Construction and Building Materials 47 (2013) 56–65

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Shrinkage of heavyweight magnetite concrete with and without fly ash

Keun-Hyeok Yang [a,*], Jae-Sung Mun [b], Hyun-Ju Shim [c,1]

[a] Department of Plant Architectural Engineering, Kyonggi University, Suwon, Kyonggi-do, Republic of Korea
[b] Department of Architectural Engineering, Kyonggi University, Suwon, Kyonggi-do, Republic of Korea
[c] Department of Architectural Engineering, Chungang University, Seoul, Republic of Korea

HIGHLIGHTS

- This study provides valuable basic data on the shrinkage behaviors of heavyweight magnetite concrete.
- We verify that the shrinkage strain of concrete is related to the equivalent porosity of the aggregates.
- We ascertain the effect of fly ash on the autogenous and drying shrinkage of heavyweight magnetite concrete.
- We also modified the GL 2000 model to reasonably evaluate the shrinkage behavior of heavyweight magnetite concrete.

ARTICLE INFO

Article history:
Received 3 March 2013
Received in revised form 2 May 2013
Accepted 5 May 2013
Available online 29 May 2013

Keywords:
Heavyweight concrete
Shrinkage strain
Time function
Equivalent porosity
Magnetite
Fly ash

ABSTRACT

This study examined the shrinkage behavior of heavyweight magnetite concrete up through the age of one year. The substitution level of conventional sand for magnetite fine aggregate varied from 0% to 100% in increments of 25%, and the substitution level of fly ash for cement varied from 5% up to 35%. Autogenous shrinkage strains were also measured for five different concrete mixes with fly ash and compared with predictions obtained from CEB-FIP equations. Test results showed that the shrinkage strains of heavyweight concrete (HWC) were significantly affected by the pore structure of different aggregates. Based on the experimental observations, the GL 2000 model (including time function and ultimate shrinkage strain) was modified by introducing the parameter of an equivalent porosity of aggregates to reasonably evaluate the shrinkage behavior of HWC. In general, both the CEB-FIP equations and the original GL 2000 model underestimated the shrinkage strains of HWC. This trend became more severe with the increase in ages and equivalent porosities of aggregate. In contrast, the modified GL 2000 model gave significantly more accurate results, regardless of the substitution level of conventional sand.

1. Introduction

Heavyweight concrete (HWC) walls are generally known [1–3] to be useful for structural elements for protecting against radioactive emissions in nuclear power plants, medical units, and other structures where radiation shielding is required. Because the shielding capacity of walls has a direct relationship to the member thickness and density of the concrete, HWC can be a viable option for a particular shielding use where space is limited. For design of an HWC member, it is desirable to consider the predominant factors such as inelastic behavior, thermal conductivity, the coefficient of expansion, and structural properties of the material [4–6]. In particular, the magnitude of the HWC shrinkage strain needs to be quantitatively examined and compared with conventional models [7], including code equations [8,9], for reasonable design of HWC walls, because cracking induced by shrinkage can severely decrease the shielding capacity of HWC. However, most existing studies [1–6] have not provided sufficient information and measurements to understand the shrinkage behavior of HWC.

Although the density and aggregate content of HWC are important components in the radiation protection properties of concrete, the economic burden arising from the careful sorting process and transportation of heavyweight aggregates is also too important to be neglected. The present experimental program used magnetite aggregates to produce HWC because of their high density, widespread availability, and general local acceptability. The type and quantity of aggregates significantly affect the amount of concrete shrinkage because the movement of moisture in the microstructures of pastes is strongly related to the restraining action of the aggregates [10]. Tarr and Farny demonstrated [11] that hard and dense aggregates reduce the shrinkage of concrete. However, Imamoto and Arai [12] showed that there was no distinguishing correlation between the shrinkage strain of concrete and the physical properties (absorption

---

* Corresponding author. Tel.: +82 (0)31 249 9703.
E-mail addresses: yangkh@kyonggi.ac.kr (K.-H. Yang), whenwhere3@hotmail.com (J.-S. Mun), iwandh@daum.net (H.-J. Shim).
[1] Tel.: +82 (0)2 827 0182.

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.05.034

and density) of conventional normalweight aggregates. Thus, the influence of aggregate type on the shrinkage strain of concrete is still controversial, even for ordinary normalweight aggregates. Literature specific to the shrinkage strain of heavyweight magnetite concrete is quite scarce.

Conventional sand and fly ash are frequently recommended as substitutions for heavyweight fine aggregate and cement, respectively, in the mixing design of HWC. These substitutions are effective in preventing segregation by adjusting the grading of the heavyweight aggregates and minimizing temperature crack by reducing the heat of hydration, respectively. The present study prepared 15 heavyweight magnetite concrete mixes with the various substitution levels of conventional sand and fly ash, based on practical mixing conditions. To examine the correlation between the aggregate particle properties and the concrete shrinkage, this study also measured the following properties of the aggregates; absorption, density, grading, pore size distribution, and specific surface area. The shrinkage strains measured in the 15 HWC mixes were analyzed according to an equivalent porosity of the aggregates and used for modifying the GL 2000 model proposed by Gardner and Lockman [13]. For five mixes with fly ash substitutions, autogenous shrinkage strains were measured, analyzed according to the pore size distribution of the pastes and then compared with predictions obtained from CEB-FIP equations [8].

2. Experimental details

2.1. Concrete specimens

Fifteen magnetite-aggregate-containing concrete mixes were prepared with different substitution levels (R_S) of conventional sand for magnetite fine aggregate and substitution levels (R_F) of fly ash for ordinary Portland cement (OPC), as given in Table 1. The mixes were divided into three groups. In groups I and II with water-to-binder ratios (W/B) of 0.35 and 0.55, respectively, R_S varied from 0% to 100% by volume in increments of 25%. In group III with a W/B of 0.45 and an R_S of 0%, R_F varied from 5% up to 35%. In all concrete mixes, the volumetric fine aggregate-to-total aggregate ratio (S/a) and unit water content were fixed at 40% and 180 kg/m^3, respectively. All concrete mixes were designed to have low workability because the initial HWC slump is often recommended to be less than 100 mm [4]. A commercially available, polycarboxylate-based, high-range water-reducing agent was added to the Group I concrete mixes by 0.5% of the cement content.

2.2. Casting, curing and testing

All aggregates were prepared in a saturated surface-dried (SSD) state, dry-mixed with OPC in a mixer pan for 1 min and then wet-mixed for another minute. The slump and air content of fresh concrete were measured in accordance with ASTM C143 [14] and ASTM C231 (pressure method) [14], respectively. After testing the fresh concrete, specimens were cast to measure their compressive strength, modulus of elasticity and shrinkage strains. All specimens were cured at a constant temperature and relative humidity of 21 ± 2 °C and 60 ± 2%, respectively.

The shrinkage strains and autogenous shrinkage strains of concrete were monitored using 100-mm waterproof electrical resistance strain (ERS) gauges installed at the center of specimen molds. The autogenous shrinkage strains of concrete with fly ash were measured using prisms with dimensions of 150 × 150 × 150 mm^3. The prisms were manufactured using a 5-mm-thick acrylic panel, and their inner sides were wrapped with a stiff vinyl to minimize the frictional action between the concrete and the acrylic panel. Immediately after casting of the concrete, the outer layers of the prisms were completely sealed using a caulking material and aluminum tape in order to completely block out moisture migration. The total shrinkage strain of the concrete was also recorded using a 150 × 150 × 550 mm^3 steel prism mold, which was de-molded at an age of one day. The shrinkage strains were recorded up through a sample age of one year. The ERS readings from the specimens were recorded automatically using a data logger. The compressive strength and modulus of elasticity of the concrete were also measured using 100 mm × 200 mm cylinder specimens aged for 28 days. The modulus of elasticity of the concrete was calculated as the slope of the line joining zero stress and 40% peak stress from the measured stress–strain curves. The density of the concrete was also measured in accordance with ASTM C138 [14].

To examine the effect of the type of aggregates on the shrinkage behavior of concrete, various properties of the aggregates were tested, including density, absorption, grading, porosity, and specific surface area. The density and absorption of coarse aggregates were measured in accordance with ASTM C127 [14], and those of fine aggregates followed ASTM C127 [14]. The grading of aggregates was recorded in accordance with ASTM C33[14]. The pore size distribution and specific surface area of the aggregates were determined using an Autopore IV 9500 porosimeter (Micromeritics Instrument Corporation, Norcross, GA) under pressures ranging from 0 to 227 MPa. In addition, the specific surface area for fine aggregates was recorded by BET-based measurement techniques using nitrogen gas.

2.3. Materials

Ordinary Portland cement was used as the main binder for all concrete mixes, and fly ash was added as the mineral admixture for the concrete mixes in group III. The Blaine fineness and specific gravity of OPC were 4020 cm^2/g and 3.15, respectively, while those of fly ash were 3388 cm^2/g and 2.2, respectively. The chemical compositions of OPC and fly ash, which were obtained from X-ray fluorescence (XRF) analysis, are given in Table 2. The fly ash had a low calcium oxide (CaO) concentration but was rich in both silicon and alumina; this indicated that the mass ratio of silicon oxide (SiO_2) to aluminum oxide (Al_2O_3) was 1.91, indicating that the fly ash belongs to class F.

The chemical composition of magnetite was mainly ferric oxide (Fe_2O_3), titanium dioxide (TiO_2), and silicon oxide (SiO_2), as given in Table 3. The magnetite fine aggregates had a slightly lower Fe_2O_3 content compared with magnetite coarse aggregates. The density, specific surface area and fineness modulus of magnetite fine aggregates were higher than those of natural sand, as given in Table 4. In contrast, the water absorption of magnetite aggregates was recorded to be approximately 0.6%, which was lower than that of natural sand. The magnetite fine

Table 1
Details of concrete mix proportions.

Group	Specimen	W/B	R_s (%)	R_F (%)	S/a (%)	R_{sp} (%)	Unit weight (kg/m^3)			Fine aggregates		Magnetite coarse aggregate
							Water	Cement	Fly ash	Sand	Magnetite	
I	S0-35	0.35	0	–	40	0.5	180	514.3	–	–	1025	1689
	S25-35		25							171	740	
	S50-35		50							343	494	
	S75-35		75							514	247	
	S100-35		100							685	–	
II	S0-55	0.55	0	–		–		327.3	–	–	1025	1842
	S25-55		25							187	807	
	S50-55		50							374	538	
	S75-55		75							561	269	
	S100-55		100							747	–	
III	F5-45	0.45	–	5		–		380	20	–	1025	1754
	F15-45			15				340	60			
	F20-45			20				320	80			
	F25-45			25				300	100			
	F35-45			35				260	140			

Note: W/B = water-to-binder ratio, R_s = substitution level of sand for magnetite fine aggregate, R_F = substitution level of fly ash for OPC, S/a = fine aggregate-to-total aggregate ratio by volume, and R_{sp} = water-reducing admixture-to-binder ratio by weight.
In specimen notations, the first letter indicates the substitute material, and the second and third parts give the addition level of the substitute material and the W/B, respectively. For example, S25-35 is a concrete mix with an R_s of 25% and a W/B of 35%; F5-45 is a concrete mix with an R_F of 5% and a W/B of 45%.