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Design and performance of ternary blend high-volume fly ash concretes of moderate slump

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HIGHLIGHTS

- HVFA concretes of similar performance to moderate slump OPC concretes were produced.
- Fine limestone powder as a ternary addition improved performance of HVFA mixtures.
- With moist curing, surface and uniaxial resistivities provided comparable results.
- Beyond 1 d, there was no correlation between resistivity and strength.
- Increasing aggregate volume fraction can also increase concrete sustainability.

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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%.

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1. 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 μm [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

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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.

2. 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).

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.

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].

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 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.

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[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.