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Experimental study on strength and durability of lightweight aggregate concrete containing silica fume

Kwang-Soo Youm [a], Jiho Moon [b], Jae-Young Cho [c], Jung J. Kim [d,*]

[a] Infra Structure Team, Technical Division, GS E&C, Grand Seoul, 33 Jong-ro, Jongno-gu, Seoul 110-130, Republic of Korea
[b] New Transportation Research Center, Korea Railroad Research Institute (KRRI), Uiwang-si, Gyeonggi-do, Republic of Korea
[c] Infra & Offshore Team, Technical Division, GS E&C, Grand Seoul, 33 Jong-ro, Jongno-gu, Seoul 110-130, Republic of Korea
[d] Department of Civil Engineering, Kyungnam University, 7Kyungnamdaehak-ro, Masanhappo-gu, Changwon-si 631-701, Republic of Korea

HIGHLIGHTS

- The water absorption ratio of LWAC is proportional to that of the corresponding LWA.
- The frost resistance capacity of LWAC depends on the types of LWA.
- The chloride ion penetration resistance of LWAC depends on silica fume contents.

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ABSTRACT

In this study, the mechanical property and durability performance of high strength lightweight aggregate concrete (LWAC) with silica fume for 91 days were presented. LWACs were designed to have the design compressive strength of 60 MPa at 28 days and the oven-dry density below 1900 kg/m^3. Nine mixtures with three aggregate types and silica fume replacement ratio of 0%, 3.5% and 7.0% by cement weight were prepared. The splitting tensile strength, the compressive strength and the modulus of elasticity tests were conducted at 7 days, 28 days, 56 days and 91 days. The chloride penetration resistance tests were done at 28 days, 56 days and 91 days. The chloride diffusion coefficient based on the measurement of chloride penetration depth was also measured at 7 days, 14 days, 28 days, 56 days and 91 days. The rapid freeze-thaw cycling tests were conducted and the relative dynamic modulus was evaluated up to 300 cycles. The results indicate that the durability against chemical deterioration for LWAC incorporated to silica fume depends on the compositions of hardened cement pastes in concretes, while the durability against physical attack depends on the types of aggregates.

1. Introduction

Due to the relatively low density and high thermal insulating capacity of lightweight aggregate concrete (LWAC) than those of normalweight aggregate concrete (NWAC), the applications of LWAC have been growing and increasing in many fields recently [1–4]. For instance, energy saving houses constructed with LWAC could decrease the heating energy consumption by more than 30% during winter season because of lower thermal conductivity of LWAC than that of NWAC [1]. Since the dead weight of bridge could be reduced, many LWAC bridges with the design compressive strength of concrete as 55 MPa–60 MPa were built in Norway [2]. The high strength LWAC bridge was built with the average measured the compressive strength of 73.5 MPa at 35 days, despite its design strength was 45 MPa at 28 days [3]. LWAC has been found to be well suitable for the floating offshore platform since it helps to avoid an excessive hull displacement [4]. The durability performance of several concrete offshore structures mainly below 40 MPa was investigated after 20 year operation [5,6].

The incorporation of pozzolanic materials in concrete has many beneficial effects to enhance the mechanical properties of concrete. The calcium silicate hydrates in cement matrix of concrete increase by pozzolanic reactions. The fine pozzolanic particles fill spaces between clinker grains, thereby resulting in a denser cement matrix and interfacial transition zone (ITZ) between cement matrix and aggregates; this lowers the permeability and increases the compressive strength of concrete. Seleem et al. [7] investigated the chloride penetration resistance of NWAC and showed that

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* Corresponding author.

E-mail addresses: ksyoum@gsconst.co.kr (K.-S. Youm), jmoon1979@krri.re.kr (J. Moon), jycho02@gsconst.co.kr (J.-Y. Cho), jungkim@kyungnam.ac.kr (J.J. Kim).

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silica fume as a partial replacement of cement is the most effective in preventing chloride ingress among other pozzolanic materials. Leng et al. [8] showed that the chloride ion diffusion coefficient of concrete decreased by replacing cement of pulverized fuel ash. Nonetheless, there was few published study on the durability performance of high strength LWAC over 60 MPa [9]. The possibility of high strength LWAC below 45 MPa was shown by three mixtures of LWAC with the lightweight aggregate of scoria [10]. Liu et al. [11] experimentally evaluated the chloride penetration resistance for normal strength LWAC. Kockal et al. [12] examined the enhancement of LWAC durability with a compressive strength up to 60 MPa using fly ash aggregate through rapid chloride ion penetration test and rapid freeze-thaw test. Furthermore, Youm et al. [13] conducted the long-term experiments to find out the upper limit on LWAC strength or strength ceiling of LWAC with regard to the various types of lightweight aggregates.

Since the floating offshore plant has been emerging as a promising business for the next generation in Korea, many Korean shipbuilding and plant construction companies have drawn much more attention to the merits and feasibility of LWAC as an offshore structural material. Therefore, it is urgently needed to evaluate the mechanical properties of high strength LWAC and investigate the durability performance of it in harsh marine environment. The aim of this research is twofold. One is to evaluate the mechanical properties of high strength LWAC for the design compressive strength of 60 MPa at 28 days and the oven-dry density below 1900 kg/m^3. Two types of lightweight coarse aggregates for high strength LWAC were selected from the previous experimental results [13], where LWAC with the selected lightweight aggregates have recorded the first and second highest compressive strength at 28 days among other five different LWACs. The other aim of this study is to investigate the durability of high strength LWAC with regard to the resistance on chloride ion penetration and freeze-thaw cycling. Silica fume is used as a partial cement replacement material in order to reduce the permeability and increase the resistance on harsh environment.

2. Experimental programs

2.1. Materials

Two types of commercial lightweight coarse aggregates imported from the USA and Belgium were selected for high strength LWAC based on the previous experimental results [13]. Table 1 summarizes scanning electron microscope (SEM) images, 3-Dimensional (D) and 2-D sliced images scanned by 3-D X-ray computed tomography and the physical properties of lightweight aggregates. Crushed expanded clay aggregate, named ‘Argex’, has the particle density of 1130 kg/m^3 and 24 h water absorption ratio of 14%. Crushed slate aggregate, named ‘Stalite’, has the particle density of 1470 kg/m^3 as well as the water absorption ratio of 6%. SEM images as shown in Table 1, ‘Argex’ and ‘Stalite’ have open pores and closed pores respectively. The particle size distributions for ‘Argex’ and ‘Satalite’ provided by manufacturer were presented in Fig. 1. Normalweight coarse aggregate with a specific density of 2.65 was made from crushed granite in Korea. Two kinds of fine aggregate materials were used as follows: one is clearly washed sea-sand with a fineness modulus of 2.3 and the other is crushed fine aggregate to secure a reasonable consistency and minimum segregation. Type I Ordinary Portland Cement (OPC) with a Blaine surface area of 3315 cm^2/g and a specific density of 3.15 manufactured in Korea and silica fume containing about 94% SiO$_2$ with a BET specific surface of 20.3 m^2/g were used in this study. The particle size distribution for silica fume was presented in Fig. 2.

2.2. Mixture design

Nine concrete mixtures with three different coarse aggregates and silica fume contents were designed to obtain the design cylindrical compressive strength of 60 MPa and the oven-dry density below 1900 kg/m^3 at 28 days as summarized in Table 2. The specimens were labeled ‘NN’, ‘St’ and ‘Ag’ according to the types of coarse aggregates of normal weight aggregate, Stalite and Argex respectively. Cement was partially replaced with silica fume of 0%, 3.5% and 7.0% by weight. The partial replacement ratio of silica fume with cement was denoted as ‘0.0’, ‘3.5’ and ‘7.0’; for instance, ‘St-3.0’ represents the Stalite-based LWAC with 3.0% replacement ratio of silica fume. The water-to-binder ratio was determined as 0.281 for NWAC, 0.259 for LWAC with Stalite, and 0.242 for LWAC with Argex. The used cement contents were varying from 539 kg/m^3 to 640 kg/m^3 according to the coarse aggregate types. The high range water-reducing superplasticizer of polycarboxylate was added at constant rate of 1.0% of the binder content weight. The reason why changes water-to-binder ratio and cement contents is to make high strength concrete above 60 MPa considering the characteristics of types of aggregates.

2.3. Mixing and curing

Lightweight aggregates were immersed in water before 24 h of casting. For each mixture, the specimens were cast and cured in water (20 ± 2 °C) until the time of testing after demolding at 24 h. For each mixture, a total of 91–100 × 200 cylinders (diameter × height) was prepared for the compressive strength, the splitting tensile strength, the modulus of elasticity and the chloride ion penetration tests. Six 100 × 100 × 400 mm prisms were prepared for the freeze-thaw cycling tests for each mixture.

2.4. Test methods

2.4.1. Physical and mechanical testing

The slump and air content of fresh concrete were recorded in accordance with American Standard Test Method (ASTM) C143 and ASTM C231 respectively. Wet-density of LWAC was measured in compliance with ASTM C567 at 28 days while oven-dry density was recorded after specimens were dried at 105 ± 5 °C according to BS EN 206-1. The splitting tensile strength and the modulus of elasticity tests were performed at 7 days, 28 days, 56 days and 91 days while the compressive strength was measured at 2 days, 5 days, 7 days, 28 days, 56 days and 91 days to find out the early strength development as per ASTM C469, ASTM C39 and ASTM C469 respectively.

2.4.2. Resistance to chloride penetration testing

Two kinds of chloride penetration tests were implemented to investigate the chloride penetration resistance of LWAC and NWAC. One is rapid chloride ion penetration testing (RCPT) in accordance with ASTM C1202 [14]. This method is widely used and adopted as a standard test in order to measure not just chloride ions but all the ionic movement by determining the total charge passing the specimen, expressed in coulombs. After cutting the specimen with 50 mm thick and 100 mm diameter, the cut slice was installed in the cell containing with 0.3 mol NaOH solution and 3.0% NaCl solution on both sides of the slice. A potential of 60 V is applied for six hours recording of the current at every 30 min. RCPT was done on six specimens for each mixture at the age of 28 days, 56 days and 91 days.

The other is Nordic Standard NT Build 492 [15] to determine the chloride diffusion coefficient based on the measurement of chloride penetration depth. In order to force the chloride ions to migrate into the concrete, an adjusting external electrical potential is applied to the specimens filling in the cathode of 10% NaCl solution and anode of 0.3 mol NaOH respectively. After passing the specified duration, the specimens are cut in half and 0.1 mol AgNO$_3$ solution is sprayed to measure the chloride penetration depth. Finally, the chloride diffusion coefficient can be estimated by Eq. (1).

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left[x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right] \tag{1}$$

where D_{nssm} is the non-steady-state migration coefficient in $\times 10^{-12}$ m^2/s, U is the absolute value of the applied voltage in V, T is the average value of the initial and final temperature in the anolyte solution in °C, L is the thickness of the specimen in mm, x_d is the average value of the penetration depths in mm, and t is the test duration in hour. NT Build 492 test were conducted on six specimens for each mixtures at 7, 14, 28, 56 and 91 days. Considering that the amount of charge passed from the experiments of RCPT is not a physical property of concrete, we try to link it to the diffusion coefficient, which is a physical property of concrete, from the experiments of NT Build 492.

2.4.3. Rapid freeze-thaw cycling testing

It is recommended that the rapid freeze-thaw cycling test in accordance with ASTM C330 [16], which modifies test procedures of ASTM C666 [17], should be more suitable and reasonable in case of LWAC since this method reflects the characteristics of lightweight aggregate and LWAC [18]. The LWAC specimens dried in for another 14 days to a relative humidity of 50% and a temperature of 20 °C prior to the freezing and thawing test after 14 days of water curing according to ASTM C330, while the rapid freeze-thaw experiments on NWAC were performed after 14 days in water prior to testing in compliance with the procedure A of ASTM C666 in which the specimens were periodically frozen and thawed in water at the specified cycle per day. Both testing were decided at six cycles per day up to 300 cycles and the freeze-thaw resistance of specimens was evaluated by the changes in the relative dynamic modulus at every 30 cycles until its values dropped below 60% of the initial value.