Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

High Electrical Resistivity Concrete Mixture Design Using Supplementary Cementitious Materials

Katherine Kuder[1], Jack Tinnea[2], Ryan Tinnea[2], Samuel Bellomio[3], Michael Fanoni[3], David Johnson[3], and Jessica Towns[3]

[1] *901 12th Ave; Seattle, WA 98122-1090, <kuderk@seattleu.edu>, Seattle University; Assistant Professor Civil and Environmental Engineering*
[2] *Tinnea and Associates, LLC; 2018 E Union St; Seattle, WA 98122-2836,< jackt@tinnea.net>, <rtinnea@tinnea.net>, Corrosion Engineer*
[3] *Seattle University; 901 12th Ave; Seattle, WA 98122-1090, <likwid101@yahoo.com>, <fanonim1@seattleu.edu>,< johnson3@seattleu.edu>, <jessica.a.towns@gmail.com>, Research Assistant Civil and Environmental Engineering*

ABSTRACT

Stray current from direct current trolley rail systems can corrode underground metal pipes, potentially causing damage to ferrous underground utility lines. In this work, a concrete mix design was developed using supplementary cementitious materials that satisfies constructability and resistivity criteria for use in Seattle's trolley line system. This concrete will serve as a protective measure against corrosion. Concrete mixes using Type III Portland cement with ternary combinations of Class F fly ash, silica fume and slag were evaluated. Samples were subjected to environmental conditioning similar to the Seattle area. The influence of the supplementary cementitious materials on fresh and hardened state properties was determined. Compressive strength and resistivity of the mixes were monitored over time. The results indicate that a constructible, high resistivity concrete mix design can be achieved through the proper use of supplementary cementitious materials.

INTRODUCTION

As part of the city's greater effort to expand its mass transportation, trolley systems are being developed in Seattle, Washington. These trolleys are powered by substations producing 850V direct current (DC). The positive feed comes from an overhead catenary and the negative return to the substation is provided by welded rails. Stray current control is provided by the use of rail-to-earth isolation devices, welded rails, ungrounded power substations, and placement of the power substations near points of maximum load such as passenger stations and extreme grades.

Despite these measures, even well designed direct current rail systems can produce stray currents that can expedite corrosion of underground utility pipelines. To address this problem, Seattle Public Utilities (SPU) has adopted two preventative measures: use of a continuous dielectric rubber boot and high resistivity concrete.

Fig. 1 presents a photo of an installed rail with a typical cross-section. The rubberized dielectric boot provides the primary protection against stray current, while high resistivity concrete is secondary protection. Secondary protection can be necessary if standing water forms a conductive bridge over the rail boot to the adjacent concrete (shown in

Fig. 1), or if the boot is damaged during construction.

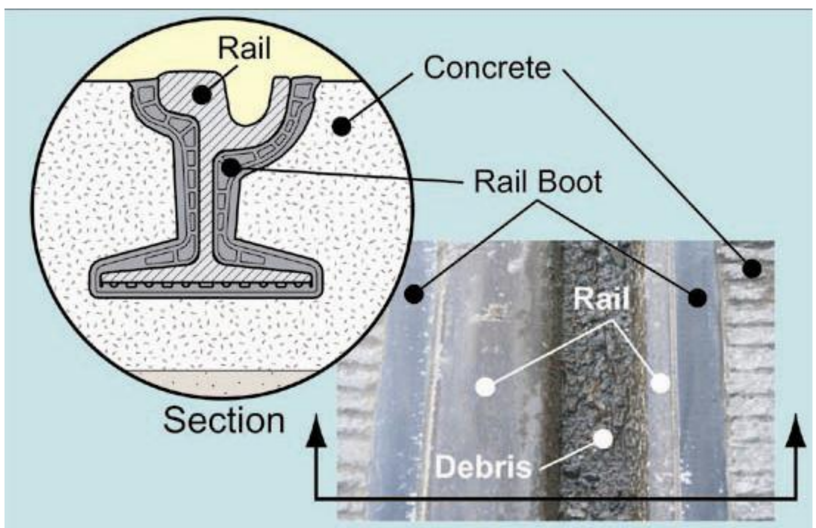

Fig. 1. Cross Section of Trolley Rail and Rubber Boot Embedded in Concrete in the Field

The South Lake Union trolley line, constructed in 2007, incorporated a customized, high resistivity concrete mix [Burke, Tinnea et al. 2007]. While this mix achieved the desired resistivity (about 25 times that of normal concrete), there were a number of constructability issues. In particular, the concrete had poor workability and an elongated curing time (requiring special construction measures to allow for opening to traffic in heavily congested areas). The concrete also developed unsightly cracks.

BACKGROUND

Concrete is a porous material that is not inherently conductive. However, if water is present in the pores, current can travel through the concrete, decreasing the resistivity of the material. Thus, concrete resistivity is related to the size and connectivity of its pores as well as its moisture condition. Previous research suggests that supplementary cementitious materials (SCMs) can be used as a partial cement replacement to increase the resistivity of mortar and concrete [Burke, Tinnea et al. 2007; Bellomio, Fanoni et al. 2009] and that the degree of improvement depends on the type and amount of SCM used. Burke and colleagues evaluated the resistivity of ready-mix-produced concrete specimens and found that silica fume significantly enhances resistivity. In subsequent work, a more systematic approach was taken to investigate the effect of fly ash and slag on mortar resistivity. The data suggest that when used as a 10% cement replacement both fly ash and slag improve resistivity [Bellomio, Fanoni et al. 2009]. Greatest increases in resistivity were observed with Class F fly ash.

SCMs are believed to increase concrete resistivity by the production of hydration products and improved particle packing. SCMs demonstrate pozzolanic behaviour, reacting with the free lime that results from the hydration of Portland cement to form C-S-H gel. This additional C-S-H gel fills the voids in the composite, reducing overall porosity, and occurs more slowly than Portland cement hydration. Research has shown that finely ground silica fume particles accelerate early hydration by providing nucleation sites, while after the first three days a pozzolanic reaction with lime occurs until either the silica fume or lime is exhausted [Zelic, Rusic et al. 2000; Kadri and Duval 2009]. In addition to increasing resistivity, SCM use is environmentally advantageous because it reduces the amount of Portland cement required (reducing the CO_2 emissions associated with cement production) and uses a waste material that would otherwise be land-filled. Other benefits of using slag and fly ash in concrete are well-known and typically include improvements in workability, mechanical behaviour and durability [Mehta 2009].

RESEARCH OBJECTIVE

The objective of the present study was to develop a high resistivity concrete mix for the Seattle trolley system that adheres to specific constructability criteria, which are summarized in

Table 1. Ternary combinations of SCMs (Class F fly ash, silica fume and slag) were used to produce a concrete mix that is: (1) highly workable so that standard work crews can place and finish the concrete, (2) able to gain sufficient early strength to allow the release of traffic on the roadways (minimizing road closures) and (3) highly resistive to prevent corrosion of underground utilities.

Table 1. Project Goals

Property	Specification
Workability	101.6 – 152.4 mm slump
Compressive Strength	25 MPa at 24 hours
Resistivity	100 Kohm-cm at 365 days

EXPERIMENTAL PROGRAM

The experimental program was designed to develop a concrete mix design for use in the SPU trolley system and required: (1) replicating the production of concrete that could be supplied locally by ready-mix companies, (2) simulating the environmental conditioning to which the concrete would be exposed in the field and (3) evaluating the resistivity of the concrete over time.

Concrete Mix Design. Four mixes were tested to develop a high resistivity concrete. Table 2 presents the base mix, which has a water/binder = 0.37. This mix was developed from a standard mix design used by SPU that can be easily supplied by local ready-mix companies. To increase early strength, Type III cement was used rather than the standard Type I. Portland cement was partially replaced by silica fume (3% by weight) and fly ash (10% by weight) to increase resistivity. Three additional mixes were cast with 5, 10 and 15% of the cement being replaced with slag (LaFarge NewCem slag). These mixes were selected based on previous concrete and mortar research. Research by Burke et al. showed that silica fume significantly enhances resistivity in concrete mixes [Burke, Tinnea et al. 2007]. Furthermore, binary mortar mixes containing fly ash were found to be more effective than slag mixes at increasing resistivity. Data also suggest that ternary mortar mixes with fly ash and slag develop high resistivities with time when SCM content was optimized [Burke, Tinnea et al. 2007; Bellomio, Fanoni et al. 2009].

Table 2. Base Concrete Mix Design

Material	Quantity
Type III cement (Lafarge), kg/m^3	331
River Sand (SSD), kg/m^3	671
#57 Coarse Aggregate (SSD), kg/m^3	845
Fly Ash (Class F, Centralia WA), kg/m^3	38
Silica Fume (BASF Rheomac SF100) , kg/m^3	12
Water, kg/m^3	140
Air entrainer (Daravair 1000), ml/m^3	461
Water reducer (WRDA 64), ml/m^3	369
Superplasticizer (ADVA 100), ml/m^3	1506

Sample Preparation. The mixing procedure was developed based on discussions with SPU and local ready-mix suppliers to simulate field mixing. Special care was taken to ensure that the silica fume was well dispersed. Prior to preparing each actual mix for casting, a "butter" mix was created in the mixer and then discarded. A butter mix is a scaled-down replica that is a quarter to a half of the size of the concrete mix to be made. The butter mix serves to moisten the inside of the mixer so the concrete combines smoothly. The mixer was a Goldblatt, rotary drum- type mixer.

After the butter mix was discarded, the concrete was prepared. First, coarse aggregate, half of the water, and the silica fume were placed in the mixer and allowed to mix for 45-60 seconds. Sand was then added and mixed for 30-45 seconds. The mixer was stopped, and the barrel was scraped to ensure consistency in mixing. The mixer was then restarted, and cement, fly ash, and slag (as applicable) were added slowly. Admixtures and the second half of the water were then added. The concrete was poured into a bin and mixed by hand with a trowel. Slump, air content and density tests were performed based on applicable ASTM testing standards [ASTM C192-98 1998; ASTM C143-03 2003; ASTM C138/C138M-09 2009; ASTM C 173/173M-09 2009].

The concrete was cast into 101.6 x 203.2 mm cylindrical molds. The molds were placed on a Syntorn PowerPulse vibration table set at level eight and vibrated for approximately 20-30 seconds. The molds were filled in two lifts of equal volume. Excess concrete was scraped off to ensure a level surface. Caps were placed on the cylinders to prevent evaporation.

To replicate field curing conditions, samples to undergo 24-hour compressive strength tests were wrapped in insulation and placed in a VWR-Scientific Model 2005 incubator in which the temperature was held at approximately 22° C. The insulation allowed heat to remain inside the concrete and expedite the hydration reaction, increasing high early strength. Insulated cylinders have similar curing conditions to slabs because of the low exposed surface area to volume ratio. Therefore, it is expected that the concrete used in the field will develop strength in a similar manner to the insulated cylinders [Whiting, Nagi et al. 1994].

The remaining resistivity and compression strength samples were covered in burlap and allowed to cure at ambient laboratory conditions for 24 hours. The specimens were then demolded and subjected to curing conditions simulating the Seattle climate. The samples were stored in curing chambers which were kept at 75% relative humidity. In addition, the specimens were submerged weekly for one-hour to simulate precipitation.

Compressive Strength. Compression strength was determined using a 1,334 kN capacity Riehle hydraulic testing machine. Cylinders were capped with neoprene pads and steel platens to ensure uniform seating. Loading was applied in displacement-control at a rate of 0.51 mm/min. Compressive strength was defined as the maximum loading sustained divided by the cross-sectional area. Compression testing was conducted at 1, 3, 7, 28 and 56 days. Three replications were made.

Resistivity. Resistivity was measured using a custom-designed and built Wenner Four Probe setup [Tinnea, Tinnea et al. 2009] based on the "Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability [FM 5-578 2004]." Four equally-spaced electrodes were placed in direct and solid contact with the sample. To ensure contact between the sample and the probes, 11 micrometer Class 1 filter paper was placed between the sample and the probes, and wet with water before measurements were taken. This filter paper was found to be the most effective medium to ensure good contact, while providing consistent results [Tinnea, Tinnea et al. 2009]. Outside electrodes applied small alternating currents while the potential difference was measured between the two inner electrodes. Resistivity was determined as:

$$\rho = \frac{2\pi AR}{K} \tag{1}$$

where ρ = resistivity (ohm-cm), A = distance between inner electrodes (cm, K = correction factor to account for specimen geometry, and R= resistance (ohms) measured with the AC Nilsson resistivity meter. In the setup used, A= 3.81 mm; therefore, K = 1.8 [Morris, Moreno et al. 1996].

Four readings were taken for each specimen, one along four longitudinal axes that are spaced 90° apart. Three replications were made. As this is a non-destructive test, the specimens were removed from the curing chamber for the test and then replaced after testing. For all samples, measurements were taken at 1, 2, 3, 7, 28, 56, 140, 168 and 196 days**.** In addition, 84 day readings were taken for the base and 5% slag mixes. This variation in measurement readings was due to equipment problems with the Wenner Probe that occurred after 56 day and that were resolved for the 140 day readings.

RESULTS AND DISCUSSION

Fresh State Properties. Table 3 presents the fresh state properties of the concrete mixes. Little variation between mixes was seen in the properties measured and all are in ranges typical of normal concrete. In addition, the workability of the mixes was in the target range of 101.6 – 202.4 mm.

Compressive Strength.

Fig. **2** presents the average compressive strength versus age for the mixes tested. In general, compressive strength increases with age. At 24 hours, the average strength for the base and 5% slag mixes both exceeded the desired 25 MPa, while the 10 and 15% slag mixes were slightly below the target by 1.3 and 0.8 MPa, respectively. These strengths are approximately equal to the target strength of 25 MPa, particularly due to the low standard deviations observed. At 56 days, the average compressive strength of the base, 5 and 10% slag mixes are similar (52 MPa), while the 15% slag has a lower strength of 46 MPa.

Table 3. Unit Weight, Air Content and Slump for Concrete Mixes Tested

Mix	Unit weight (kg/m^3)	Air content (%)	Slump (mm)
Base	2,372	3.3	198
5% SL	2,339	4.0	168
10% SL	2,339	3.8	142
15% SL	2,339	4.1	152

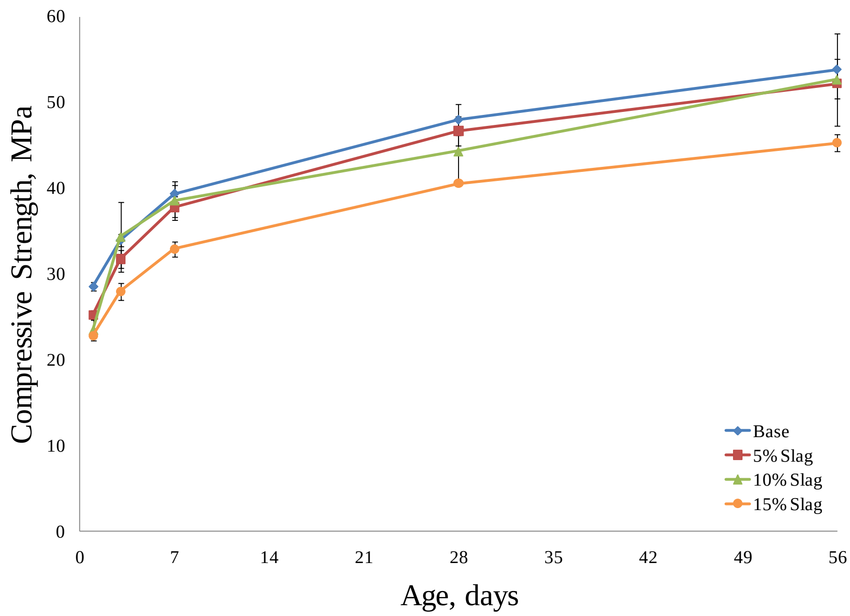

Fig. 2. Average Compressive Strength (with Standard Deviations) Versus Age for Base Mix and Mixes with 5, 10 and 15% Cement Replaced with Slag

Resistivity. Fig. 3 presents the average resistivity versus age for the samples tested up to 196 days. As expected, the base mix initially has the highest resistivity due to the hydraulic activity of the Portland cement. However, as time passes, the pozzolanic reaction with the slag occurs, increasing the resistivity of the mixes. The fly ash, which is at the same replacement level in each mix, is also assumed is also assumed undergo a pozzolanic reaction with available free lime. At 196 days, the 10% slag mix has the greatest resistivity of 59 kohm-cm, followed by the 5%, base and 15%, respectively.

The aim of this research was to produce a concrete mix design with a 365 day resistivity of at least 100 kohm-cm. However, at the time of preparing this manuscript, only 196 days worth of data had been obtained. Previous work by Tinnea and colleagues suggest that regression equations from the log-log plots of resistivity versus age data after 28 days could be used to predict long-term resistivity [Burke, Tinnea et al. 2007]. They observed a bi-linear trend in data with a “knee” at approximately 28 days and hypothesized that this change in slope was due to the pozzolanic reaction which became dominant after 28 days. Similar trends were seen in this study.

Table 4 presents the projected 365 day resistivity for the four mixes tested. Based on these projections, all mixes are expected to achieve high resistivities, with the 10% slag mix exceeding the project goal of 100,000 ohm-cm. The lowest resistivity is seen for the 15% slag mix. These findings are similar to what was observed with the compression strength testing and suggest that there is not enough free lime to react with the slag when 15% of the Portland cement is replaced.

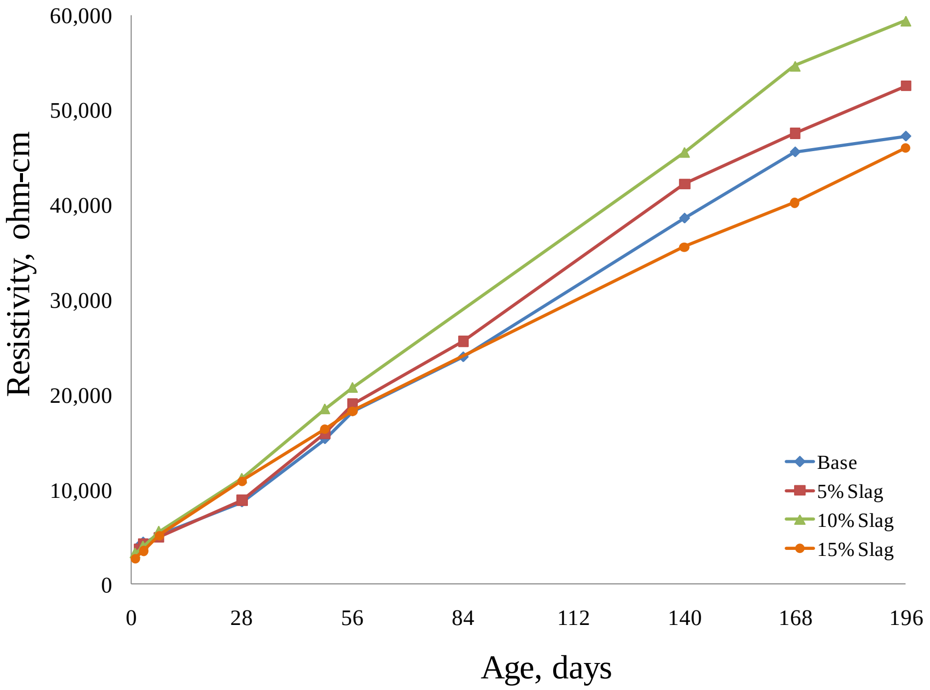

Fig. 3. Resistivity Versus Age for Base Mix and Mixes with 5, 10 and 15% Cement Replaced with Slag

Table 4. Projected 365-day Resistivity for Mixes Based on Log-Log Plots of Resistivity Versus Age After 28 Days

Mix	Projected 365-day Resistivity (ohm-cm)
Base Mix	87,482
5% Slag	97,310
10% Slag	104,499
15% Slag	77,952

CONCLUSION

The objective of this research was to produce a constructible, high resistivity concrete for use in the Seattle trolley line development. The results indicate that a ternary mix of silica fume, fly ash and slag achieve these goals. Based on projected 365-day resistivity values, the 10% slag mix should be used to maximize resistivity. Future work should include evaluating resistivity values up until 365 days. In addition, it would be useful to relate resistivity changes directly to microstructural changes through mercury intrusion porosimetry, rapid chloride penetration tests and microscopic observations to more accurately explain the positive effect of the SCMs on resistivity.

ACKNOWLEDGEMENTS

The authors extend sincere thanks and appreciation to Shaunie Cochran, Ly Pham, and Seattle Public Utilities for their generous support and assistance throughout this work. Thank you also to Tampson Omps from Glacier Northwest and Rob Shogren from Lafarge North America for supplying research materials as well as useful input regarding current industry practices.

REFERENCES

ASTM C138/C138M-09 (2009). "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete." 04(02).

ASTM C143-03 (2003). "Standard Test Method for Slump of Hydraulic Cement Concrete." 04.02.

ASTM C192-98 (1998). "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." 04.02, 112-118.

ASTM C 173/173M-09 (2009). "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method." 04(02).

Bellomio, S., M. Fanoni, et al. (2009). High Early Strength, High Resistivity Concrete, Seattle University.

Burke, D., J. Tinnea, et al. (2007). "Estimating Long-Term Concrete Electrical Resistivity." *Materials Performance*, 2-8.

FM 5-578 (2004). "Concrete Resistivity as an Electrical Indicator of its Permeability."

Kadri, E. and R. Duval (2009). "Hydration Heat Kinetics of Concrete with Silica Fume." *Construction and Building Materials* 23(11), 3388-3392.

Mehta, P. K. (2009). "Global Concrete Industry Sustainability: Tools for Moving Forward to Cut Carbon Emissions." *Concrete International*, 45-48.

Morris, W., E. I. Moreno, et al. (1996). "Practical Evaluation of Resistivity of Concrete in Test Cylinders Using a Wenner Array Probe." *Cement and Concrete Research* 26(12), 1779-1787.

Tinnea, R., J. Tinnea, et al. (2009). Testing of High-Resistivity Concrete. NACE International Corrosion Conference, Atlanta, GA.

Whiting, D., M. Nagi, et al. (1994). "Early Strength Gain of Rapid Highway Repair Concrete." *Concrete International*, 28-35.

Zelic, J., D. Rusic, et al. (2000). "Role of Silica Fume in the Kinetics and Mechanisms During the Early Stage of Cement Hydration." *Cement and Concrete Research* 30(10), 1655-1662.