region 10
under the sponsorship of the US Department of Transportation
University-Research and Innovative Technology Administration (RITA).f

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Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**	
4. Title and Subtitle Field Validation of Recycled Concrete Fines Usage		**5. Report Date** February 15, 2015	
		6. Performing Organization Code	
7. Author(s) Donald J. Janssen and Lily B. Grimshaw		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700		**10. Work Unit No. (TRAIS)**	
		11. Contract or Grant No. DTRT12-UTC10	
12. Sponsoring Organization Name and Address United States of America Department of Transportation Research and Innovative Technology Administration		**13. Type of Report and Period Covered**	
		14. Sponsoring Agency Code	

15. Supplementary Notes

Report uploaded at www.pacTrans.org

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 strength 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.

17. Key Words concrete mixing water, pH, conductivity, recycled concrete fines		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 44	**22. Price** NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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Acknowledgments

The authors would like to thank Greg McKinnon, Ward Zeiler, and Sean Haywood of Stoneway Concrete, and Dr. Robert Shogren of LaFarge North America for their assistance with technical aspects of this project. They would also like to thank Dr. Julie Vandenbossche of the University of Pittsburgh for the loan of the sensors used for characterizing the recycled concrete fines water as well as Nicole Dufalla of NCE for her assistance with the database developed under NCHRP-IDEA Project Number 166. And finally, they would like to thank Jeff McClintock for his assistance with the test specimen preparation.

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 strength at fines contents below the allowed limits in other cases.

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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 strength 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 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 strength 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 strength. 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 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 cubic yard 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. More than 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 wastewater 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 min and to not delay set time more than 90 min. 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 to 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 g 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 g	Slag g	Flyash g	Water g	Sand g
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 were μSiemens/cm.

2.4.2 pH

The pH of a cementitious material can be influenced by the pH of the mix-water, with higher pH values leading to accelerated reaction rates but possibly lower long-term strength (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 strength 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.

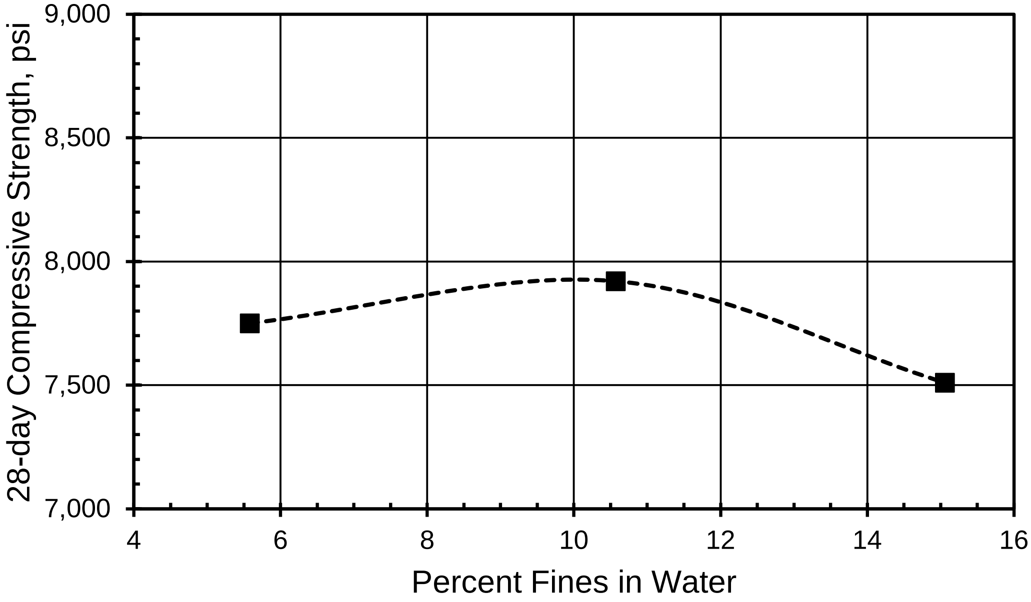

Figure 3.1 28-day compressive strength for 37.5% slag mixture with Stoneway Hauser wash-out fines (after Dufalla et al. 2014).

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:

$$\% \text{ 3-day} = -0.0108*(\exp(pH)/cond)+2{,}222/cond+0.3752*CaO\%+78.1 \qquad (3.1)$$

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.

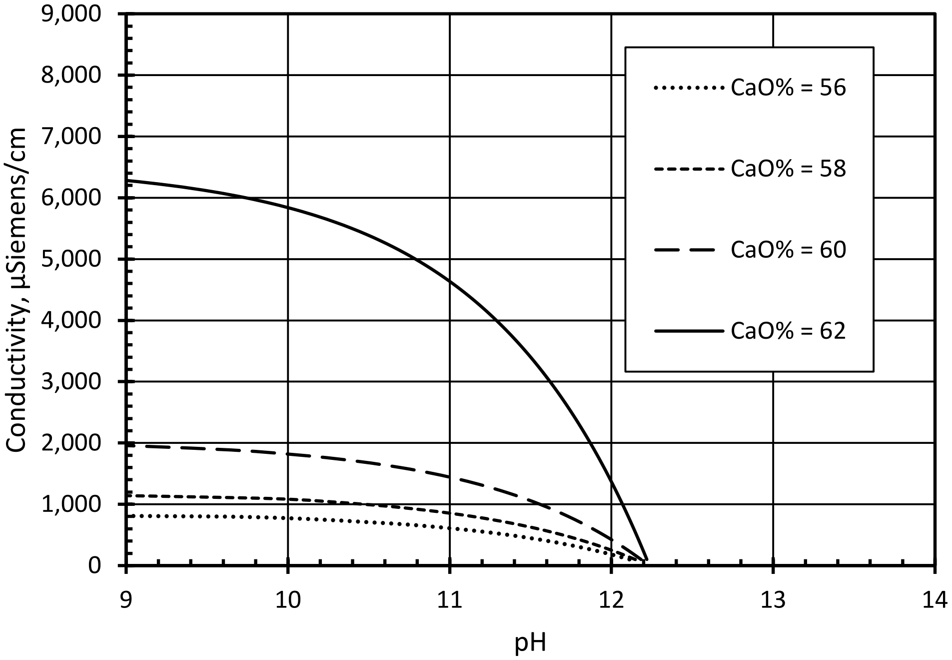

Figure 3.2 Prediction curves for 90 percent of 3-day strength at 90% confidence.

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.

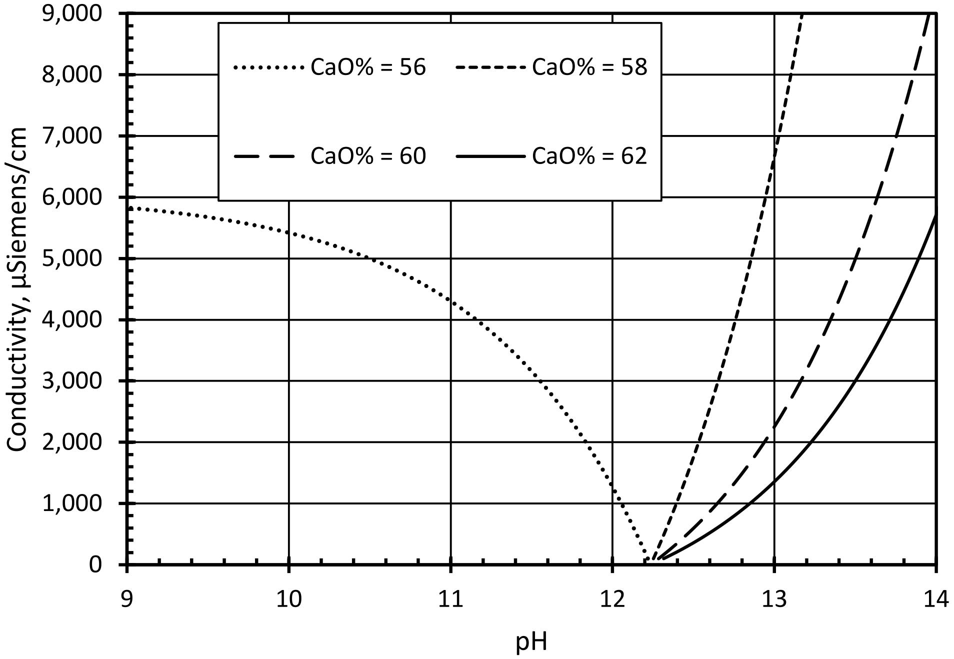

Figure 3.3 Prediction curves for 90 percent of 3-day strength at 85% confidence.

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:

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

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 tap 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.

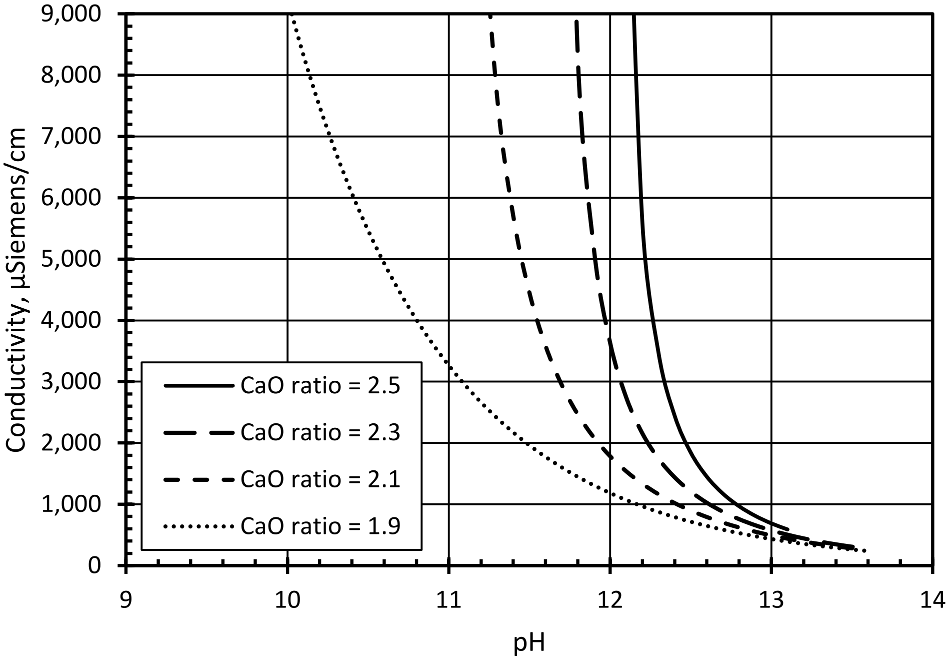

Figure 3.4 Prediction curves for 90 percent of 28-day strength at 90% confidence.

Chapter 4

Ready-Mix Concrete Plant Sampling

Sampling was performed at the Stoneway Concrete plant on Houser Way in Renton, Washington. 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).

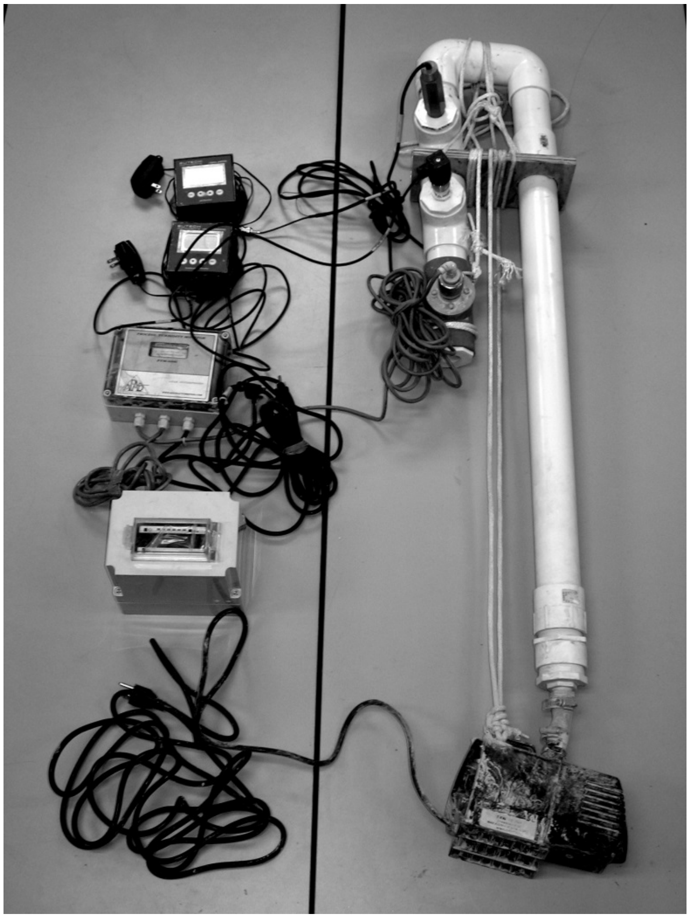

Figure 4.1 Sensor assembly.

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).

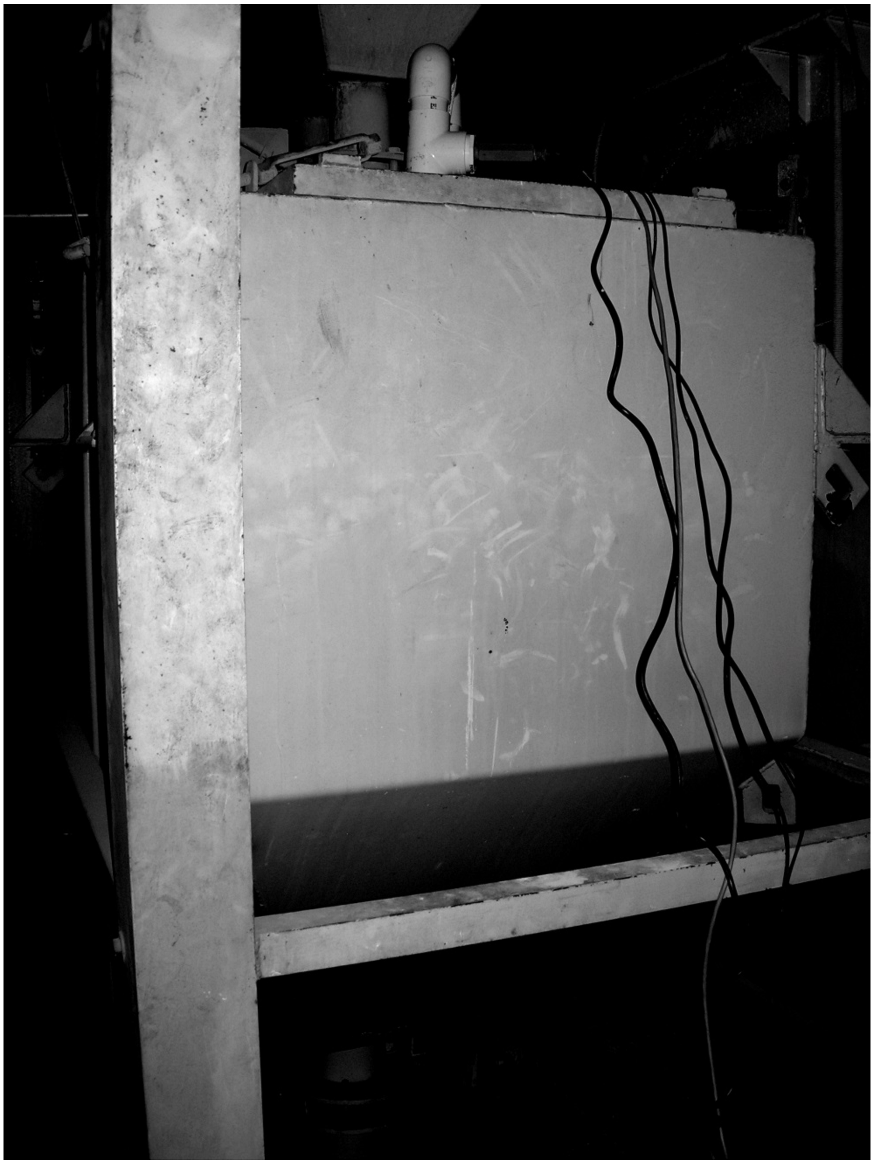

Figure 4.2 Sensor assembly in mix-water weigh hopper.

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 in. x 8 in. 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 strength (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 strength 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. Graph as in Chapter 3 have been prepared for each set of mixture proportions (CaO% or CaO-ratio), and the data points (pH and conductivity) are plotted on each graph. Solid symbols are used for strength 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 strength) and 5.2 (28-day strength).

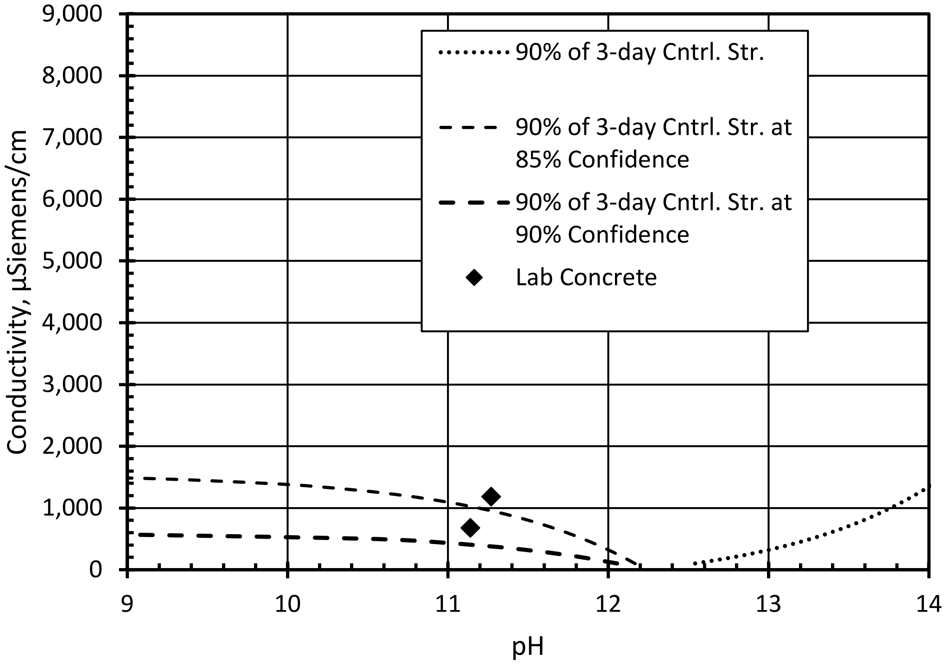

Figure 5.1 3-day strength graph for laboratory simulation (CaO% = 53.1).

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.

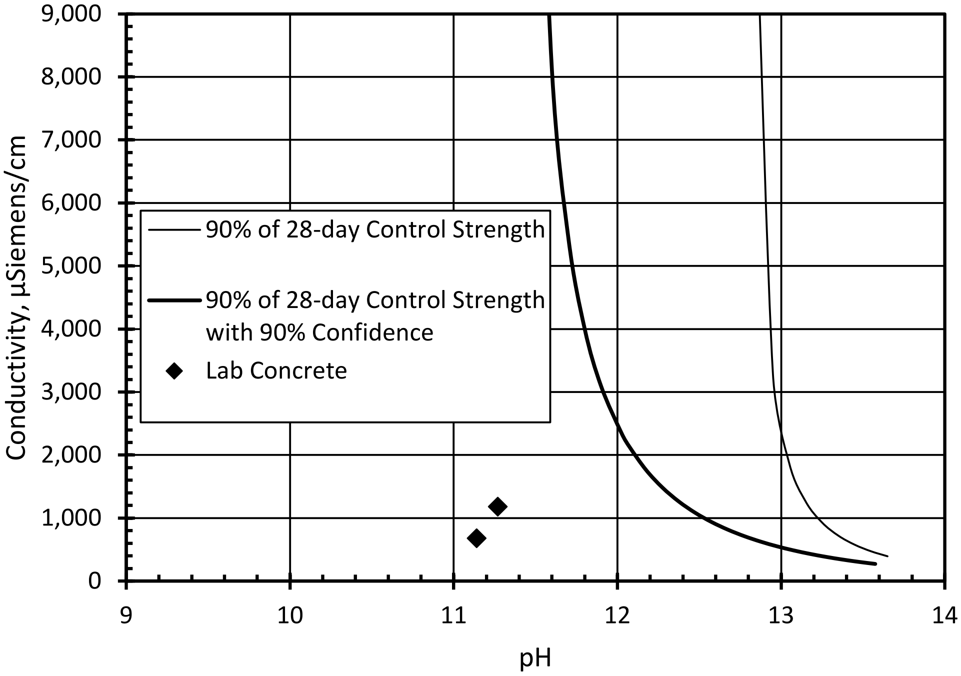

Figure 5.2 28-day strength graph for laboratory simulation (CaO-ratio = 2.21).

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.

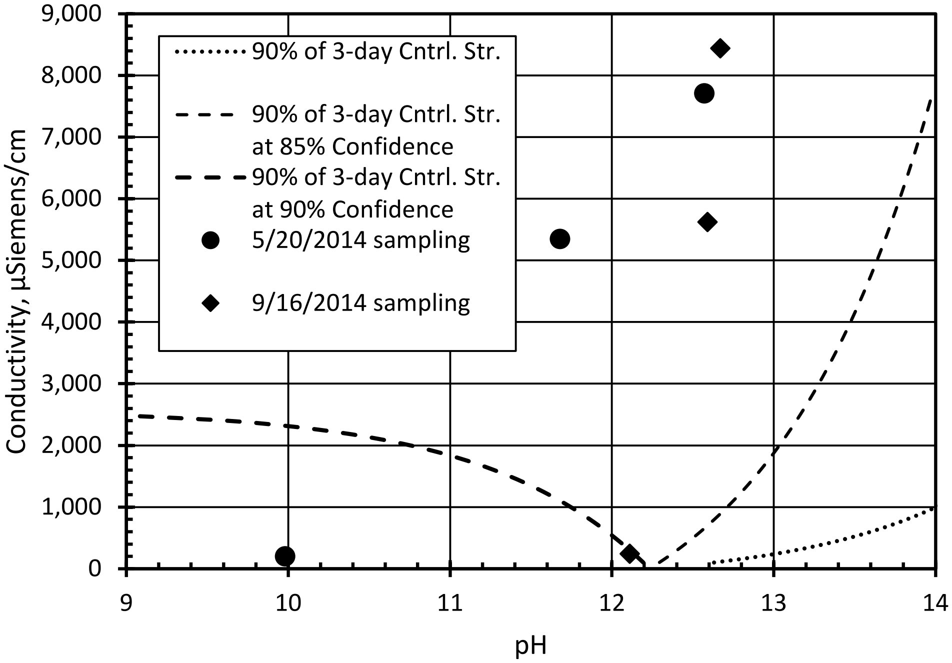

Figure 5.3 3-day strength graph for 5/20/2014 and 9/16/14 sampling (CaO% = 60.6).

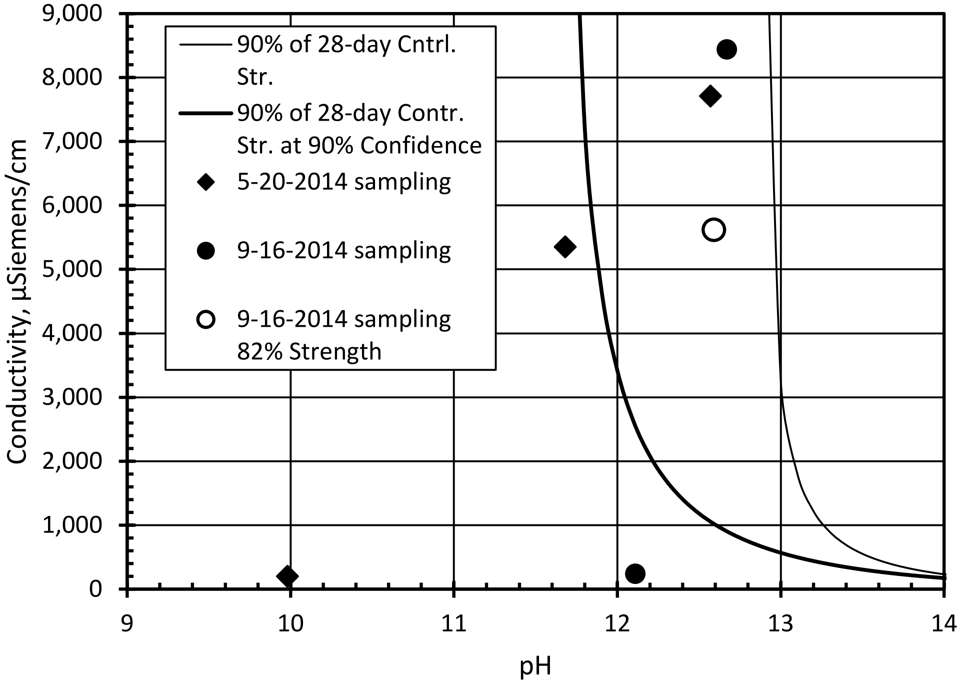

Figure 5.4 28-day strength graph for 5/20/2014 and 9/16/14 sampling (CaO-ratio = 2.28).

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

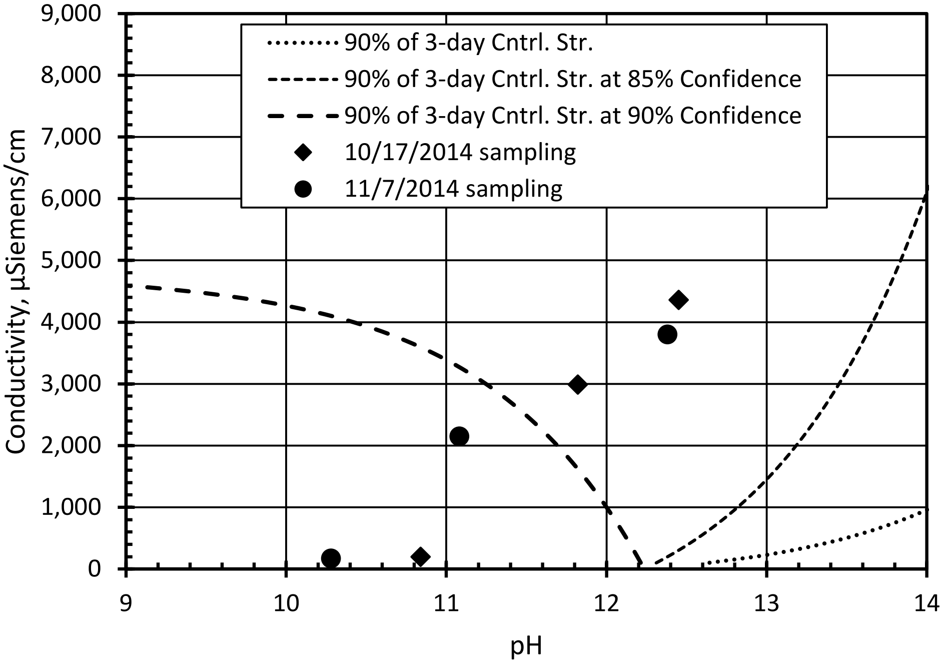

Figure 5.5 3-day Strength Graph for 10/17/2014 and 11/7/2014 Sampling (CaO% = 61.7).

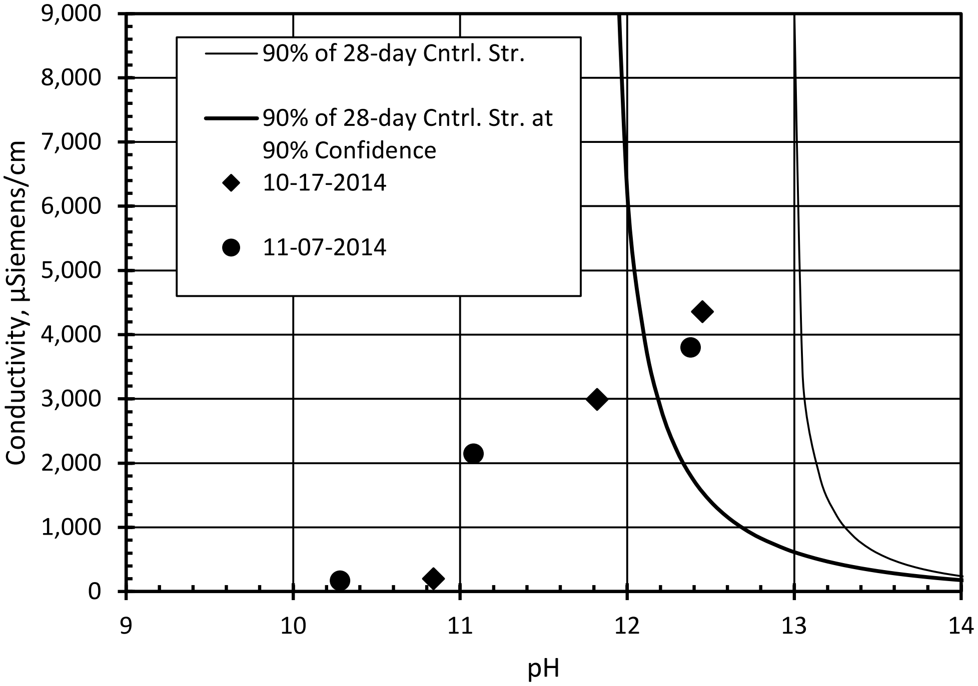

Figure 5.6 28-day strength graph for 10/17/2014 and 11/7/2014 sampling (CaO-ratio = 2.38).

Chapter 6

Discussion

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

6.1 Strength 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 Strength 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 28-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 conductivity 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 strength 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 of the 3-day 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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