Ternary Blends for Controlling Cost and Carbon Content

High-volume fly-ash mixtures can be enhanced with additions of limestone powder

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While extensive research has been performed on high-volume fly ash (HVFA) concrete since the mid-1980s,[1] a recent survey showed that fly ash comprises only about 15% of the total cementitious material used in ready mixed concrete in the United States.[2] The survey also indicated that greater use of fly ash is limited by an ongoing dominance of prescriptive specifications over performance specifications, as well as by concerns over early-age performance of HVFA mixtures. A broader shift toward performance specifications will depend largely on cultural changes within the engineering community—changes that may naturally occur with ongoing education, experience, and time. Concerns over early-age performance of HVFA, which are the focus of this article, may be allayed through the development of innovative mixtures.

Early-age performance concerns for HVFA concrete generally focus on delayed setting times and reduced strength gain, particularly in cold weather. Approaches that have been advocated for improving the performance include using chemical admixtures,[3] using a high-early strength cement (Type III per ASTM C150, "Standard Specification for Portland Cement"),[4] and lowering the water-cementitious material ratio (*w/cm*) by increasing the cement content of the mixture.[1,5] An additional approach—including limestone powder in HVFA mixtures—is more sustainable than the latter approach and has been shown to help accelerate early-age reactions,[5-9] decrease setting times,[8,10] and increase early-age strengths.[11]

In Phase I of the study described herein, HVFA mixtures were modified by replacing a portion of the fly ash with a fine limestone powder.[12] While this approach significantly reduced the setting time of the HVFA mixtures comprising either a Class C or a Class F fly ash, early-age strengths still fell short of those of ordinary portland cement (OPC) concrete mixtures. Thus, in Phase II, further modifications to these ternary mixtures were employed, including reducing the *w/cm* and switching from Type I/II to Type III cement (both per ASTM C150). Representative results from both phases are presented.

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Materials and Methods

For Phase I testing, mixtures were prepared using a Type I/II cement (meeting the standard chemical and physical requirements for both Types I and II cement per ASTM C150). The Type I/II cement has a reported Blaine fineness of 373 m^2/kg; a calculated Bogue phase composition of 52.6% C_3S, 16.9% C_2S, 6.9% C_3A, and 10.4% C_4AF by mass; and a reported limestone content of 2.9% by mass. Some of the mixtures in Phase II were prepared using Type III cement (also per ASTM C150). The Type III cement has a reported Blaine fineness of 576 m^2/kg and a calculated Bogue phase composition of 56.2% C_3S, 18.1% C_2S, 6.1% C_3A, and 9.3% C_4AF by mass. The reported oxide composition, density (per ASTM C188, "Standard Test Method for Density of Hydraulic Cement"), and particle size characteristics for both cement types are provided in Table 1.

Fly ashes used in both phases were Class C and Class F per ASTM C618, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete." Their chemical compositions, measured densities, and particle size characteristics are provided in Table 1.

The Class C fly ash has a median particle diameter similar to that of the Type I/II cement, while the Class F fly

Table 1:
Oxide composition and physical characteristics of cements and fly ashes. Values are percent by mass unless noted otherwise

Composition or property	Type I/II cement	Type III cement	Class C Fly ash	Class F Fly ash
SiO_2	19.7	21.1	38.4	59.7
Al_2O_3	4.9	4.3	18.7	30.2
Fe_2O_3	3.4	3.1	5.1	2.8
CaO	62.0	63.4	24.6	0.7
MgO	3.0	2.8	5.1	0.8
SO_3	3.0	3.6	1.4	0.02
Na_2O	0.54 eq.	0.54 eq.	1.7	0.2
K_2O	see Na_2O	see Na_2O	0.6	2.4
Loss on ignition	2.6	0.9	0.3	0.8
Density	3270 ± 10 kg/m^3	3090 ± 10 kg/m^3	2630 kg/m^3	2160 kg/m^3
d10*	2.18 µm	1.17 µm	0.85 µm	3.23 µm
d50*	11.88 µm	7.03 µm	10.30 µm	25.34 µm
d90*	35.81 µm	16.74 µm	69.37 µm	99.06 µm

(Note: 1 kg/m^3 = 0.06 lb/ft^3, 1 µm = 0.00004 in.)

*Based on a particle size distribution determined using a laser diffraction wet method with isopropanol as the solvent. For each material type, the d10, d50, and d90 values are dimensions that exceed 10%, 50%, and 90% of the particle diameters within the sample, respectively.

ash is coarser. Their respective CaO percentages, 24.6% and 0.7% by mass, provide a reasonable representation of the expected extremes in these values for the fly ashes commonly available in the United States. The Class C fly ash is hydraulic. A paste comprising the Class C ash and water will flash-set just a few minutes after mixing, accompanied by the liberation of a significant amount of heat. In past studies, this fly ash has been observed to produce considerable increases in setting times when used with a variety of portland cements.[4,5,8,13]

Based on previous research,[10] a high-purity ultrafine natural calcium carbonate (limestone) powder with a median particle diameter of 0.7 µm (0.00003 in.), 90% finer than 2 µm (0.00008 in.), and 65% finer than 1 µm (0.00004 in.) was used in the ternary blends for both phases. It has a reported density of 2710 kg/m^3 (169 lb/ft^3) and reported $CaCO_3$ and $MgCO_3$ contents of 98% and 1% by mass, respectively.

For all of the concrete mixtures, the coarse aggregate was a siliceous gravel having a 19 mm (3/4 in.) nominal maximum size, a specific gravity of 2.57, and water absorption of 1.8%, while the fine aggregate was natural silica sand having a specific gravity of 2.61, water absorption of 1.1%, and a fineness modulus of 2.82.

The mixture proportions used in Phases I and II are summarized in Table 2. Because of the significant differences among the specific gravities of the four powders, replacing cement and proportioning on a mass basis would produce mixtures with different initial porosities, unit weights, and yields. Thus, to enable the fairest comparison among mixtures and to evaluate the influence of the fine limestone powder additions separately from any changes in initial mixture porosity or volumetric paste content, all of the Phase I concrete mixtures were designed to maintain constant volume fractions of water, powders, coarse aggregate, and fine aggregate based on a plain OPC mixture with 335 kg/m^3 (564 lb/yd^3) of portland cement and a water-cement ratio (*w/c*) by mass of 0.4.

Phase I Mixture 1-PC was prepared using Type I/II cement as the only powder and served as the control for the study. As previously noted, all cement replacements were made on a volumetric basis using the measured specific gravities of the cement, fly ashes, and limestone powder. The designations for the Phase I mixtures indicate the cement replacement levels as a percentage of the total binder volume followed by an F, C, or L for Class F fly ash, Class C fly ash, and limestone powder, respectively.

The dosage of high-range water-reducing admixture (HRWRA) used for each mixture was adjusted to be the minimum that produced at least a 25 mm (1 in.) slump. Different dosages of HRWRA were used in the plain mixture, Class F fly ash mixtures, and Class C fly ash mixtures; but the dosage per unit volume of concrete was kept constant for all of the Phase I mixtures with the same fly ash type. No air-entraining admixture was used in any of the Phase I or Phase II concretes.

The four ternary blends from Phase I (Mixtures 3-30F10L, 5-30C10L, 7-45F15L, and 9-45C15L) were selected for modification in Phase II. In Phase II, the water contents (and thus the *w/cm* and water-powder mass ratio [*w/p*]) were reduced; and, in some cases, the cement type was changed to boost early-age strengths. The dosages of HRWRA were adjusted so that the concrete would have a minimum workability for proper casting. For one mixture (3A-30FL10), HRWRA alone did not provide sufficient workability, so a mid-range water-reducing admixture was also added.

For the two concretes with a 40% cement replacement, the water content was reduced by increasing the sand content so that the content of

Table 2:
Concrete mixture proportions for Phase I and Phase II concretes (Phase II mixtures are highlighted in the darker shaded rows). Cement was ASTM C150 Type I/II unless noted otherwise

Mixture	Cementitious material, kg/m³ (lb/yd³)	Cement, kg/m³ (lb/yd³)	Class F fly ash, kg/m³ (lb/yd³)	Class C fly ash, kg/m³ (lb/yd³)	Limestone 0.7 μm, kg/m³ (lb/yd³)	Coarse aggregate, kg/m³ (lb/yd³)	Fine aggregate, kg/m³ (lb/yd³)	Water content, kg/m³ (lb/yd³)	*w/p**	HRWRA, mL/m³ (fl oz/yd³)	Water reducer, mL/m³ (fl oz/yd³)
1-PC	335 (564)	335 (564)	—	—	—	1040 (1750)	858 (1444)	134 (226)	0.40	1675 (43.3)	—
2-40F	292 (491)	201 (338)	91 (153)	—	—	1040 (1750)	858 (1444)	134 (226)	0.46	836 (21.6)	—
3-30F10L	297 (499)	201 (338)	68 (114)	—	28 (47)	1040 (1750)	858 (1444)	134 (226)	0.45	836 (21.6)	—
3A	297 (499)	201 (338)	68 (114)	—	28 (47)	1040 (1750)	941 (1583)	102 (172)	0.34	3260 (84.2)	870 (22.5)
4-40C	310 (522)	201 (338)	—	109 (183)	—	1040 (1750)	858 (1444)	134 (226)	0.43	653 (16.9)	—
5-30C10L	311 (523)	201 (338)	—	82 (138)	28 (47)	1040 (1750)	858 (1444)	134 (226)	0.43	653 (16.9)	—
5A	311 (523)	201 (338)	—	82 (138)	28 (47)	1040 (1750)	911 (1532)	114 (192)	0.37	1233 (31.8)	—
6-60F	270 (454)	134 (226)	136 (229)	—	—	1040 (1750)	858 (1444)	134 (226)	0.50	836 (21.6)	—
7-45F15L	278 (467)	134 (226)	102 (172)	—	41.6 (70)	1040 (1750)	858 (1444)	134 (226)	0.48	836 (21.6)	—
7A†	347 (583)	168 (282)	127 (214)	—	51.7 (87)	1040 (1750)	858 (1444)	109 (183)	0.31	2527 (65.3)	—
7B†	335 (564)	162 (273)	123 (207)	—	50.2 (84.4)	1040 (1750)	858 (1444)	112 (189)	0.33	2527 (65.3)	—
8-60C	298 (501)	134 (226)	—	163 (275)	—	1040 (1750)	858 (1444)	134 (226)	0.45	653 (16.9)	—
9-45C15L	298 (502)	134 (226)	—	122 (206)	41.6 (70)	1040 (1750)	858 (1444)	134 (226)	0.45	653 (16.9)	—
9A†	373 (627)	168 (282)	—	153 (258)	51.7 (87)	1040 (1750)	858 (1444)	109 (183)	0.29	2054 (53.1)	—
9B†	358 (603)	161 (271)	—	147 (248)	49.9 (84)	1040 (1750)	858 (1444)	114 (191)	0.32	2054 (53.1)	—

*Water-powder ratio (*w/p*) is based on the total mass of the powder (p), including cement, fly ash, and limestone powder

†Prepared with Type III cement

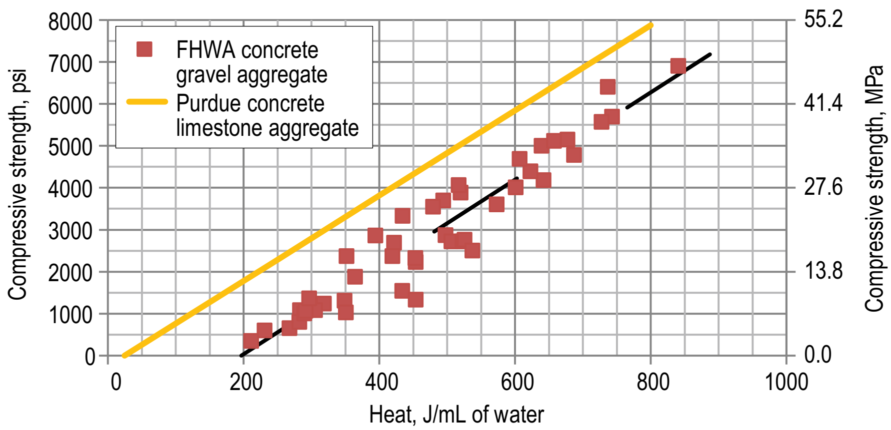

Fig. 1: Measured compressive strength as a function of measured cumulative heat release (per unit volume of water). The strength-heat release relationship (dashed line) is a best-fit line used for adjusting mixture proportions. The relationship labeled as Purdue concrete is based on data from Reference 14

cementitious materials (powders) per unit volume of concrete remained constant, effectively maintaining a true 40% reduction in the amount of cement used per unit volume of concrete. The magnitude of the water reduction was selected to achieve at least a 13.8 MPa (2000 psi) 1-day compressive strength, based on a calibration curve of compressive strength versus cumulative heat release that had been established based on the measured results at each of three ages for the Phase I concretes (refer to Fig. 1).[14] In Fig. 1, the target strength can be used to determine a target cumulative heat release value that in turn is used to compute the necessary change (reduction) in water content to achieve this strength level. For example, if a compressive strength of 13.8 MPa (2000 psi) is desired at 1 day and the current heat release value at 1 day is 300 J/mL, the projected requisite heat release of 400 J/mL can be achieved by decreasing the current water content by 25%.

For the mixtures with 60% cement replacement, strength was boosted by reducing the water content and changing the cement type. Water content was reduced by increasing the powder content in the mixture. The updated powder content for the Phase II mixtures was selected so that at 60% cement replacement (45% fly ash and 15% limestone powder) the new concrete mixture would contain about 50% of the cement per unit volume that was employed in Mixture 1-PC, the control OPC (target) concrete. Also, Type III cement replaced the Type I/II cement used in Phase I mixtures. Phase II Mixture 7A incorporated Class C fly ash and Mixture 9A incorporated Class F fly ash. Early-age compressive strengths significantly exceeded those of the control OPC concrete (Table 3). Because of these very high early-age strengths, Mixtures 7B and 9B were produced with higher *w/p* values (0.33 and 0.32, respectively).

Mixtures were prepared and cast according to ASTM C192/C192M, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," and the setting time was determined according to ASTM C403/C403M, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance," on mortar that was wet-sieved from the concrete according to ASTM C172, "Standard Practice for Sampling Freshly Mixed Concrete." The ASTM C403 test method reports single-operator coefficients of variation for times of initial and final setting of 7.1% and 4.7%, respectively.

Specimens were protected from moisture loss in their molds for the first 24 hours and then demolded and cured in limewater until testing for strength and transport properties at ages typically specified for construction projects. For all concrete mixtures, compressive strength was determined according to ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," using unbonded caps at ages of 1, 3, 7, and 28 days. The transport properties of the mixtures were evaluated at 56 days per AASHTO TP95, "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration" and ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" (commonly called the rapid chloride penetration test [RCPT]). AASHTO TP95 and ASTM C1202 tests were conducted using 100 x 200 mm (4 x 8 in.) cylinders cut to 50 mm (2 in.) lengths for the RCPTs. For the RCPTs, the initial measured current and cumulative charge passed over time were recorded for each test specimen. The AASHTO TP95 surface resistivity values were divided by a geometry correction factor of 1.95[15] to account for the cylindrical specimens (rather than the default geometry for the device: a large plate). Also, as outlined in AASHTO TP95, a factor of 1.1 was applied to the measured resistivity values to account for the limewater curing to represent the value expected from moist-cured cylinders.

Results and Discussion

Figure 2 presents the measured initial and final setting times for all 15 concrete mixtures. As was observed in a previous study,[10,12] both fly ashes Class F and Class C cause initial and final setting delays due to dilution and retardation (for Class C ash). For the Class F fly ash mixtures, the presence of limestone powder accelerated the reactions to the point that both the initial and final setting times of Mixture 3-30F10L were basically equivalent to those of the mixture

Table 3:
Compressive strengths and projected costs for the 15 concrete mixtures. Bold strength values match or exceed 13.8 MPa (2000 psi) at 1 day or corresponding strength values for Mixture 1-PC at later ages (Phase II mixtures are highlighted in the darker shaded rows)

Mixture	Strength, MPa (psi)				Projected cost, $/m³ ($/yd³)	Cost/28-day Strength, $/(m³·MPa), ($/(yd³·ksi))
	1-day	3-day	7-day	28-day		
1-PC	**19.8 (2870)**	**28.8 (4180)**	**35.5 (5150)**	**46.5 (6750)**	70.13 (53.62)	1.51 (7.94)
2-40F	7.4 (1080)	12.9 (1870)	16.3 (2370)	25.7 (3730)	55.81 (42.67)	2.17 (11.43)
3-30F10L	8.5 (1230)	15.4 (2230)	18.7 (2720)	31.6 (4580)	56.99 (43.57)	1.80 (9.51)
3A	**18.6 (2690)**	27.6 (4010)	32.9 (4780)	42.5 (6160)	66.36 (50.74)	1.56 (8.24)
4-40C	7.4 (1080)	16.0 (2320)	19.0 (2760)	27.8 (4030)	56.21 (42.97)	2.02 (10.66)
5-30C10L	9.0 (1310)	18.7 (2720)	24.8 (3600)	37.7 (5470)	57.09 (43.65)	1.52 (7.98)
5A	**16.3 (2370)**	**30.3 (4390)**	**38.4 (5570)**	**48.2 (6990)**	59.21 (45.27)	1.23 (6.47)
6-60F	Not measured	5.5 (800)	7.3 (1060)	11.9 (1730)	49.76 (38.04)	4.17 (21.99)
7-45F15L	4.1 (590)	6.9 (1000)	9.4 (1360)	16.9 (2460)	51.41 (39.31)	3.04 (15.98)
7A*	**25.5 (3690)**	**32.3 (4680)**	**35.3 (5120)**	**45.2 (6560)**	63.35 (48.44)	1.40 (7.38)
7B*	**19.7 (2860)**	24.4 (3550)	28.0 (4070)	38.2 (5550)	$61.14 (46.75)	1.60 (8.42)
8-60C	2.2 (320)	6.7 (970)	9.2 (1330)	12.9 (1870)	50.35 (38.49)	3.91 (20.58)
9-45C15L	4.5 (650)	10.6 (1540)	17.2 (2500)	25.1 (3640)	51.84 (39.63)	2.07 (10.89)
9A*	**26.8 (3880)**	**39.3 (5700)**	**47.6 (6900)**	**61.0 (8840)**	63.31 (48.41)	1.04 (5.48)
9B*	**23.0 (3330)**	**34.5 (5000)**	**44.1 (6400)**	**56.1 (8130)**	61.04 (46.67)	1.09 (5.74)

*Prepared with Type III cement

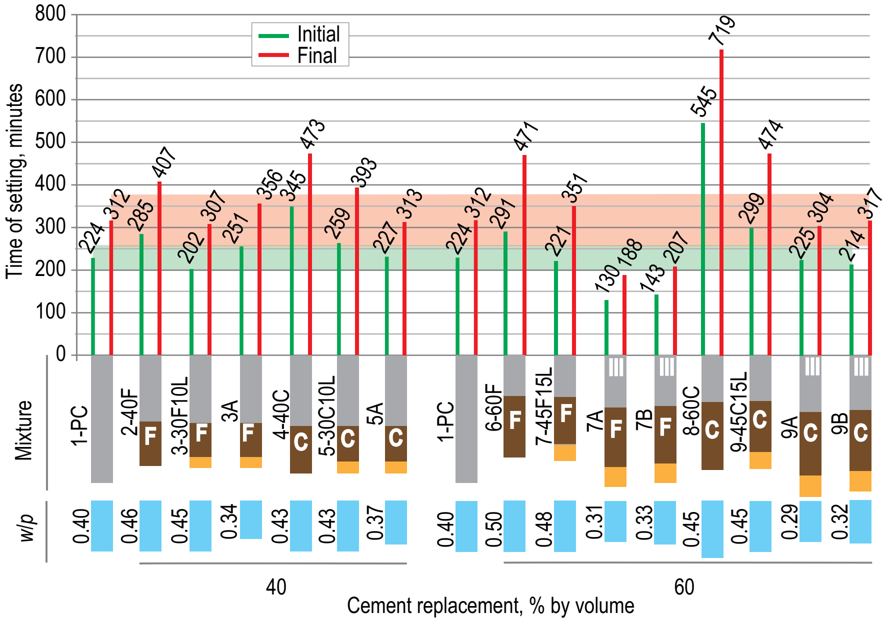

Fig. 2: Initial and final setting times measured on extracted mortar specimens for the 15 concrete mixtures. The green band indicates a time range of ±30 minutes relative to initial setting time for the OPC control (Mixture 1-PC), and the red band indicates a range of ±60 minutes relative to the final setting time for Mixture 1-PC. For reference, the colored bars adjacent to each mixture label indicate relative mass proportions per unit volumn of concrete for powder (gray is cement, brown is fly ash, and orange is limestone) and water (blue). Within the bars, marks "F" and "C" are the class of fly ash and "III" is Type III cement.

containing only cement (1-PC). For the Phase I mixtures with 60% cement replacement, the limestone powder eliminated the initial setting delay and decreased the final setting delay from 159 minutes (Mixture 6-60F) to 39 minutes (Mixture 7-45F15L). Phase II Mixture 3A did not show the expected acceleration of setting time, despite having a reduced water content, due to the adverse effect of the water-reducing admixtures used. Even so, it still presented acceptable initial and final setting times in comparison to Mixture 1-PC. Phase II Mixtures 7A and 7B exhibited excessively high acceleration (their initial setting times were 94 and 81 minutes less than Mixture 1-PC, respectively).

For mixtures with Class C fly ash, limestone powder accelerated the reactions but did not always completely eliminate the setting delays because this Class C ash tends to retard setting considerably. In mixtures with 40% cement replacement, the presence of limestone powder decreased the initial setting delay from 121 minutes (Mixture 4-40C) to 35 minutes (Mixture 5-30C10L) and the final setting delay from 161 minutes (Mixture 4-40C) to 81 minutes (Mixture 5-30C10L). In mixtures with 60% cement replacement, the presence of limestone powder decreased the initial setting delay from 263 minutes (Mixture 8-60C) to 75 minutes (Mixture 9-45C15L) and the final setting delay from 353 minutes (Mixture 8-60C) to 162 minutes (Mixture 9-45C15L). Mixtures 5A, 9A, and 9B had initial and final setting times that were comparable to those of the control (Mixture 1-PC).

The performance of the HVFA mixtures was evaluated on the assumption that equivalent performance criteria for initial and final setting times are those that are within ± 30 minutes and ±60 minutes of the OPC mixture values, respectively (represented by the green and red bands in Fig. 2). Using these criteria, all mixtures containing Class F fly ash and limestone, for both cement replacement levels (excluding Mixtures 7A and 7B), are considered to have equivalent performance. On the other hand, the only mixtures containing Class C fly ash that would be considered acceptable would be Mixtures 5A, 9A, and 9B. For the data from the 15 concrete mixtures shown in Fig. 2, the average ratio between the final and initial setting times is 1.46 (standard deviation of 0.09), in reasonable agreement with the ratio of 1.35 found by Brooks in summarizing data obtained in 10 previous fly ash concrete studies.[16]

Table 3 presents the measured compressive strengths and the projected costs of the mixtures. For compressive strength, the coefficients of variation for three replicate specimens varied from 0.67 to 2.7% for the various mixtures. The values in bold achieved a minimum of 13.8 MPa (2000 psi) 1-day compressive strength or reached 90% of the compressive strength measured for the OPC control mixture at later ages. Projected costs for the mixtures are based on assumed base material costs of: Type I/II cement at $121.25/tonne ($110/ton), Type III cement at $132.28/tonne ($120/ton), coarse or fine aggregate at $13.23/tonne ($12/ton), fly ash at $44.09/tonne ($40/ton), limestone powder at $77.16/tonne ($70/ton), water at $0.55/tonne ($0.50/ton), and any chemical admixtures at $2204.62/tonne ($2000/ton).

In general, mixtures containing Class F fly ash had lower strengths than comparable mixtures containing Class C fly ash. The addition of limestone powder recovered a portion of the loss in compressive strength at all ages but had a larger impact at 28 days than at early ages. The target 1-day compressive strengths of 13.8 MPa (2000 psi) were achieved only by Phase II Mixtures 3A, 5A, 7A, 7B, 9A, and 9B. The impact of limestone powder on the 28-day strength was more pronounced in the Class C fly ash mixtures. When cost per unit strength at 28 days is considered, Mixtures 5A, 7A, 9A, and 9B each offer a better cost benefit than the OPC control mixture, whereas Mixture 3A has a comparable cost benefit.

Figures 3 and 4 present the measured durability-based transport (electrical) properties. The only mixtures that did not perform similarly to or better than Mixture 1-PC were Mixtures 4-40C and 8-60C, with 40 and 60% cement replacement with Class C fly ash and no limestone, and Mixture 6-60F, with 60% cement replacement with Class F fly ash and no limestone.

As shown in Fig. 3, in mixtures with Class F fly ash at both replacement levels, limestone decreased the charge passed to about one half that of Mixture 1-PC. In mixtures with Class C fly ash, limestone powder decreased the charge passed to less than half that of the corresponding mixture containing only cement and Class C fly ash. Contributions to these reductions in charge passed in the systems containing limestone powder may include the acceleration of the cement and fly ash reactions in the presence of fine limestone,[10] differences in the phase assemblage due to the presence of limestone,[11] and reductions in the conductivity of the pore solution in these systems. Even greater reductions were observed for mixtures with reduced water content and Type III cement. Similar improvements were observed for the surface resistivity results (Fig. 4).

It is clear that in addition to restoring setting times, fine limestone substitutions for a portion of the fly ash in an HVFA concrete mixture also offer significant improvements in measured compressive strengths and transport properties. A more detailed analysis of the relationships between the various measured transport (electrical) properties (and strengths) is provided in an Appendix available as part of the online version of this article. While good correlation is observed between the measured RCPT and surface resistivity values, little correlation is observed between

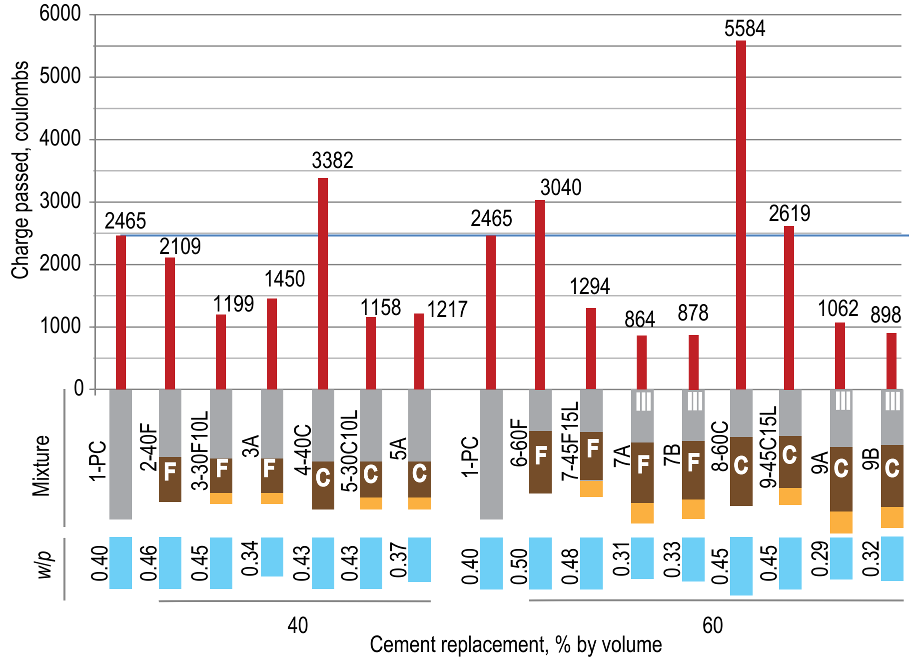

Fig. 3: Measured cumulative charge passed (RCPT) at 56 days for the 15 concrete mixtures. Coefficients of variation for three replicate specimens ranged from 2.1 to 19.1% for the various mixtures. The blue line indicates the charge passed for the control (Mixture 1-PC). For reference, the colored bars adjacent to each mixture label indicate relative mass proportions per unit volumn of concrete for powder (gray is cement, brown is fly ash, and orange is limestone) and water (blue). Within the bars, marks "F" and "C" are the class of fly ash and "III" is Type III cement.

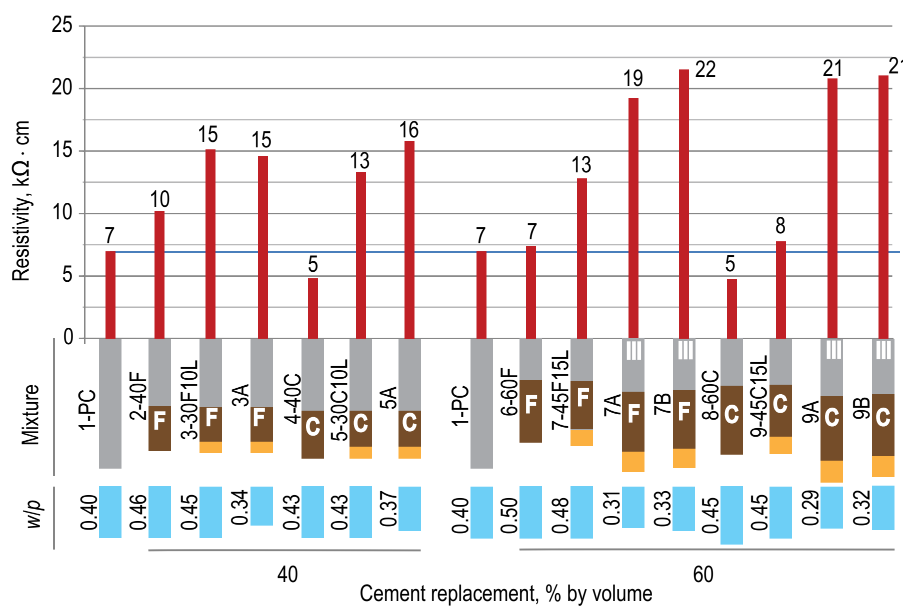

Fig. 4: Measured (geometry corrected) surface resistivity at 56 days for the 15 concrete mixtures. Coefficients of variation for three replicate specimens ranged from 0.6% to 9.9% for the various mixtures. The blue line indicates the resistivity for the control (Mixture 1-PC). For reference, the colored bars adjacent to each mixture label indicate relative mass proportions per unit volumn of concrete for powder (gray is cement, brown is fly ash, and orange is limestone) and water (blue). Within the bars, marks "F" and "C" are the class of fly ash and "III" is Type III cement.

strength and transport properties, as at equal strength levels, the mixtures with fly ash (and limestone) provide improved transport properties in comparison to the control 100% OPC concrete.

Summary

The following points from this study are highlighted:

- HVFA mixtures with 40 to 60% cement replacement can be proportioned to have similar setting times and superior transport properties to OPC concretes by the judicious combination of a fine limestone powder with Class C or Class F fly ash to create a sustainable ternary blend. Some of these mixtures exhibited 28-day compressive strengths that were less than that of the OPC (target) concrete, but they still may be sufficient for many construction applications;
- When equivalence of early-age strengths is required, the HVFA mixtures can be further modified via reductions in water content and/or switching to a Type III cement;
- Water content adjustments can be estimated based on a previously established calibration curve between compressive strength and cumulative heat release, as was demonstrated for the 40% cement replacement HVFA concretes in this study;
- At equivalent strength levels, the RCPT values and the surface resistivities of ternary mixtures can be superior to those measured for conventional OPC concrete;
- HVFA concrete mixtures, in addition to being environmentally friendly, are also an economical alternative to their OPC concrete counterparts. This is true whether materials costs are considered on a per unit volume of concrete ($/m^3 or $/yd^3) or a per unit strength ($/[m^3·MPa] or $/[yd^3·ksi]) basis.

Finally, it should be noted that all of the results presented in the current study were obtained employing ideal curing conditions in limewater; the robustness of these ternary blend concrete mixtures to the variable curing conditions often encountered in the field should therefore be the topic of future research.

Acknowledgments

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Note: Additional information on the ASTM and AASHTO standards discussed in the article can be found at www.astm.org and www.transportation.org, respectively.

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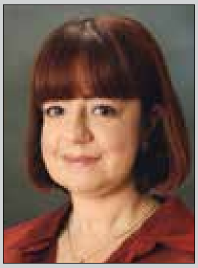

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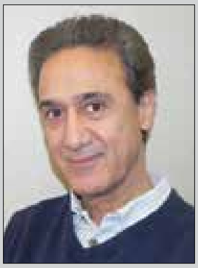

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Appendix: Comparing Measured Transport (Electrical) Properties and Strengths

A further comparison of the measured electrical properties (and strengths) was conducted and representative results are provided in Fig. 5 through 9. Figure 5 illustrates a comparison of the cumulative charge passed in the RCPT and the value that would be predicted for this quantity based on the measured average initial current for each concrete mixture.[17] Fans were employed to cool the RCPT specimens during the 6-hour test, so it is not surprising that, in general, a better agreement between experimental and computed values is observed for the case where no effects of Joule heating are included in converting the initial current to a 6-hour charge passed value by simple integration. The four most conductive specimens (for example, those with charge passed greater than 2500 coulombs) likely still had some specimen heating, as evidenced by their better agreement with the computed values that do include a Joule correction.[18] A high correlation between initial current and cumulative charge passed has also been observed by others.[19, 20]

In Fig. 6, the initial measured current has been used to calculate an initial specimen bulk resistivity to compare directly to the measured (geometry corrected) surface resistivity for each specimen. Once again, a favorable comparison is observed, with most of the data falling near the expected one-to-one relationship, as reported previously for specimen conductivity.[17] It should be noted that the measured surface resistivity values were first multiplied by a factor of 1.1, as recommended in AASHTO T95, "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration," when limewater curing is employed, before being further modified by dividing by the appropriate geometry correction factor of 1.95.

Plots of the RCPT cumulative charge passed as a function of surface resistivity and conductivity are provided in Fig. 7 and 8, respectively. Because charge passed is proportional to conductivity, one would expect an inverse (1/x) relationship when it is plotted against resistivity and this is indeed observed in Fig. 7, with the fitted exponent to the plotted power law relationship being within 7% of its expected value of –1.0. Other research groups[20,22] have provided similar plots to Fig. 7 (without making a geometry factor correction) but did not note the concurrence of their exponents (–1.04 and –1.06, respectively) with this expected value. When these surface resistivity values are converted to their counterpart conductivities, the expected linear relationship between conductivity and charge passed is obtained (Fig. 8). From a practical viewpoint, the resistivity tests were easier and faster to conduct and presented lower variability than the RCPT in this study, the average coefficient of variation of the resistivity tests being 3.9% versus 8.4% for the RCPT, a result in agreement with previous studies.[23]

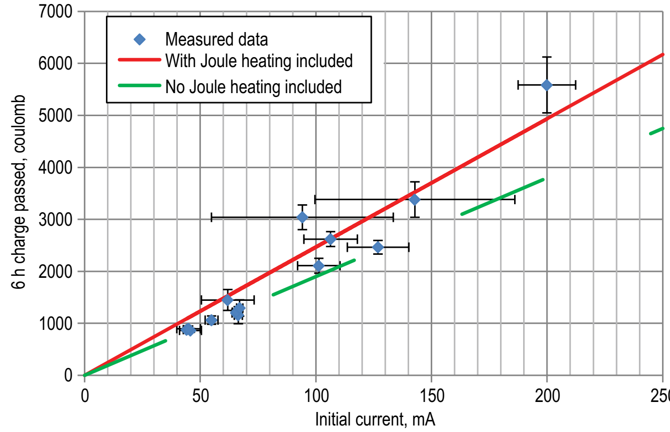

Fig. 5: Measured cumulative charge passed over 6 hours (RCPT) as compared with measured initial current (both at 56 days) for the 15 concrete mixtures. Lines indicate conversion of initial current to cumulative charge passed with (current changes with temperature) and without (constant current) a Joule heating correction.[18] Error bars indicate ± one standard deviation for the measured data

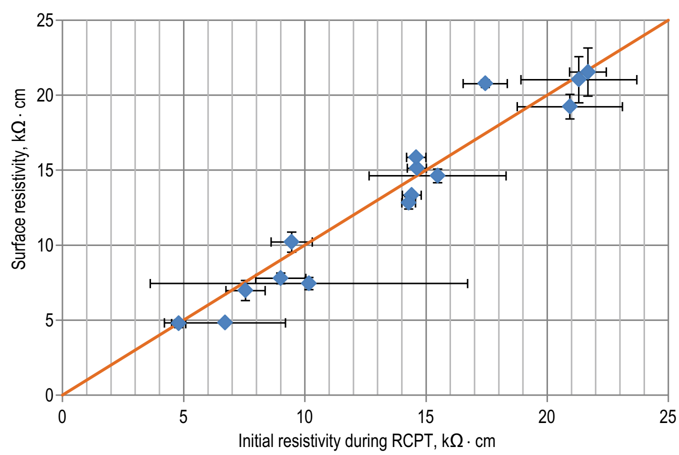

Fig. 6: Measured surface resistivity as compared with resistivity calculated from initial current in the RCPT (both at 56 days) for the 15 concrete mixtures. The diagonal line indicates the expected one-to-one relationship. Error bars indicate ± one standard deviation for the measured data

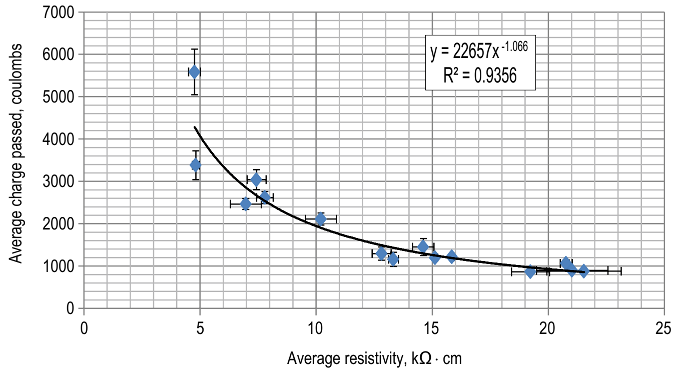

Fig. 7: Average cumulative charge passed (RCPT) as a function of measured average surface resistivity at 56 days for the 15 concrete mixtures. Error bars indicate ± one standard deviation for the measured data

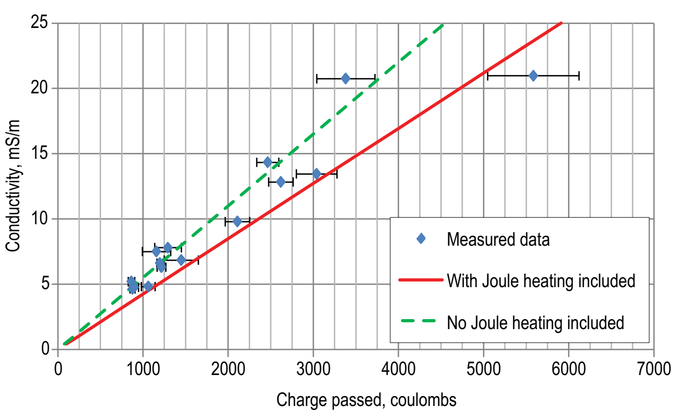

Fig. 8: Calculated specimen conductivity as compared with cumulative charge passed for the 15 concrete mixtures. Diagonal lines indicate model relationships for calculations that are performed with and without the effects of Joule heating of the specimens being included.[21] Error bars indicate ± one standard deviation in measured charge passed

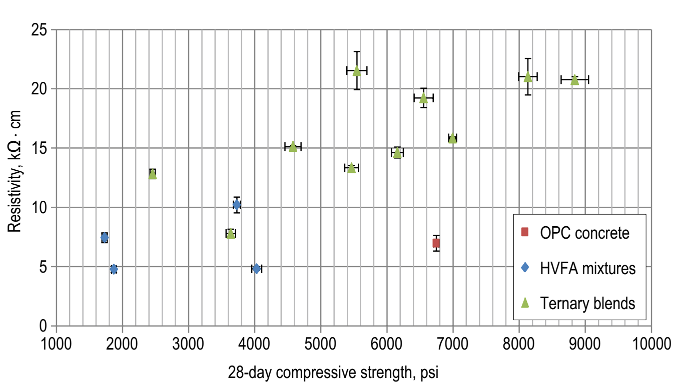

Fig. 9: Surface resistivity (56 day) as a function of 28-day compressive strength for the 15 concrete mixtures. Error bars indicate ± one standard deviation for the measured data (Note: 1000 psi = 6.9 MPa)

Finally, Fig. 9 plots one of the electrical properties (surface resistivity) versus measured compressive strength, to illustrate that there is not an overarching relationship between these two properties, but rather one that depends on the components of the binder. In agreement with general consensus[24] for equivalent strength levels, the concretes with fly ash or with fly ash and fine limestone provide superior transport properties in comparison to the control (target) OPC concrete, as exemplified by their higher resistivity values in Fig. 9. These superior transport properties should produce sustainable concretes with extended service lives in comparison to concretes based solely on portland cement, when both are designed to the same strength requirements.

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Note: Additional information on the AASHTO standard discussed in the article can be found at www.transportation.org.