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Air-void structure, strength, and permeability of wet-mix shotcrete before and after shotcreting operation: The influences of silica fume and air-entraining agent

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ABSTRACT

It is well known that the air-void structure of hardened concrete has substantial effects on the mechanical properties and durability of concrete. In this study, laboratory evaluations were conducted to quantify the effects of air-entraining agent (AEA) and silica fume on the air-void characteristics of wet-mix shotcrete (WMS) before and after shotcreting process. For this purpose, a high-resolution image analyzer capturing elaborate graphical layouts of air-void structure using the linear transverse method was employed. Also, this study examined the effects of air-void characteristics, such as air content and spacing factor, on the strength and permeability of WMS. Based on the findings of this study, it can be concluded that: (1) shotcreting process considerably reduces overall air contents in WMS; (2) incorporating AEA with a 4.5% silica fume replacement ensures both satisfactory spacing factor and good retention of small entrained air bubbles even after shotcreting, which may improve the freeze-thaw and scaling resistance; (3) the compressive and flexural strengths of WMS were reduced as the air content increased and average spacing factor decreased; and (4) the air content affected the permeability of WMS, but no consistent correlation was found between spacing factor and permeability.

1. Introduction

Hardened concrete contains numerous voids in its hydrated matrices, mostly formed during the mixing, compaction, and hardening process [1]. The voids in hardened concrete can be classified into several types depending on their size, namely gel pores, capillary pores, and air voids as shown in Fig. 1 [2]. Among them, the air voids, in turn, are subdivided into well-dispersed spherical entrained air voids smaller than 1000 μm in diameter and large irregular entrapped air voids larger than 1000 μm in diameter primarily caused by poor compaction and agitation. It is well identified that the air-void characteristics, such as air content, size distribution, spacing (dispersion), and shape of air voids, have substantial effects on the mechanical properties, volume stability, and durability of hardened concrete [3,4]. A previous study [5] found that every 1% increase in air contents decreases compressive strength of concrete by 4–6%. Other studies [6,7] have shown that the pore sizes of cement-based materials affect the moisture-induced volume changes, such as drying shrinkage and swelling, because the liquid held in pores is subjected to a strong pore fluid pressure (or capillary stress) applied on the meniscus at the liquid-vapor interface, and this pressure increases as the pore radius decreases. More importantly, it is reported that ensuring appropriate number, spacing, and distribution of small entrained air bubbles in concrete is a key to handling the durability issues such as freeze-thaw and scaling since the well-entrained air-void system provides empty chambers within the hydrated matrices to relieve the internal hydrostatic pressure driven by the expansion of water on freezing (about 9% expansion in volume) [4,8]. If the air-void system is inadequate, repetitive freeze-thaw cycles and resulting internal hydrostatic pressure will cause high tensile stresses in the void walls, ultimately leading to progressive microcracks and eventual spalling. As a result, deleterious substances including chloride, sulfate, and acid can readily penetrate the hydrated matrices and reinforcement, which will result in various types of concrete deterioration.

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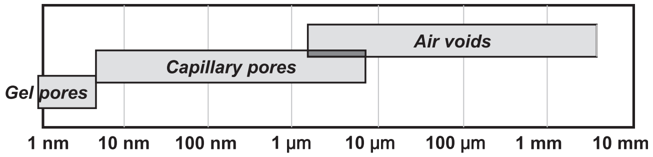

Fig. 1. Categorization of pores in concrete by sizes [2].

Shotcreting is one of the construction techniques spraying fresh concrete or mortar with either a dry- or wet-mix form using a high air pressure feeder; for this reason, it is also often termed “sprayed concrete”. Shotcrete is used for a variety of structural and repair applications including tunnel lining, slope/surface protection, and renovating existing structures [9]. However, it has been reported that wet-mix shotcreting process typically involves a substantial loss of initial air contents [1,10,11], which may compromise the overall durability and performance of shotcrete. Previous research studies [1,12] described that securing 1–1.5% more initial air contents in freshly mixed shotcrete is adequate to compensate the air losses during pumping, but there has been no comprehensive research published directly comparing the actual air-void structure before and after shotcreting from a microscopic perspective. In recognition of the importance of air-void system in hardened concrete, the present study aims at quantitatively evaluating the air-void characteristics of wet-mix shotcrete (WMS), mainly focusing on the effects of air-entraining agent (AEA) and silica fume on the air-void structure before and after shotcreting process. Furthermore, the effects of air-void characteristics, such as air content and spacing factor, on the strength and permeability of WMS are investigated.

2. Experimental program

2.1. Materials and mixture proportions

This study employed Type I ordinary portland cement conforming to ASTM C150, whose fineness and specific gravity are 3200 cm^2/g and 3.15, respectively. The chemical compositions of the cement used are presented in Table 1. The coarse aggregate used was washed crushed rock with a maximum size of 10 mm, a specific gravity of 2.57, and a fineness modulus of 2.66. The fine aggregate included was washed river sand with a specific gravity of 2.65 and a fineness modulus of 5.70. Both coarse and fine aggregates met the gradation specification requirement for ACI 506 as shown in Fig. 2. The silica fume used had a specific surface area of 150,000–300,000 cm^2/g and a specific gravity of 2.22; the SiO_2 content was greater than 97% and the CaO content was less than 1%. The AEA used was a sulfonate silica powder with a bulk density of 1.2 g/cm^3. The superplasticizer included was a polycarboxylate-based polymer powder with a bulk density of 0.37 g/cm^3.

Six different shotcrete mixtures were prepared in accordance with the mixture proportions shown in Table 2. The main experimental variables were replacement of silica fume (0, 4.5, and 9% by mass of the binder) and additions of AEA (0.005% by mass of the binder) and superplasticizer (0.17–0.24% by mass of the binder). For all mixtures, the slump, water-to-binder ratio, and fine aggregate fraction were fixed to 120 ± 30 mm, 0.435, and 0.70, respectively.

Table 1
Chemical compositions and physical properties of cement.

Chemical composition (%)						Fineness (cm^2/g)	Specific gravity
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3		
20.8	6.3	3.2	61.2	3.3	2.3	3200	3.15

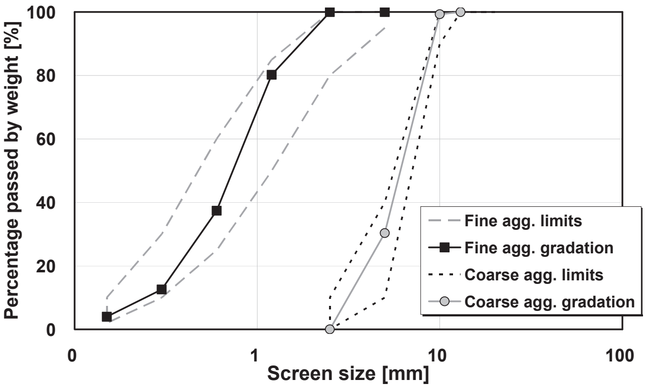

Fig. 2. Aggregate gradation curves and suggested gradation limits in ACI 506.

2.2. Experimental methods

2.2.1. Specimen production

To produce “before-shotcreting” specimens, the materials were mixed in a pan mixer and then cast in molds. For the preparation of “after-shotcreting” specimens, all the materials were mixed in a shotcrete pump equipped with a 280 L mixer and then were spayed into 150 × 150 × 500 mm beam molds inclined approximately 70° from the ground in order to minimize the rebound during shotcrete placement; the diameter of a hose extending from the pump was 51 mm, and the air pressure at pumping was constantly kept at 620–650 kPa. Subsequently, sample coring and cutting were done in order once the specimens were hardened. Three replicate specimens were prepared for each testing program. For microscopic visual examinations, there was no need for chemical surface treatment for the sample preparation, rather the surface of samples was just polished using various sized SiC powders, from No. 60 to No. 600. Finally, the samples were washed with high-pressure water prior to the microscopic visual examinations. More detailed descriptions of the testing method can be found elsewhere [13].

2.2.2. Air-void characterization

The total air contents in fresh WMS were measured using the pressure method specified in KS F 2421 (*Standard test method for air content of fresh concrete by the pressure method*). The air-void characteristics of hardened WMS, such as size distribution, air content, and spacing factor, were graphically examined using an image analyzer (HF-MA C01) as shown in Fig. 3. In this test method, the recognition accuracy was enhanced by performing measurements with software, which is programmed to automatically detect and quantify the air voids based on the linear transverse method specified in ASTM C457 (*Standard test method for microscopical determination of parameters of the air-void system in hardened concrete*). The surface area observed for the image analysis was 58 cm^2 conforming to the requirement specified in ASTM C457 for a nominal maximum aggregate size of 10 mm [2].

2.2.3. Compressive and flexural strengths

The compression test was performed as per KS F 2405 (*Standard test method for compressive strength of concrete*) using 100 mm cube specimens prepared in accordance with KCI-SC101. The flexural strength was measured according to KS F 2408 (*Standard test method for flexural strength of concrete*) using full-scale beam specimens with dimensions of 100 × 100 × 460 mm. The strength