Cement & Concrete Composites 45 (2014) 102–110

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Fluid transport in high volume fly ash mixtures with and without internal curing

Igor De la Varga [a,*], Robert P. Spragg [b], Carmelo Di Bella [c], Javier Castro [d], Dale P. Bentz [e], Jason Weiss [b]

[a] *SES Group & Associates LCC, Turner-Fairbank Highway Research Center, Federal Highway Administration, 6300 Georgetown Pike, McLean, VA 22101, USA*
[b] *School of Civil Engineering, Purdue University, West Lafayette, IN, USA*
[c] *EMPA – Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland*
[d] *Faculty of Engineering, Universidad del Desarrollo, Santiago, Chile*
[e] *National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA*

ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 27 August 2013
Accepted 15 September 2013
Available online 28 September 2013

Keywords:
Transport properties
High volume fly ash
Internal curing
Chloride
Water absorption

ABSTRACT

The transport of fluid and ions in concrete mixtures is central to many aspects of concrete deterioration. As a result, transport properties are frequently measured as an indication of the durability that a concrete mixture may be expected to have. This paper is the second in a series investigating the performance of high volume fly ash (HVFA) mixtures with low water-to-cementitious ratios (w/cm) that are internally cured. While the first paper focused on strength and shrinkage, this paper presents the evaluation of the transport properties of these mixtures. Specifically, the paper presents results from: rapid chloride migration (RCM), rapid chloride penetration test (RCPT), apparent chloride diffusion coefficient, surface electrical resistivity, and water absorption. The test matrix consisted of mortar samples with two levels of class C fly ash replacement (40% and 60% by volume) with and without internal curing provided with pre-wetted lightweight fine aggregates (LWA). These mixtures are compared to plain ordinary portland cement (OPC) mortars. The results indicate that HVFA mixtures with and without internal curing provide benefits in terms of reduced transport coefficients compared to the OPC mixtures.

1. Introduction

Fly ash is a by-product of coal combustion in power plants that can be used in concrete as a cement replacement [1]. The replacement of cement with fly ash can contribute positively in improving the sustainability of the concrete construction industry in a number of ways: (1) using less cement so that the clinker factor per cubic yard of concrete is reduced, (2) using a waste product (fly ash) that no longer needs to be landfilled, and (3) improving properties affecting the durability of concrete. The amount of fly ash replacement for cement that is typically used in concrete pavements and transportations structures is limited by specifications to approximately 20–25% by mass, due to strength and de-icer scaling concerns [2]. High volume fly ash (HVFA) concrete mixtures where cement replacement is increased to be on the order of 50% or more have demonstrated the potential to perform very well or achieve specific characteristics in a series of studies [3]. For example, the use of HVFA in mass concrete applications can reduce the heat of hydration and resulting thermal effects [4], thereby minimizing early-age cracking.

Concerns with the use of HVFA are related to slow rate of hydration which can result in slow strength gain and extended curing times. To overcome these limitations, the research team has taken an approach that can be used to offset the slow strength development of HVFA mixtures [5]. This approach consists of reducing the water-to-cementitious materials mass ratio (w/cm). However, as the w/cm is reduced, increased autogenous shrinkage is typically observed [6]. In addition, the low w/cm concrete mixtures may become more difficult to water cure, as the curing water can only penetrate a few millimeters due to the much denser microstructure that forms [7]. This issue of self-desiccation in high performance concrete has been discussed by Philleo [8]. Internal curing (IC) has been developed as one potential approach to improve curing and to distribute curing water throughout the concrete's cross section. IC consists of mixing in pre-wetted porous lightweight aggregates (LWA) that act as water reservoirs within the concrete, and subsequently exploiting the mechanism of chemical shrinkage to draw water from the LWA to the paste as needed during hydration, thereby curing the concrete from within [7].

The use of HVFA mixtures with a low w/cm may be expected to improve performance in terms of reduced transport properties (i.e., water and ion penetrability). Transport properties depend on total porosity, pore size distribution, pore connectivity, and pore tortuosity [9]. Internal curing elevates the rate of hydration at later ages,

---

[*] Corresponding author. Tel.: +1 202 493 3433.
E-mail address: igor.delavarga.ctr@dot.gov (I. De la Varga).

0958-9465/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cemconcomp.2013.09.017

which refines the pore structure and reduces the transport of water and ions through the cement matrix at a given age [10]. Bentz [11] suggested that the quality of the interfacial transition zone (ITZ) is another factor to consider in transport performance when comparing mixtures with and without IC, but to a lesser degree than the pore tortuosity of the bulk matrix [12]. It has been shown that IC improves the quality of the ITZ [13,14], which also reduces transport.

This paper presents a series of tests that highlight the transport properties of HVFA mixtures with IC, following up on an initial study that focused on mechanical properties, shrinkage, and early-age cracking [5].

2. Materials and mixture proportions

As previously mentioned, this paper considers an approach to use a HVFA mixture as a potential substitute for a typical concrete mixture design. For example, a conventional pavement mixture design in the state of Indiana would consist of a water-to-cement ratio, $w/c = 0.42$ to achieve specific performance requirements, including early-age strength. To use higher volumes of fly ash, the w/c (w/cm) has to be reduced to compensate for the otherwise low early age strength. As a result, a $w/cm = 0.30$ was used with 40% and 60% replacement by volume of cement with fly ash. The testing matrix consisted of six mixtures. Two plain mortar mixtures were prepared using ordinary portland cement ($w/c = 0.30$; $w/c = 0.42$). Two HVFA mortars were prepared with w/cm of 0.30 with 40% and 60% of the cement replaced with fly ash (by volume). These two HVFA mortar mixtures were also prepared with presoaked LWA for internal curing. The mixture proportions of the mortars are summarized in Table 1. The mixture with a w/c of 0.42 would correspond to a typical mixture design used in transportation structures (e.g., bridge deck). In Table 1, "L" stands for LWA and identifies the internally-cured mortars.

An ordinary portland cement (OPC), ASTM C150-09 Type I/II, was used in this study, with a Blaine fineness of 476 m^2/kg, a density of 3170 $kg/m^3 \pm 10\ kg/m^3$, an estimated Bogue potential phase composition of 52% C_3S, 18% C_2S, 8% C_3A, and 9% C_4AF by mass, and a Na_2O equivalent of 0.5% by mass. A Class C fly ash (ASTM C618-08a) was also used with a density of 2630 $kg/m^3 \pm 10\ kg/m^3$. The fine aggregate used was ordinary river sand with a fineness modulus of 2.71 and an apparent specific gravity of 2.58. Rotary kiln expanded shale (i.e., a lightweight fine aggregate) was used with a fineness modulus of 3.97 and an oven dry specific gravity of 1.38. The lightweight aggregate (LWA) was measured to have a 24 h water absorption of 17.5% by dry mass, when this material was tested using the paper towel technique [15,16]. A polycarboxylate-based high-range water-reducing admixture (HRWRA) was added at variable dosage by mass of cement in order to maintain the same (mini) slump in all mortars [17]. While the fly ash replacement for cement was performed on a volumetric basis, the w/cm of the last five mortars was maintained constant on a mass basis (following current industry practice), implying that these mixtures have variable initial capillary porosities.

In this study, sealed curing conditions were used for many of the mortar specimens, both those with and without IC. These curing conditions were selected as providing the most representative match for the curing that would be experienced by the interior of a concrete member in the field [18]. To proportion the internally cured mixtures a methodology is used that is based on a procedure developed by Bentz, and reported in Bentz et al. [7], in which the amount of LWA is calculated based on the chemical shrinkage occurring in the sample. In this study, a chemical shrinkage value of 6.4% was assumed for all the internally cured mixtures.

3. Test methods

A series of tests were performed to assess the transport properties of the plain, HVFA, and internally cured HVFA mixtures. A total of five different tests methods were used. The tests are divided into 3 main groups. The first set of tests (3.1–3.3) is related with the movement (i.e., diffusion) of chloride ions in concrete. The second test (3.4) describes the electrical properties (e.g., surface resistivity) of the mixtures. Finally, the third test (3.5) describes water absorption (ASTM C1585).

3.1. Rapid chloride migration – NT Build 492

The rapid chloride migration test (RCM) was conducted to determine the non-steady state chloride migration coefficients following the NT Build 492 procedure [19,20]. The RCM test accelerates the chloride transport by applying an electrical potential across the specimen for a specified period of time. The test samples were prepared from cylinders with a diameter of 102 mm [4 in.] and length of 204 mm [8 in.]. The day after casting, the samples were demolded, sealed in double plastic bags and stored at (23 ± 0.5) °C [(73.4 ± 0.8) °F] until the age of testing was reached. The reason for this is that the IC effects are better observed in sealed-cured samples rather than in moist-cured samples. Additionally, as mentioned above, sealed-curing provides the most representative match for the curing that would be experienced by the interior of a concrete member in the field [18]. The cylinders were cut into disks having a length of (51 ± 2) mm [(2 ± 0.08) in.] from the central part of the original cylinder. The samples were vacuum-saturated and placed in a rubber sleeve. The top portion of the sleeve is used to create a reservoir where 0.3 M NaOH is placed in contact with the upper surface of the sample. The bottom of the sample is placed in a solution of 10% NaCl. The test is illustrated in

Table 1
Mixture proportions of the mortars used in this study.

Mortar mixture	0.42–0%	0.30–0%	0.30–40%	0.30–60%	0.30–40%-L	0.30–60%-L
Cement (kg/m^3)	612	731	453	307	453	307
Fly ash (kg/m^3)	–	–	252	384	252	384
Water (kg/m^3)	257	219	211	207	211	207
Water for IC (kg/m^3)	–	–	–	–	38	37
Fine aggregate (SSD) (kg/m^3)	1418	1418	1418	1418	998	1006
Oven dry LWA (kg/m^3)	–	–	–	–	236	232
HRWRA (g/100 g) cementitious material	–	0.5	0.2	0.1	0.2	0.1
Fly ash (%) (by volume)	–	–	40	60	40	60
Water/cementitious material (w/cm)	0.42	0.30	0.30	0.30	0.30	0.30
Equivalent w/c	0.42	0.30	0.47	0.67	0.47	0.67
Volume fraction of aggregate (%)	55	55	55	55	55	55

1 kg/m^3 = 1.69 lb/yd^3.
"L" stands for LWA and identifies the internally-cured mortars.