Construction and Building Materials 55 (2014) 431–439

Contents lists available at ScienceDirect

Construction and Building Materials

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

An initial trial mixture proportioning procedure for structural lightweight aggregate concrete

Keun-Hyeok Yang [a,*], Gwang-Hee Kim [a,1], Yong-Hwa Choi [b,2]

[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

HIGHLIGHTS

- This study established a straightforward mixture proportioning procedure for LWAC.
- Equations to predict compressive strength and initial slump of LWAC were formulated.
- Replacement of lightweight aggregates on slump and strength of LWAC was ascertained.

ARTICLE INFO

Article history:
Received 23 June 2013
Received in revised form 11 November 2013
Accepted 28 November 2013
Available online 14 February 2014

Keywords:
Lightweight concrete
Mixture proportions
Dry density
Compressive strength
Slump

ABSTRACT

In this study, a straightforward mixture-proportioning procedure for structural lightweight-aggregate concrete (LWAC) was developed to determine the unit content of each ingredient to achieve the target values for slump, compressive strength, dry density, and air content of the concrete. To develop this approach, the design equations to determine the water-to-cement ratio and the unit water content were empirically formulated by performing a regression analysis over 347 data points. These data points were compiled from ordinary Portland cement concrete mixtures with expanded fly ash or clay lightweight aggregates. To determine the volumetric ratio of coarse aggregate per unit weight, a mathematical solution was established under two boundary conditions: the absolute volume and the dry density of concrete. The reliability of the proposed procedure was verified by testing five ready-mixed concrete batches at different replacement levels of lightweight fine aggregates for natural sand. In the concrete batches, expanded clay particles that were manufactured in a rotary kiln were used as the lightweight aggregates. The required values of the target parameters and the experimental values were compared. The results demonstrated that the proposed procedure provided a reasonable guide to obtain the first trial mixture of LWAC that varied with the requirements of the concrete and the properties of lightweight aggregates.

1. Introduction

Structural lightweight-aggregate concrete (LWAC) is commonly defined [1,2] as concrete that is made of lightweight aggregate and conforms to ASTM C 330 [3] and satisfies the requirements of a 28-day compressive strength that exceeds 17 MPa and a dry density of 1120–1920 kg/m^3. Since the 2000s, the practical application of structural LWAC has particularly gained interest because of the global movement toward developing sustainable buildings and infrastructures [4]. A lower thermal conductivity capacity of concrete helps improve the energy consumption efficiency of commercial and residential heating and cooling systems, which subsequently reduces the amount of CO_2 emission from the residential environments [5]. A lower concrete density also allows the structural elements to have smaller and lighter members than the conventional building materials, which reduces the dead load and the seismic effect on building structures. However, difficulties are sometimes encountered in field applications of LWAC during the concrete-production phase because simple mixing formulae or recipes to achieve the designed concrete are not easily available.

Lightweight-aggregate concrete often has a more complicated production process than normal-weight concrete (NWC) because the porous aggregates have excessively high water absorption and low density. Water absorption by the aggregates results in severe slump loss and a rapid setting time for the fresh concrete. The aggregate particles have a lower density than the surrounding

* Corresponding author. Tel.: +82 (0)31 249 9703.
E-mail addresses: yangkh@kgu.ac.kr (K.-H. Yang), ghkim@kgu.ac.kr (G.-H. Kim), cyhwa0724@kgu.ac.kr (Y.-H. Choi).
[1] Tel.: +82 (0)31 249 9757.
[2] Tel.: +82 (0)31 249 1377.

http://dx.doi.org/10.1016/j.conbuildmat.2013.11.108
0950-0618/

Nomenclature

C	unit cement content (kg/m^3)
f_0	reference concrete compressive strength (=10 MPa)
F_L	unit lightweight fine aggregate content (kg/m^3)
F_S	unit normal weight fine aggregate content (kg/m^3)
f'_c	28-day concrete compressive strength (MPa)
f'_{cr}	proportioning strength of concrete (MPa)
G_L	unit lightweight coarse aggregate content (kg/m^3)
R^2	correlation coefficient between the test results and the predictions that are obtained from the equations
R_{LFA}	volumetric replacement level of the lightweight fine aggregates for natural sand
S_0	reference slump of concrete (=300 mm)
S_i	initial slump of fresh concrete (mm)
V_G	volumetric ratio of coarse aggregates per unit weight of aggregate
υ_A	entrained air content per unit volume of fresh concrete
υ_C	volume of cement per unit volume of concrete (m^3/m^3)
υ_{FL}	volume of lightweight fine aggregate per unit volume of concrete (m^3/m^3)
υ_{FS}	volume of natural sand per unit volume of concrete (m^3/m^3)
υ_{GL}	volume of coarse aggregate per unit volume of concrete (m^3/m^3)
υ_W	volume of water per unit volume of concrete (m^3/m^3)
W	unit water content (kg/m^3)
W_0	reference unit water content (=100 kg/m^3)
W_{net}	net water content to account for the moisture content that is added with the aggregates (kg/m^3)
γ_0	reference dry density of concrete (=2300 kg/m^3)
γ_C	apparent density of cement (kg/m^3)
γ_{con}	dry density of concrete (kg/m^3)
γ_{GL}	apparent density of coarse aggregate (kg/m^3)
γ_W	apparent density of water (kg/m^3)
λ_s	sample standard deviation to calculate the required average strength
ρ_{GL}	bulk density of coarse aggregate (kg/m^3)

matrix, which may cause segregation by flowing to the upper surface of the concrete. A change in the density and the aggregate particle grading changes the dry density and the strength of the concrete. Chandra and Berntsson [5] proposed a technique to calculate concrete composition based on the volume and the strength of the mortar in the concrete and the strength of the aggregate particles. However, it is difficult to quantitatively measure the aggregate strength, particularly for artificially manufactured aggregates because some particles may be strong and hard, whereas other particles may be weak and friable. Furthermore, there are few available correlations between the limit strength of LWAC and the volume of lightweight coarse and fine aggregates (the limit strength of LWAC can be graphically obtained from the relationship between the strength development of the concrete and the corresponding mortar) [6.7]. The water absorption and the moisture content of mixed aggregates, including the surface water content, have not been considered when determining the net water content. However, the effect of the free water, which originates from the moisture content of the aggregates, on the workability and compressive strength development are more severe in LWAC than in NWC. ACI 211.2-98 [1] recommends weight and volumetric methods for determining the mixture proportions of structural LWCA. Proportioning using the weight method is based on the amount of contained water and the relative density factor of the individual aggregate sizes in an as-batched moisture condition. The volumetric method requires information on the dry-loose bulk density of the aggregates, the moisture content of the aggregates, the optimum fine-aggregate-to-total-aggregate ratio, and the cement content. To determine these necessary data, the ACI 211.2-98 procedures provide design charts and tables based on experimental results, which were obtained using limited test parameters. Thus, the ACI 211.2-98 procedures sometimes yield an improper mixture proportion, which requires tedious trial-and-error examination [8]. Bogas and Gomes [6] proposed a simple mix design method for structural LWAC. Although their method can be generalized to any type of lightweight aggregate, it is derived from LWAC that is made with natural sand; thus, the method is potentially limited for LWAC with lightweight coarse and fine aggregates. Chen et al.'s method [7] uses a limit strength concept, which produces some difficulties because of a flawed assumption that beyond the limit strength, the concrete strength varies linearly with the mortar strength.

The objective of this study is to establish a first trial mixture proportioning procedure for structural LWAC. This procedure can easily determine the content of each ingredient per unit volume of concrete to achieve the target slump, the target 28-day compressive strength, the target dry density and the target air content. To examine the effect of various parameters on the requirements and to formulate the design equations, a comprehensive database with 347 LWAC specimens [8] was analyzed using a non-linear multiple-regression (NLMR) analysis method. The reliability of the proposed procedure was verified by testing five ready-mixed concrete batches using different replacement levels of lightweight fine aggregates for natural sand. Three examples of the proposed procedure are described in Appendix A for an easy practical approach.

2. Database of LWAC

To examine the production of structural LWAC under various mixture proportions and 28-day compressive strengths, comprehensive datasets were compiled from the available literature [8]. Most reports do not provide complete information on the mixture proportions, the physical properties of lightweight aggregates, and the corresponding test results. To analyze the mixture proportions of concrete that were compiled from different sources, the absolute volume method was employed, where the volume of fresh concrete is assumed equal to the sum of the absolute volumes of each ingredient: cement, fine and coarse aggregates, water, and entrained air. Although the information provided in the literature was somewhat limited, the distribution of various parameters in the database can be summarized as follows (see Fig. 1).

The used aggregates are combinations of either lightweight coarse and fine materials (all-lightweight) or lightweight coarse material and natural normal-weight sand (sand-lightweight). The database included 39 all-lightweight concrete mixes and 308 sand-lightweight concrete mixes. The expanded fly ash or clay particles were mainly used for the lightweight aggregates. The dry densities of the lightweight coarse and fine aggregates are 1000–1600 kg/m^3 and 1000–1850 kg/m^3, respectively. The water absorption values of both lightweight coarse and fine aggregates are between 5% and 28%. The maximum size of the used coarse aggregates is usually 19 or 25 mm, which results in a fineness modulus between 6.2 and 7.28. The 28-day compressive strength (f'_c) is 11–40 MPa for the all-LWAC and 15–57 MPa for the sand-LWAC. Forty-six datasets for high-strength above 40 MPa are included in the sand-LWAC. The dry density (γ_{con}) of the