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Design and Performance of Ternary Blend High-Volume Fly Ash Concretes of Moderate Slump

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Abstract

One approach to increasing the sustainability of concrete construction is to replace a significant portion of the ordinary portland cement (OPC) with a supplementary cementitious material, such as fly ash. This paper presents mixture proportions and measured properties for a series of six high-volume fly ash (HVFA) concretes, five containing a ternary component of a fine limestone powder, with cement replacement levels of 40 % or 60 % by volume, targeting moderate slump (150 mm) applications. Special emphasis is given to electrical resistivity measurements, comparing measurements conducted in a uniaxial vs. a surface configuration, and assessing the capability of measurements of the bulk resistance of the fresh concrete to anticipate setting times in these HVFA mixtures. The degree to which relationships exist between compressive strength and either cumulative heat release or uniaxial resistivity are presented. In general, ternary blend HVFA concretes can be formulated to provide acceptable strengths at both early ages and over the longer term, with an increased resistivity that implies an enhanced durability and increased service life. However, to achieve moderate slumps at the requisite lower water-to-cementitious material ratios, high dosages of high-range water-reducing admixtures (HWRA) will likely be required, which can negatively impact early-age properties (e.g., setting time and 1 d strengths). Thus, optimum mixture proportioning will require the careful selection and evaluation of the available HRWRA products, both individually and in potential combinations. Finally, another viable route to reducing cement content is to increase the aggregate volume fraction, as demonstrated by the OPC control concretes investigated in this study where aggregate volume fraction was increased from 70 % to 72.5 %, concurrently achieving a 10 % reduction in cement content. In the ternary blend HVFA mixtures, further increases to 75 % aggregates were possible, resulting in overall cement reductions (per unit volume of concrete) of between 45 % and 63 %.

Keywords: Cement content; compressive strength; electrical resistivity; high-range water-reducing admixture; high-volume fly ash concrete; isothermal calorimetry; setting; sustainability; ternary blend.

Introduction

While high-volume fly ash (HVFA) concrete mixtures have been promoted and occasionally employed for many years, they have received renewed attention during the recent concrete sustainability movement [1]. Recent investigations have indicated that one of the drawbacks of such mixtures, excessive setting time delays, can be alleviated by the judicious volume-based replacement of ¼ of the fly ash in a mixture by a fine limestone powder with a median particle diameter on the order of 1 micrometer [2]. Reductions in the water-to-cementitious materials mass ratio (*w/cm*) and switching from an ASTM C150 Type I/II to a Type III cement can provide further improvements to meet or exceed early-age strength targets with these ternary blends. In the previous study [2], target slumps were only on the order of 25 mm, representing a typical pavement mixture. However, it is anticipated that performance could vary significantly for higher slump mixtures of these ternary blends, because of the higher dosages of high-range water reducing admixture (HRWRA) that may be required. Higher dosages could induce additional retardation of the hydration and pozzolanic reactions and thus offset the performance benefits of the fine limestone additions, for example. One goal of the present study is to investigate these ternary blend concretes proportioned for a more moderate targeted slump of nominally 150 mm. This will assist in providing practicing engineers with the tools and guides needed to develop cost-effective HVFA concrete mixtures.

A second goal of the present study is to investigate the electrical properties of these HVFA mixtures and their relationships to one another and to setting times and strength development. Here, three types of electrical resistivity measurements are performed. Surface and uniaxial measurements of the resistance of hardened concrete cylinders are performed at various ages, while twin steel (screw rod) probes are embedded in a cylinder of each fresh concrete mixture to monitor its "bulk" resistance during the first day of curing [3]. The goal of the electrical measurements on the hardened concretes is to provide an indication of their expected durability, capitalizing on the relationship between conductivity and diffusivity [4-6] and the observations that reinforced concretes with higher resistivity generally exhibit lower corrosion rates [7]. For the fresh concrete, the goal is to use the initial measurements of electrical resistance to anticipate the subsequent setting time of each concrete mixture [3, 8]. Because previous research has demonstrated a good correlation (with the expected inverse proportionality) between surface resistivity and rapid chloride permeability test (RCPT) measurements for HVFA concrete mixtures [2, 9], the current study focuses instead on the equivalence between uniaxial and surface resistivity measurements.

Materials and Methods

The ASTM C150 Type I cement [10] was obtained from the Cement and Concrete Reference Laboratory (CCRL) proficiency sample program (http://ccrl.us/Psp/Reports.htm), specifically CCRL cement 192 distributed in January 2014. The ASTM C150 Type III cement was obtained from a U.S. manufacturer. Oxide compositions and other characteristics, as obtained from the manufacturer's mill sheet or the CCRL proficiency sample report, are provided in Table 1. The densities reported in Table 1 were obtained using helium pycnometry at the National Institute of Standards and Technology (NIST), while the Brunauer-Emmett-Teller (BET) surface areas were obtained at NIST using nitrogen as the sorbent gas (coefficient of variation of 2 % for three replicate specimens [11]). Particle size distributions (PSDs) were measured at NIST using laser diffraction with isopropanol as the dispersant, and each PSD was characterized by its D_{10}, D_{50} (median), and D_{90} diameters, where the subscript represents the cumulative percentage smaller than the listed diameter. As would be expected, the Type III cement exhibits a significantly higher fineness than the Type I/II cement, in terms of its PSD characteristics (particularly its D90 value), its measured BET surface area, and its manufacturer-reported Blaine fineness value as per ASTM C204 [10] (Table 1).

Both a Class C and a Class F fly ash, according to ASTM C618 specifications [10], were employed in the study; their characteristics are also provided in Table 1. While the Class F fly ash generally contains larger particles, it actually exhibits a higher surface area, consistent with its lower density (higher porosity). A fine limestone (calcium carbonate) powder with a median particle diameter of 1.6 µm and a BET surface area of 9.93 m^2/g [12] was used in the ternary blends. It has a reported density of 2700 kg/m^3 and a reported $CaCO_3$ content of 98 % by mass. The coarse aggregate was classified as a dolomitic limestone, with a 19 mm (¾ in) nominal maximum size, a density of 2800 kg/m^3, and an absorption of 0.4 %. A locally available concrete sand having a density of 2590 kg/m^3, an absorption of 1.1 %, and a fineness modulus of 2.60 was used. To obtain sufficient slumps, two HRWRAs were utilized together in varying quantities in the different concrete mixtures, namely Glenium 7710 from BASF and Viscocrete from Sika Corporation[1].

Table 1. Characteristics of the Cements and Fly Ashes used in the Study

	Type I	Type III	Class C Fly ash	Class F Fly ash
CaO (mass %)	64.20	62.27	24.6	0.7
SiO_2	20.86	18.56	38.4	59.7
Al_2O_3	4.77	5.70	18.7	30.2
Fe_2O_3	2.05	2.16	5.1	2.8
MgO	3.09	2.35	5.1	0.8
SO_3	2.81	4.47	1.4	0.02
Total alkalies	0.46	1.03	2.09	1.78
LOI	1.13	2.49	0.3	0.8
Limestone addition	Not reported	3.82	---	---
Blaine Fineness (m^2/kg)	401	481.4	Not reported	Not reported
D_{10}, D_{50}, D_{90} (µm)	1.4, 13.0, 42.3	1.3, 10.6, 30.8	0.9, 8.6, 50.2	1.7, 18.4, 83.1
Density (kg/m^3)[A]	3150 ± 10	3070 ± 10	2650 ± 10	2490 ± 10
BET surface area (m^2/g)	1.14	1.69	0.90	1.28

[A]Uncertainties in density represent one standard deviation for ten replicate measurements.

Concrete mixtures were designed with an assumed (entrapped) air content of 2 % and targeting a 28 d compressive strength of 40 MPa, along with a nominal slump of 150 mm. The details of the mixture proportions can be found in Table 2. A fixed ratio of coarse to fine aggregates was maintained in all mixtures. In the control mixtures based on the Type I cement, the volume fraction of aggregates was varied from 70 % to 75 % in 2.5 % increments (three mixtures), the latter two mixtures producing reductions in cement content of 10.4 % and 17.1 % relative to the initial 70 % aggregate mixture, respectively. The control mixture with 75 % aggregate exhibited a high degree of segregation and bleeding, likely due to the combination of its low paste content and the high dosage of HRWRAs that was required to achieve the target slump. Subsequently, the two Type III cement control mixtures were prepared with 70 % and 72.5 % aggregates by volume, respectively, while the aggregate volume fraction in each of the HVFA mixtures was maintained near 75 %, as the presence of the fly ash and fine limestone in these mixtures enhanced mixture

[1] Certain commercial products are identified in this paper to specify the materials used and the procedures employed. In no case does such identification imply endorsement or recommendation by the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.

Table 2. Mixture Proportions for the Eleven Concrete Mixtures (kg/m^3 or L/m^3 for HRWRA).

Mixture	Cement	Cement reduction	Fly Ash	Limestone	Water	*w/cm*[A]	Fine Agg	Coarse Agg	Glenium 7710	Viscocrete
Control (Type I) – 70 % Agg	396.5	---	---	---	158.6	0.40	850	1029	2.08	---
Control (Type I) – 72.5 % Agg	355.1	10.4 %	---	---	142.0	0.40	886	1073	2.20	0.35
Control (Type I) – 75 % Agg	328.7	17.1 %	---	---	131.5	0.40	909	1101	1.90	0.92
Control (Type III) – 70 % Agg	395.1	---	---	---	158.1	0.40	847	1025	2.86	---
Control (Type III) – 72.5 % Agg	354	10.7 %	---	---	141.6	0.40	884	1070	2.20	0.55
Type I/F ash/limestone	220	44.5 %	86.9	31.4	115	0.34	915	1107	1.37	1.46
Type III/F ash/limestone	148.1	62.5 %	135.2	48.9	103	0.31	924	1119	1.44	3.44
Type III/F ash/limestone (additional water)	146.2	63.0 %	133.4	48.2	114.7	0.35	912	1104	0.97	2.0
Type I/C ash/limestone	217.2	45.2 %	91.3	31	125.6	0.37	904	1094	1.35	0.90
Type I/C ash	218.8	44.8 %	122.7	---	119.5	0.35	910	1102	1.36	0.76
Type III/C ash/limestone	145.7	63.1 %	141.5	48.1	117.3	0.35	909	1101	1.05	1.61

[A] For computing *w/cm* in this study, cementitious materials includes all three powders: cement, fly ash, and fine limestone.

cohesiveness and stability, so that bleeding and segregation were minimal. To achieve sufficient 1 d strengths, the *w/cm* (and water content) of the HVFA mixtures was reduced relative to that of the control mixtures, the reduction being greater for the more inert Class F fly ash than for the more reactive Class C fly ash, based on previous results with these two particular fly ashes [2]. Consistent with the previous study [2], the fly ash to fine limestone volumetric ratio was maintained at 3:1 in all ternary blends. A 40 % volumetric replacement of cement by fly ash/limestone was designed in the concrete mixtures based on the Type I cement, while a 60 % replacement level was chosen for those based on the Type III cement. When compared to the original control Type I cement mixture with 70 % aggregates, the HVFA mixtures achieve cement content reductions of between 44.5 % and 63.1 %, attesting to a high degree of sustainability in terms of projected reductions in the energy and CO_2 footprints of these concretes.

As mentioned previously, when the mixtures were prepared, a slump of 150 mm ± 50 mm was targeted. From Table 2, it can be seen that a higher dosage of the HRWRAs was required for the mixtures containing the Class F fly ash than those with the Class C fly ash, likely due to both their lower water content and the higher surface area of the Class F fly ash producing an increased water demand. In a similar manner, the mixtures employing the Type III (higher surface area) cement required more HRWRA than mixtures based on the Type I cement. For most mixtures, after the initial concrete mixing and measurement of its slump, additional HRWRA (and mixing) was required to increase the slump. For a few mixtures, three or four iterations of adding HRWRA were necessary to achieve an acceptable slump.

The prepared concrete mixtures were evaluated for the following fresh and hardened properties, according to the relevant ASTM standard test methods [10]: fresh concrete temperature (ASTM C1064, ± 0.1 °C standard deviation), slump (ASTM C143), unit weight and calculated air content (ASTM C138), mortar sieving and penetrometer testing for setting (ASTM C403), isothermal calorimetry (ITC) on a sealed specimen of the sieved mortar, electrical resistance measurements on fresh concrete, and electrical resistivity (surface and uniaxial) and strength measurements (ASTM C39; 3 replicates) on hardened cylinders. The ASTM C403 standard test method reports single-operator coefficients of variation for times of initial and final setting of 7.1 % and 4.7 %, respectively. All freshly prepared cylinders were sealed with their caps and placed in a moist room (23 °C, ≥ 98 % RH) for 24 h, demolded after 1 d, and subsequently cured in the same moist room until the time of their testing.

Surface resistance was measured using a 4-point (Wenner) probe arrangement with a probe spacing of 38 mm. The measured surface resistance values were converted to a resistivity using an appropriate geometry factor to account for the specimen geometry and size. Uniaxial resistance was measured by using a special attachment to connect the 4-point probes to two round steel plates, using wet sponges at the top and bottom interfaces to assure good electrical contact between these metal plates and the cylindrical concrete specimens. These uniaxial measurements were subsequently corrected for the contributions of these sponges to the measured response, based on the manufacturer's documented recommendations. Generally, from the prepared set of cylinders for a given concrete mixture, 15 to 18 cylinders were measured at 1 d, 3 cylinders were measured at 7 d, 6 cylinders were measured at 28 d, and 3 cylinders were measured at 90 d. Once the electrical properties of these hardened cylinders had been determined, the same specimens were subsequently utilized for strength testing (or returned to the moist room to be re-evaluated at a later age).

To measure the electrical resistance of the fresh concrete, a special attachment was employed as shown in Figure 1. The twin steel screw rods are insulated with heat-shrink tubing at the top of their embedded length to prevent short-circuiting along the layer of bleed water that may form at the top concrete surface. Additionally, a rigid spacer is employed at the top outside surface of the cylinder cap to help maintain a fixed spacing between the rods when they are inserted into the fresh concrete specimen. Alligator clips are subsequently attached to the exposed sections of the rods to monitor the specimen's electrical impedance, using a frequency scan from 10 Hz to 10 kHz conducted every 5 min in the present study. In this study, the electrical resistance was determined as the real component of the impedance measured at a frequency of 10 kHz.

Figure 1. Twin steel screw rods for embedding in a cylinder of fresh concrete to measure its electrical resistance. The cap with holes is for a 100 mm by 200 mm concrete cylinder mold.

Results

The fresh properties of the eleven concrete mixtures are presented in Table 3. In general, the fresh concrete temperature and air content (with one exception) were consistent among the mixtures, while the slump was found to exhibit a higher variability. Increasing the aggregate volume fraction in the control concretes generally produced a reduction in measured slump, even as HRWRA dosages were increased. Mixtures with a higher cement replacement level (60 %) were proportioned at a significantly lower *w/cm* and thus required higher dosages of HRWRA to provide an adequate slump; this generally produced significant delays in their initial and final setting times, as indicated in Table 4. For example, the initial Type III/F ash/limestone and the Type III/C ash/limestone mixtures both exhibited setting times that were delayed by more than 1.5 h with respect to the control mixtures. The previously observed ability of the fine limestone to mitigate setting time delays [2] can be observed when comparing the setting times of the two Type I/C ash mixtures, with and without limestone addition, in Table 4. It should be noted that these two mixtures had similar HRWRA dosages, so that the major difference between them is the presence/absence of the fine limestone powder. Also in agreement with previous results [2], the Class C fly ash is observed to cause more retardation in setting than the Class F fly ash, at equal volumetric replacement levels. Since the setting times are measured on the sieved mortar fraction of the concrete and setting is generally regulated by hydration occurring in the paste, the control mixtures with the same cement type but different aggregate volume fractions generally produced similar setting times, except for the mixture with the Type I cement and 75 % aggregate volume fraction where the higher HRWRA dosage produced a significant retardation on the order of 1 h, as well as the aforementioned bleeding and segregation issues. For these concrete mixtures, the ratio of the final to the initial setting times was relatively constant with an average value of 1.30, in comparison with previously observed values of 1.46 [2] and 1.35 for this ratio [13]. Thus, given an observed initial setting time in the field, an estimate of the subsequent final setting time could be obtained by simply using this multiplicative factor of 1.3.

Table 3: Fresh concrete properties measured for the concrete mixtures.

Mixture	**Temperature**	**Slump**	**Air content**
Control (Type I -70)	27.3 °C	220 mm	3.3 %
Control (Type I - 72.5)	27.4 °C	190 mm	0.2 %
Control (Type I - 75)	26.6 °C	150 mm	2.0 %
Control (Type III -70)	27.2 °C	150 mm	1.4 %
Control (Type III - 72.5)	26.8 °C	110 mm	2.0 %
Type I/F ash/limestone	28.1 °C	90 mm	2.1 %
Type III/F ash/limestone	28.7 °C	50 mm	3.4 %
Type III/F ash/limestone (additional water)	26.8 °C	110 mm	2.0 %
Type I/C ash/limestone	26.9 °C	180 mm	1.1 %
Type I/C ash	26.5 °C	220 mm	2.0 %
Type III/C ash/limestone	26.8 °C	170 mm	2.9 %
Average	27.2 °C	150 mm	2.1 %
Range	26.5 – 28.7 °C	50 – 220 mm	0.2 – 3.4 %

Table 4: Initial and final setting times measured for the concrete mixtures.

Mixture	Initial setting	Final setting	(Final/Initial)
Control (Type I - 70)	3.40 h	4.55 h	1.34
Control (Type I - 72.5)	3.62 h	4.83 h	1.34
Control (Type I - 75)	4.31 h	6.07 h	1.41
Control (Type III - 70)	3.28 h	4.44 h	1.36
Control (Type III - 72.5)	3.31 h	4.38 h	1.32
Type I/F ash/limestone	3.30 h	4.35 h	1.32
Type III/F ash/limestone	5.13 h	6.07 h	1.18
Type III/F ash/limestone (additional water)	4.75 h	5.75 h	1.21
Type I/C ash/limestone	4.44 h	5.81 h	1.31
Type I/C ash	7.59 h	9.50 h	1.25
Type III/C ash/limestone	5.93 h	7.39 h	1.25
Average (std. dev.)			1.30 (0.07)

A graphical summary of the various property measurements typically obtained at early ages is provided in Figure 2, which contains results for specimen and lab temperatures, penetration resistance (PR), ITC, and fresh concrete electrical resistance for the control (Type I – 72.5) mixture. Electrical resistance measurements of the fresh concrete were also corrected back to a base temperature of 25 °C based on the measured specimen temperature, using a correction factor of $0.98^{-(T(spec)-25)}$ with *T(spec)* measured in °C, consistent with recent measurements of the conductivity of typical pore solutions as a function of temperature [14], and in agreement with previously published data for alkali hydroxide (KOH) solutions [15]. The ITC and electrical resistance were also characterized by their derivatives with respect to time, *dW/dt* and *dR/dt*, respectively.

Correlations among the different properties can be observed in Figure 2. For example, *dW/dt* is correlated with *dR/dt*, while the log of the penetration resistance, the electrical resistance, the specimen temperature, and the heat flow all exhibit similar responses. The electrical resistance measurements on the fresh concrete were subsequently characterized by two critical times, the time when the measured resistance achieves its (first) minimum (*dR/dt* passes through zero) and, when present, the subsequent time after this minimum when *dR/dt* itself exhibits a local minimum in its positive value [3] (see Figure 2 where these two critical times occur at 1.18 h and 1.46 h, respectively). As an indication of uncertainty in these critical times, standard deviations of 0.1 h in the times of *dR/dt*=0 or this subsequent minimum in *dR/dt* were determined for the two mixtures using the Type III cement (similar paste composition).

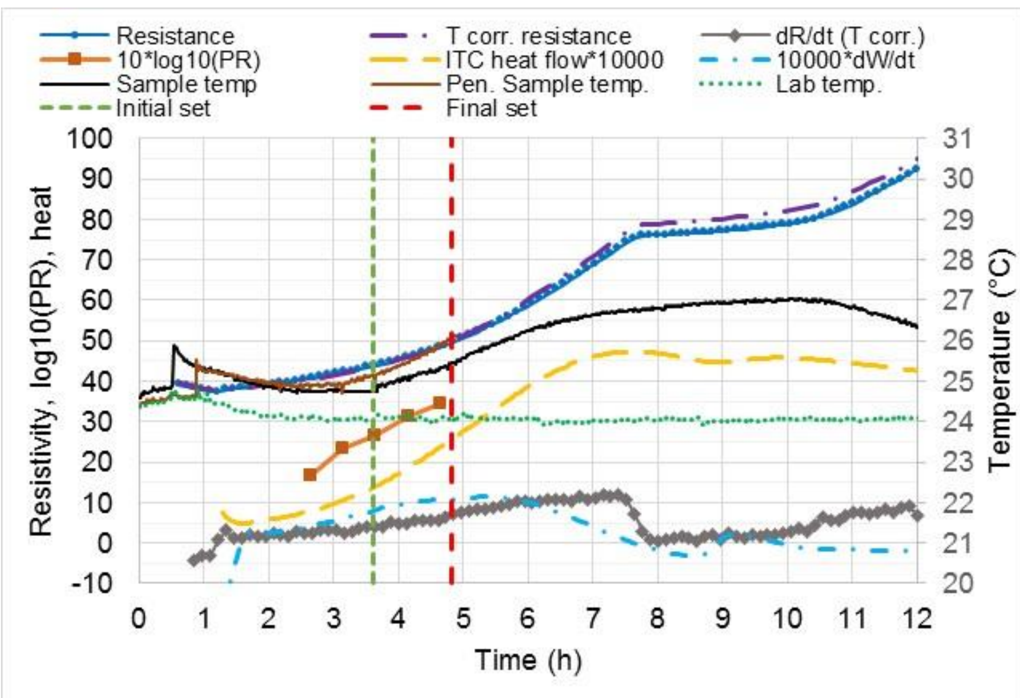

Figure 2. Property measurements at early ages for the control (Type I – 72.5) concrete mixture.

Previously, the subsequent local minimum in *dR/dt* has been successfully correlated with the initial setting time for HVFA **pastes**, allowing the anticipation of initial setting times based on early-age measurements of electrical resistance [3]. In that study, the subsequent minimum occurred at approximately one third of the initial setting time. In the present study, as shown in Figure 3, a similar relationship is once again observed between these two, suggesting that measurements of fresh concrete electrical resistance in the field could be utilized to anticipate (predict) initial setting times. For these eleven concretes, the use of the first time when *dR/dt*=0 also provides a similar predictive capability for initial setting times. Figure 3 contains two sets of plots, the latter being for the case where the electrical resistance and penetration resistance data were both corrected for any temperature differences between the two specimens, using the pore solution conductivity factor given above for electrical resistance and a conventional maturity-based approach for correcting setting times, with activation energies for the latter having been determined for similar mixtures in a previous study [16]. As can be seen in Figure 3, the extra steps of correcting for specimen temperatures did not improve the ability to anticipate setting times. It must be kept in mind though that the temperature excursions for the specimens in this study were by no means extreme, typically being on the order of just a few degrees Celsius (see Figure 2). In summary, the previously observed capability of electrical resistance measurements to anticipate setting times in HVFA pastes [3] has carried over in a reasonable manner to the HVFA concrete mixtures investigated in the present study, even though their water contents varied from about 10.3 % to 15.9 % by volume.

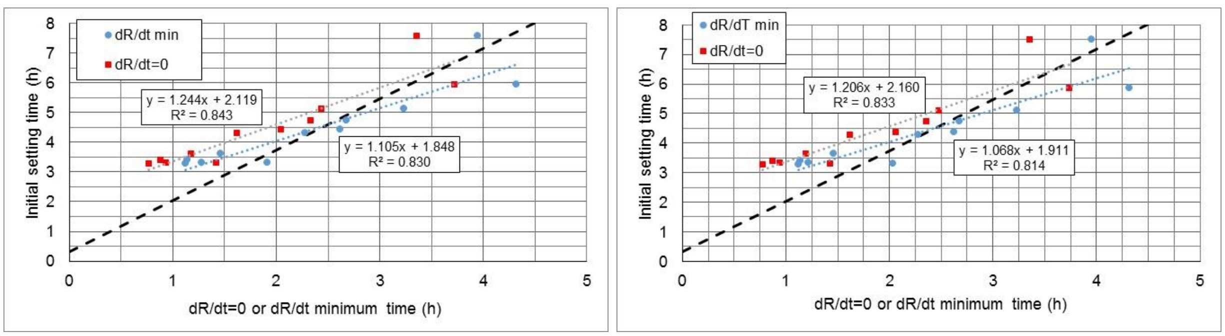

Figure 3. Correlation of initial setting time with measured electrical resistivity for original (left) and temperature-corrected (right) data. Bold dashed line indicates relationship determined previously for paste specimens (based on *dR/dt min*) in [3].

Measured compressive strengths are provided in Table 5. All of the mixtures provided 28 d compressive strengths within 10 % of the target value of 40 MPa, with the exceptions of the Type III/F ash/limestone (additional water) mixture and the 75 % aggregate OPC Type I mixture that experienced dramatic bleeding and segregation (and no measurable strength gain beyond 7 d). More variation was observed in the early age strengths, particularly those measured at 1 d, as some of the mixtures with fly ash that exhibited significant delays in setting times also produced significantly lower 1 d strengths. Once again, the benefits of replacing a portion of the fly ash with the fine limestone powder are observed in comparing the 1 d compressive strength values of the Type I/C ash and Type I/C ash/limestone mixtures in Table 5, with the latter producing a relative strength increase of 47 %. Measured compressive strengths were fairly independent of aggregate volume fraction for the 70 % and 72.5 % volume fractions investigated in this study. This agrees with the recent observation of Yurdakul et al. [17] that “strength is independent of cementitious (paste) content after a critical value is provided.” For the Type I OPC concrete, 75 % aggregates did not provide this critical volume of paste, producing a significant decrease in measured compressive strengths. But, interestingly, for the binary and ternary blends with fly ash and limestone, 28 d strengths were restored, as the paste volume of nominally 25 % was apparently adequate in these more sustainable binder systems.

Table 5: Average compressive strengths (standard deviations) vs. age for the concrete mixtures.

Mixture	1 d	7 d	28 d	90 d
Control (Type I - 70)	22.1 MPa (3.0 MPa)	Not meas.	42.9 MPa (1.4 MPa)	54.8 MPa (5.8 MPa)[A]
Control (Type I - 72.5)	22.2 MPa (1.0 MPa)	30.4 MPa (7.0 MPa)	41.8 MPa (2.4 MPa)[A]	52.6 MPa (13.1 MPa)
Control (Type I - 75)	18.9 MPa (0.4 MPa)	26.9 MPa (8.8 MPa)	26.3 MPa (3.6 MPa)	23.2 MPa (6.3 MPa)
Control (Type III - 70)	17.9 MPa (2.3 MPa)[A]	35.6 MPa (4.3 MPa)[A]	39.3 MPa (6.7 MPa)	51.5 MPa (1.7 MPa)
Control (Type III - 72.5)	29.3 MPa (8.5 MPa)	Not meas.	42.1 MPa (2.0 MPa)	47.6 MPa (4.5 MPa)
Type I/F ash/limestone	23 MPa (1.8 MPa)[A]	28.5 MPa (1.8 MPa)	38.9 MPa (10.8 MPa)[A]	56.0 MPa (9.5 MPa)
Type III/F ash/limestone	17.7 MPa (0.5 MPa)	28.5 MPa (2.7 MPa)	39.4 MPa (3.8 MPa)	44.2 MPa (4.6 MPa)
Type III/F ash/limestone (additional water)	12.1 MPa (1.8 MPa)	19.4 MPa (2.3 MPa)	28.2 MPa (1.3 MPa)[A]	48.7 MPa (3.8 MPa)
Type I/C ash/limestone	18.7 MPa (3.0 MPa)[A]	27.0 MPa (1.7 MPa)[A]	43.9 MPa (2.6 MPa)	44.1 MPa (3.7 MPa)
Type I/C ash	12.8 MPa (0.04 MPa)	30.3 MPa (5.6 MPa)[A]	40.6 MPa (2.6 MPa)[A]	52.4 MPa (6.9 MPa)
Type III/C ash/limestone	13.9 MPa (0.6 MPa)	36.1 MPa (4.0 MPa)	41.3 MPa (7.8 MPa)	55.5 MPa (8.1 MPa)

[A]Average of only two as opposed to three specimens.

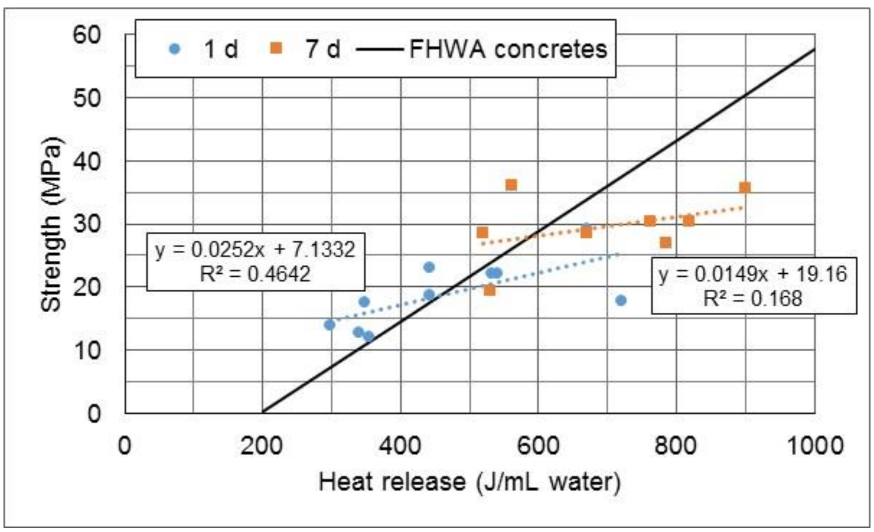

Figure 4. Measured cylinder compressive strength vs. measured cumulative heat release for sieved mortar in comparison to results from a previous study on HVFA (FHWA) concretes [2].

Previous research has demonstrated a linear relationship between measured compressive strengths for mortars and concretes and the ITC cumulative heat release normalized on a per volume of water basis [2, 18]. Results from the present study are plotted in this fashion in Figure 4.

While the data generally fit the trend line established for HVFA concretes based on the same two fly ashes in a previous study [2], they generally exhibit greater variability. Some of this higher variability is likely due to the fact that in the present study, the water contents of the mortar ITC specimens were estimated from the mixture proportions of the corresponding concretes, while in the previous study [2], they were directly assessed according to AASHTO T318 [19].

Average surface and uniaxial resistivities measured on the hardened concrete cylinders are provided in Tables 6 and 7, respectively. The average coefficients of variation (CoV) for the surface resistivity and uniaxial resistivity measurements for all concretes at all ages were 5.6 % and 7.2 %, respectively. The uniaxial resistivity values are based on a single measurement on each replicate cylinder, while the surface resistivity values are based on eight measurements (duplicates spaced at 90° increments around the exterior of the cylinder) on each hardened concrete cylinder, as per the proposed ASTM test method. In a previous study using limewater curing, an average CoV of 3.9 % was obtained for surface resistivity measurements, in comparison to a value of 8.4 % for RCPT measurements [2]. As shown in Figure 5, a reasonable agreement is observed between the uniaxial and the surface resistivity measurements for the concretes investigated in this study, cured under moist room conditions. In general, and especially so at early ages, uniaxial resistivity values tend to be slightly higher than their corresponding surface values, perhaps due to the presence of a mortar-rich (more conductive) layer formed at the surface of the cylinders during casting/rodding (e.g., a typical wall effect [20]). Larger differences between these two types of resistance measurements have been observed under other curing conditions, such as immersion for example [5, 6].

Table 6: Average surface resistivities (standard deviations) vs. age for the concrete mixtures.

Mixture	1 d	7 d	28 d	90 d
Control (Type I - 70)	0.022 kΩ·m (0.002 kΩ·m)	0.038 kΩ·m (0.004 kΩ·m)	0.060 kΩ·m (0.005 kΩ·m)	0.071 kΩ·m (0.007 kΩ·m)
Control (Type I - 72.5)	0.022 kΩ·m (0.001 kΩ·m)	0.040 kΩ·m (0.002 kΩ·m)	0.066 kΩ·m (0.004 kΩ·m)	0.085 kΩ·m (0.004 kΩ·m)
Control (Type I - 75)	0.023 kΩ·m (0.001 kΩ·m)	0.037 kΩ·m (0.003 kΩ·m)	0.060 kΩ·m (0.004 kΩ·m)	0.082 kΩ·m (0.004 kΩ·m)
Control (Type III - 70)	0.029 kΩ·m (0.002 kΩ·m)	0.050 kΩ·m (0.002 kΩ·m)	0.084 kΩ·m (0.006 kΩ·m)	0.120 kΩ·m (0.004 kΩ·m)
Control (Type III - 72.5)	0.029 kΩ·m (0.001 kΩ·m)	Not meas.	0.096 kΩ·m (0.004 kΩ·m)	0.154 kΩ·m (0.006 kΩ·m)
Type I/F ash/limestone	0.023 kΩ·m (0.001 kΩ·m)	0.043 kΩ·m (0.003 kΩ·m)	0.115 kΩ·m (0.007 kΩ·m)	0.340 kΩ·m (0.014 kΩ·m)
Type III/F ash/limestone	0.016 kΩ·m (0.001 kΩ·m)	0.048 kΩ·m (0.001 kΩ·m)	0.216 kΩ·m (0.009 kΩ·m)	0.521 kΩ·m (0.030 kΩ·m)
Type III/F ash/limestone (additional water)	0.012 kΩ·m (0.001 kΩ·m)	0.038 kΩ·m (0.003 kΩ·m)	0.151 kΩ·m (0.006 kΩ·m)	0.667 kΩ·m (0.028 kΩ·m)
Type I/C ash/limestone	0.019 kΩ·m (0.002 kΩ·m)	0.039 kΩ·m (0.002 kΩ·m)	0.085 kΩ·m (0.005 kΩ·m)	0.217 kΩ·m (0.009 kΩ·m)
Type I/C ash	0.014 kΩ·m (0.001 kΩ·m)	0.028 kΩ·m (0.002 kΩ·m)	0.070 kΩ·m (0.004 kΩ·m)	0.207 kΩ·m (0.010 kΩ·m)
Type III/C ash/limestone	0.014 kΩ·m (0.001 kΩ·m)	0.049 kΩ·m (0.001 kΩ·m)	0.180 kΩ·m (0.008 kΩ·m)	0.482 kΩ·m (0.019 kΩ·m)

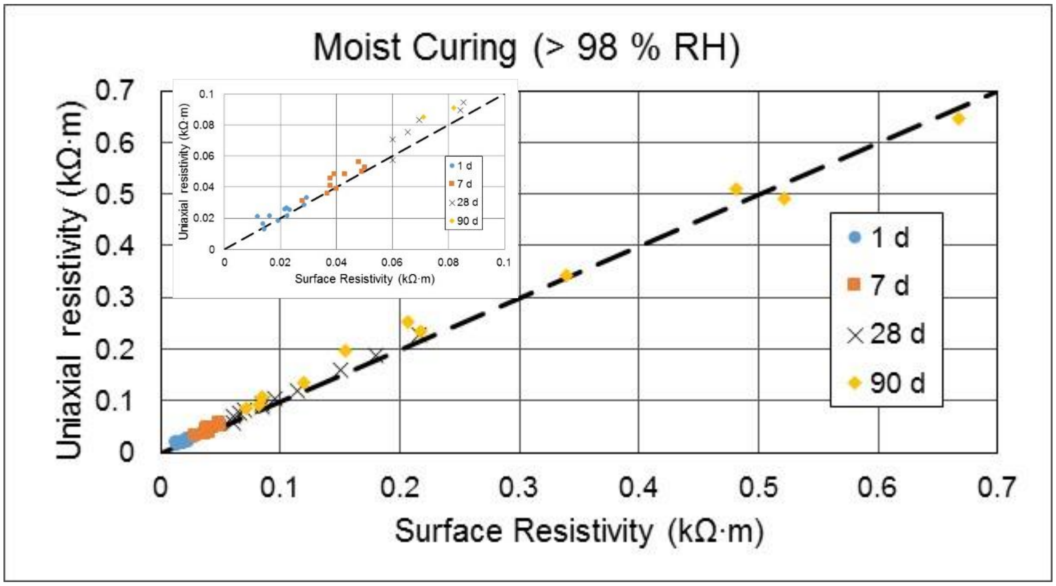

Figure 5. Agreement between uniaxial and surface resistivity measurements for the concrete mixtures. A magnification of the resistivity data near zero is provided in the inset. The dashed line indicates a 1:1 relationship.

Table 7: Average uniaxial resistivities (standard deviations) vs. age for the concrete mixtures.

Mixture	1 d	7 d	28 d	90 d
Control (Type I - 70)	0.026 kΩ·m (0.004 kΩ·m)	0.046 kΩ·m (0.004 kΩ·m)	0.071 kΩ·m (0.006 kΩ·m)	0.085 kΩ·m (0.006 kΩ·m)
Control (Type I - 72.5)	0.026 kΩ·m (0.003 kΩ·m)	0.039 kΩ·m (0.004 kΩ·m)	0.075 kΩ·m (0.004 kΩ·m)	0.107 kΩ·m (0.004 kΩ·m)
Control (Type I - 75)	0.022 kΩ·m (0.001 kΩ·m)	0.036 kΩ·m (0.002 kΩ·m)	0.057 kΩ·m (0.004 kΩ·m)	0.091 kΩ·m (0.012 kΩ·m)
Control (Type III - 70)	0.028 kΩ·m (0.002 kΩ·m)	0.053 kΩ·m (0.002 kΩ·m)	0.089 kΩ·m (0.003 kΩ·m)	0.136 kΩ·m (0.006 kΩ·m)
Control (Type III - 72.5)	0.033 kΩ·m (0.003 kΩ·m)	Not meas.	0.105 kΩ·m (0.024 kΩ·m)	0.197 kΩ·m (0.017 kΩ·m)
Type I/F ash/limestone	0.025 kΩ·m (0.001 kΩ·m)	0.049 kΩ·m (0.002 kΩ·m)	0.120 kΩ·m (0.006 kΩ·m)	0.341 kΩ·m (0.002 kΩ·m)
Type III/F ash/limestone	0.021 kΩ·m (0.002 kΩ·m)	0.056 kΩ·m (0.004 kΩ·m)	0.227 kΩ·m (0.004 kΩ·m)	0.492 kΩ·m (0.012 kΩ·m)
Type III/F ash/limestone (additional water)	0.021 kΩ·m (0.002 kΩ·m)	0.041 kΩ·m (0.003 kΩ·m)	0.159 kΩ·m (0.009 kΩ·m)	0.647 kΩ·m (0.006 kΩ·m)
Type I/C ash/limestone	0.018 kΩ·m (0.002 kΩ·m)	0.048 kΩ·m (0.002 kΩ·m)	0.094 kΩ·m (0.004 kΩ·m)	0.233 kΩ·m (0.009 kΩ·m)
Type I/C ash	0.016 kΩ·m (0.004 kΩ·m)	0.031 kΩ·m (0.002 kΩ·m)	0.083 kΩ·m (0.005 kΩ·m)	0.254 kΩ·m (0.029 kΩ·m)
Type III/C ash/limestone	0.013 kΩ·m (0.001 kΩ·m)	0.050 kΩ·m (0.004 kΩ·m)	0.187 kΩ·m (0.006 kΩ·m)	0.511 kΩ·m (0.020 kΩ·m)

In Tables 6 and 7, as would be expected, the general trend for the OPC concretes with 70 % and 72.5 % aggregates is that an increase in the volume fraction of the non-conductive aggregates and its accompanying decrease in the volume fraction of the conductive cement paste produces specimens with a slightly increased resistivity, similar to trends observed previously for oxygen permeability coefficient as a function of binder content [21]. Additionally, for similar strength levels, the mixtures with fly ash and limestone produce higher values for both surface and uniaxial resistivity at later ages of 28 d and 90 d. Contributions to the enhanced resistivities measured in these ternary blends can include a lower conductivity pore solution due to cement dilution and increased sorption/binding of alkalis by pozzolanic reaction products [22, 23], porosity reductions due to 1) a reduced water content, 2) increased hydration (at early ages due to the fine limestone), and 3) the production of more voluminous carboaluminate hydration products [24], and refinement of the pore structure, as pozzolanic calcium silicate hydrate gel (C-S-H) generally exhibits a lower diffusivity (conductivity) than that of C-S-H formed from conventional cement hydration [25]. While the latter two contributions should also lead to reductions in the ingress of chloride ions into the concrete, the reduction in pore solution conductivity may not be accompanied by a true reduction in diffusion rates of ingressing species. However, the general observation that higher resistivity concretes have lower corrosion rates [7] should still hold for these HVFA mixtures.

To follow up further on the relationship between strength and durability, the average compressive strengths are compared to their corresponding uniaxial electrical resistivity values in Figure 6. A reasonable positive correlation is observed for the 1 d results. Beyond this age, however, there is little to no correlation between measured compressive strength and uniaxial resistivity, reinforcing the concept that designing for strength and designing for durability are two different objectives [21]. It is likely that the modifications to the C-S-H structure and accompanying pore refinements in these ternary blend concretes have a much larger influence on resistivity (transport) than they do on compressive strength, the latter being generally regulated by the overall pore volume [26] and the size of critical flaws [27].

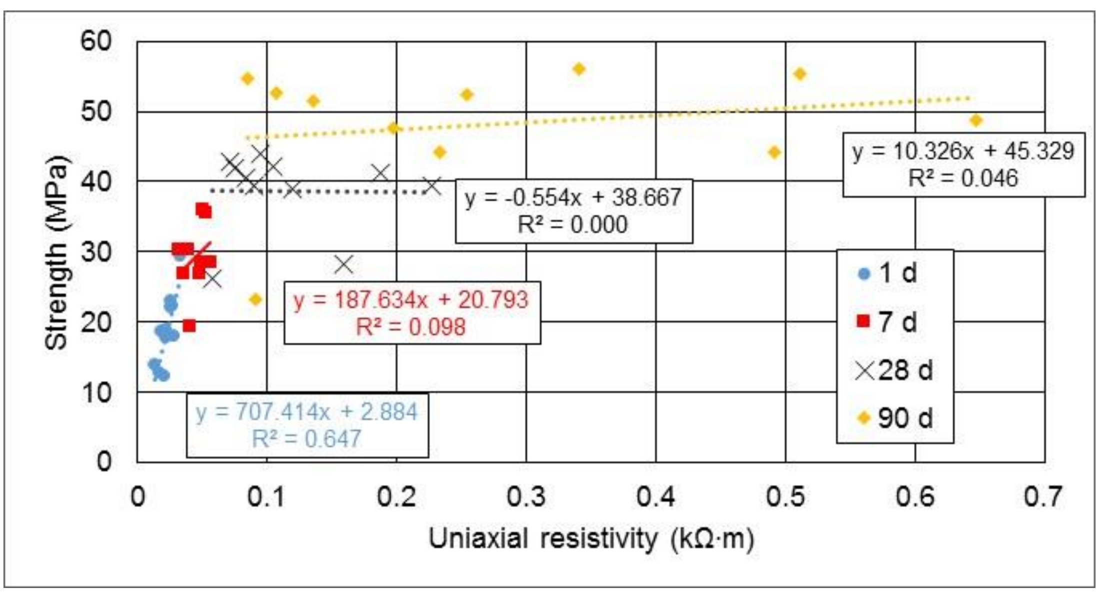

Figure 6. Correlation between compressive strength and uniaxial resistivity for the concrete mixtures as a function of age.

Conclusions

A series of HVFA concretes of moderate slump and nominal 28 d strength of 40 MPa have been prepared and evaluated. The following conclusions can be drawn from the data obtained in this study:

1) HVFA concretes of moderate slump, having similar or enhanced performance in comparison to a control 100 % ordinary portland cement concrete, could be formulated and produced. To achieve moderate slumps (150 mm) with their reduced *w/cm*, however, high dosages of HRWRAs were required that can lead to potential problems with delayed setting times and reduced early-age strengths.
2) Replacing ¼ (by volume) of the fly ash by a fine limestone powder improved the setting times, early age strengths, and electrical resistivities of the HVFA (Type I cement, Class C fly ash) concrete investigated in this study, in agreement with previous results [2].
3) Measurement of the electrical resistance of fresh concrete can be used to anticipate its initial setting time. Generally, the final setting time can be estimated as being approximately 1.3x the measured or predicted initial setting time, which can be determined from specific signatures of the resistance data.
4) For specimens cured in a moist room, there was good agreement between surface and uniaxial resistivities measured at the ages of 1 d, 7 d, 28 d, and 90 d.
5) Conversely, beyond 1 d, there was no correlation between measured compressive strengths and uniaxial electrical resistivities.
6) In addition to replacing cement with supplementary cementitious materials, another approach worthy of consideration for producing more sustainable concretes is to increase the aggregate volume fraction. In the present study for the control mixtures, increasing the aggregate volume fraction from 70 % to 72.5 % produced a 10.4 % reduction in cement content with minimal loss in measured performance. As illustrated in the present study, higher aggregate volume fraction mixtures (i.e., 75 %) may exhibit greater stability (less segregation and bleeding) when formulated as HVFA mixtures.

Because of the water reduction generally required for HVFA concretes to achieve their target strengths, the proper selection and dosage of HRWRA is critical to achieving overall performance. Further research on optimizing HRWRAs for their utilization specifically in HVFA concrete (binary and ternary) mixtures should benefit the construction industry.

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