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Tests on high-performance aerated concrete with a lower density

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HIGHLIGHTS

- This study developed high-performance aerated concrete to replace AAC block.
- Valuable data for high-strength aerated concrete with a lower density was provided.
- Prediction models for the various properties of such concrete were proposed.
- The effect of foaming volume rate on the properties of such concrete was ascertained.

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ABSTRACT

The present study tested 16 concrete mixes to develop a high-performance aerated concrete without using high-pressure steam curing processes, as an alternative to autoclaved aerated concrete (AAC) blocks. To achieve high-strength gains, particularly at an early age, for aerated concrete under an air curing environment, the binder and chemical agent were specially contrived as follows: The loss on ignition of ordinary Portland cement was controlled to 1.5% and 3% anhydrous gypsum was then added; and the content of polyethylene glycol alkylether in a polycarboxylate-based water-reducing agent was modified to 28%. Furthermore, a foaming agent based on a protein-hydrolization with enzymatic active components was used to generate independently closed pores during concrete mixing. The test parameters investigated were the foaming volume rate (V_f) of the preformed foam, water-to-binder ratio (W/B), and unit binder content (B). The qualities of the developed high-performance aerated concrete were compared with the minimum requirements specified in ASTM C 1693 for AAC and with data of existing conventional aerated concrete. Prediction models for dry density, compressive strength, stress–strain relationship, and thermal conductivity of aerated concrete were formulated from the regression analyses of the test data. All concrete mixes investigated displayed enhanced workability and defoaming resistance, achieving self-compactability performance. Furthermore, the measured mechanical properties prove that the developed high-performance aerated concrete has considerable potential for practical application when B is approximately 550 kg/m^3 and when W/B ranges between 30% and 25%, at which it fulfils the minimum requirement for class AAC-4 of ASTM C 1693.

1. Introduction

The energy consumption and the resulting CO$_2$ emission during the use of buildings are much greater than those involved in the production of the building materials [1]. It was recently estimated [2] that the energy consumption during the operation of buildings accounts for more than 40% of the total energy consumption of the country, which corresponds to approximately 13% of global CO$_2$ emissions. Considering global CO$_2$ and resource conservation issues, the demands to reduce the energy consumption in buildings have become greater. For example, since 2013, the heat transfer coefficient of exterior walls in residential buildings in South Korea has strengthened from 0.27 W/m^2 K to 0.16 W/m^2 K.

To minimize cooling and heating loads in buildings, autoclaved aerated concrete (AAC) blocks are widely used as a wall material [3]. AAC is primarily characterized as having a high porosity, resulting in a lower density and thermal conductivity compared to normal-weight concrete. ASTM C 1693 [4] classifies the strength class of AAC within the nominal dry density range of 400–800 kg/m^3 (density limit of 350–850 kg/m^3) and compressive strength of

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Nomenclature

B	unit binder content (kg/m^3)
E_c	modulus of elasticity of concrete (MPa)
F	unit pre-formed foam content (kg/m^3)
f_c	concrete stress corresponding to strain ε_c
f'_c	concrete compressive strength at 28 days (MPa)
f_o	reference value for concrete compressive strength (=1 MPa)
V_f	foaming volume rate of pre-formed foam
V_0	reference value for the foaming volume rate (=1000%)
W/B	water-to-binder ratio by weight
W	unit water content (kg/m^3)
W_n	nominal unit weight of the plastic mix of concrete (kg/m^3)
β_1	parameter for the slopes of the ascending and descending branches of stress–strain curves
γ_d	dry density of hardened concrete (kg/m^3)
γ_0	reference value for dry density of hardened concrete (=1000 kg/m^3)
ε_0	strain at the peak stress
$\varepsilon_{0.5}$	strain corresponding to $0.5f'_c$ after the peak stress
λ	thermal conductivity of concrete (W/m K)
λ_0	reference value for thermal conductivity of concrete (=1 W/m K)
ϕ	= pore diameter (nm)

2–6 MPa. This indicates that the compressive strength of AAC is relatively higher with respect to conventional aerated concrete at the same density produced by wet processing. Masonry walls constructed using AAC blocks are able to provide thermal comfort inside buildings without the use of thermal insulation. Drochytka et al. [2] showed that the energy consumption in residential buildings can be reduced by as much as 7% using AAC walls. From a life-cycle perspective, AAC walls can also save approximately 350 kg-CO$_2$/m^2 during the life-span of a building [5]. However, AAC blocks require energy consumption of 340 kWh/m^3 (which corresponds to the emission of 168.3 kg-CO$_2$/m^3) during producing because AAC should be cured under high-pressure steam conditions to form hydrogen gas from the reaction of aluminum powder and calcium hydroxide. In addition, the CO$_2$ inventory of aluminum powder and calcium hydroxide, which are the main components of AAC, are commonly estimated [6] to be 5.15 kg-CO$_2$/kg and 0.517 kg-CO$_2$/kg, respectively. Overall, high CO$_2$ footprints are expected during the production phase of AAC blocks. Structural vulnerability of AAC blocks is also reported occasionally. The open and connected air void system of AAC owing to continuous porosity results in high water absorption, which may deteriorate the thermal insulation capacity in exterior masonry walls. For these reasons, the AAC block industry has gradually declined in South Korea since 2000.

The objective of the present study is to develop high-performance aerated concrete without the high-pressure steam curing process to replace currently constructed AAC blocks. A total of 16 aerated concrete mixes were produced using a cementitious paste and foaming agent to generate air voids entrapped in the matrix. Considering the most influential factors with regard to the strength of aerated concrete [7], foaming volume rate (V_f) of preformed foam, water-to-binder ratio (W/B), and unit binder content (B) were selected as main experimental parameters. To achieve high strength gains, especially at an early age, for aerated concrete under an air curing environment, the binder and chemical agent were specially designed as follows: 3% anhydrous gypsum was added to ordinary Portland cement (OPC), of which the loss on ignition was controlled to be less than 1.5%; and the content of polyethylene glycol alkylether in a polycarboxylate-based water-reducing agent was modified to 28%. The quality and availability of the mixed aerated concrete were examined, wherever possible, through comparisons with the minimum requirements specified in ASTM C 1693 [4] for AAC blocks and existing conventional aerated concrete. In addition, empirical models to predict the various properties of the high-performance aerated concrete, which included dry density, stress–strain curves, and thermal conductivity, were established based on the regression analysis of the test data.

2. Experimental details

2.1. Materials

In general, the compressive strength of aerated concrete produced by wet processing is lower than that of AAC at the same density [7]. To overcome the low strength, a binder was preliminarily investigated [7]. In the preliminary tests, the compressive strength of OPC slightly increased with the decrease in its loss on ignition up to 1.5%, beyond which it was marginally affected by the loss on ignition. Furthermore, when anhydrous gypsum was added from 0% to 5%, the compressive strength of OPC was greatest at 3%. From this preliminary test, OPC with 1.5% loss on ignition was used as the main binder, and then anhydrous gypsum was added at an amount equal to 3% of the total binder weight. The specific gravity and specific surface area of OPC were 3.14 and 4100 cm^2/g, respectively, and those of gypsum were 2.96 and 5000 cm^2/g. The hydration products and microstructural characteristics of the pastes produced using the proposed binder were traced using X-ray diffraction (XRD) and energy-dispersive X-ray (EDX) analyses in combination with scanning electron microscope (SEM) images. XRD patterns of the pastes showed a distinct steeple peak consisting of calcium silicate hydrate ($CaO{\cdot}SiO_2{\cdot}H_2O$, CSH) gel and calcium hydroxide ($Ca(OH)_2$), which can be regarded as a main hydration product, as shown in Fig. 1. The addition of 3% anhydrous gypsum insignificantly affected the intensity of the diffraction peaks, indicating similar peak intensities in both pastes. However, it has been commonly known [8,9] that an appropriate addition of anhydrous gypsum accelerates the hydration of C_3S, which is somewhat contributes to enhancing the strength of cement pastes. The morphology of hydration products was primarily distinguished as coagulated particles for CSH gels and overlapped foils for $Ca(OH)_2$, as shown in Fig. 2. The average values of the main molar ratios, which were obtained from EDX analyses for ten different data points of the distinguished morphology of the hydration products, were also slightly affected by the addition of anhydrous gypsum. The addition of anhydrous gypsum resulted in a lower molar Si/Ca ratio in the CSH gels. This may be attributed to the introduction of Ca^{2+} cations contained in gypsum.

The foaming agent used to produce the preformed foam was manufactured based on a protein-hydrolization with enzymatic active components, which produces no chemical reaction with OPC but serves solely as a wrapping material for the air to be encapsuled in the concrete. Hence, the foaming agent used is favorable to generate independently closed pores during mixing of concrete. To obtain high-strength gains

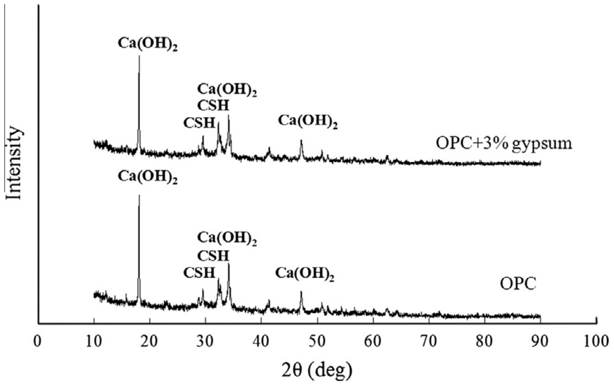

Fig. 1. XRD patterns of pastes according to the addition of anhydrous gypsum.