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Internal relative humidity and drying shrinkage of hardening concrete containing lightweight and normal-weight coarse aggregates: A comparative experimental study and modeling

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HIGHLIGHTS

- The IRH and drying shrinkage of lightweight and normal-weight concrete are measured.
- The internal curing effect of lightweight aggregates reduces IRH drop in concrete.
- Drying shrinkage should be evaluated in terms of average IRH drop.
- A model of the shrinkage coefficient is proposed.
- Ultimate shrinkage is inversely proportional to the compressive strength of concrete.

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ABSTRACT

The effect of lightweight and normal-weight coarse aggregates on the internal relative humidity (IRH) and drying shrinkage of hardening concrete was investigated experimentally. The compressive strength, elastic modulus, IRH, and drying shrinkage of concrete specimens were measured. Lightweight and normal-weight concretes exhibited different variations in IRH and drying shrinkage. The results suggest that drying shrinkage should be evaluated in terms of average IRH drop at equivalent age, considering the development of elastic modulus for lightweight and normal-weight hardening concretes. The model of the shrinkage coefficient can be useful for evaluating the drying shrinkage of lightweight and normal-weight hardening concretes.

1. Introduction

Drying shrinkage represents the volume reduction of concrete when exposed to a dry environment. It is primarily caused by moisture loss from capillary pores in hydrated cement paste in concrete. The hardened elements, including coarse aggregates, in concrete play a role in restraining the drying shrinkage of cement paste [1]. Therefore, as the elastic modulus of concrete increases, its drying shrinkage decreases owing to increase in the restraining action of hardened materials [1]. Existing models [2,3] predict the average drying shrinkage in a cross section of concrete, in which the effects of environmental conditions are included in terms of air relative humidity (RH) and volume-to-surface ratio of concrete. In addition, the restraining effect related to the elastic modulus of hardened materials is considered in the models by including the compressive strength of concrete. Such models can be effectively used for estimating the average drying shrinkage of normal-weight concrete, in which the amount of water absorbed in coarse aggregates is negligible.

Owing to the large water absorption capacity of lightweight aggregates, pre-wetted lightweight aggregates have been efficiently used for reducing the self-desiccation and autogenous shrinkage of concrete, particularly in high-performance/strength concrete with a low water-to-binder ratio [4,5]. Water loss in the hydrated cement paste can be effectively compensated by providing the additional water absorbed in lightweight aggregates for the paste, i.e., the internal curing effect [4,5], which can help cementitious binders remain hydrated. Existing studies suggest that pre-wetted

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lightweight aggregates can be effectively used as internal curing agents, especially for high-performance/strength concrete.

A field survey [6] indicated that concrete pavements that use lightweight coarse aggregates performed better than pavements that use normal-weight coarse aggregates. The difference in the long-term performance of concrete pavements is considered to be because of the difference between the drying shrinkage of lightweight concrete and normal-weight concrete. In particular, it was reported that less drying shrinkage of lightweight concrete contributed to improvement in the long-term performance of concrete pavements [6,7].

Two conflicting factors affect the magnitude of the drying shrinkage of lightweight and normal-weight concretes in the hardening stage where properties of concrete significantly changes over time, particularly in relatively early ages. The first is the difference between the additional water absorbed in coarse aggregates. As the absorption capacity of lightweight coarse aggregates is considerably higher than that of normal-weight coarse aggregates, additional water may reduce drying of hydrated cement paste, which results in decrease in the drying shrinkage of lightweight concrete [8]. The second is the elastic modulus of coarse aggregates. As the elastic modulus of lightweight aggregates is typically smaller than that of normal-weight aggregates, increase in drying shrinkage is expected in lightweight concrete owing to reduction in the restraining effect of aggregates [1].

Owing to the abovementioned conflicting factors, existing studies provide different results in terms of the type of concrete with less drying shrinkage. Compared to normal-weight concrete, lightweight concrete exhibits less drying shrinkage in [9–11], whereas it exhibits more drying shrinkage in [12–14]. This is because the variations in moisture content and the corresponding drying shrinkage of lightweight concrete over time are considerably different from those of normal-weight concrete, particularly in hardening stages [11]. As drying shrinkage essentially results from moisture loss in concrete, which varies significantly with the type of coarse aggregates with different water absorption capacities, it is considered more logical to evaluate drying shrinkage in terms of moisture loss rather than express variation in shrinkage over time when comparing the shrinkage of lightweight and normal-weight hardening concretes.

The purpose of this study is to quantitatively evaluate the effect of the moisture content and elastic modulus of coarse aggregates on the development of the drying shrinkage of hardening concrete. To this end, the internal relative humidity (IRH) and drying shrinkage of lightweight concrete were compared with those of normal-weight concrete. Concrete prism specimens that incorporated normal-weight and lightweight coarse aggregates were prepared. Variations in IRH and drying shrinkage over time were measured in addition to compressive strength and elastic modulus. The shrinkage coefficient was modeled in terms of the inverse of the fractional change in elastic modulus and ultimate shrinkage. By estimating the shrinkage coefficient from the relationship between the measured average IRH and drying shrinkage, the drying shrinkage of lightweight concrete was quantitatively evaluated in terms of average IRH drop and compared with that of normal-weight concrete.

2. Experiments

2.1. Materials and mixture proportions

To investigate the effect of the moisture content and elastic modulus of coarse aggregates on the drying shrinkage of hardening concrete, concrete specimens that included different types of coarse aggregates were fabricated. Table 1 shows the mixture proportions of the specimens used in the test. All material components, except coarse aggregates, were identical in all specimens. All specimens used type I Portland cement, satisfying ASTM C150. The water-to-cement ratio was set to be 0.5 to minimize the self-desiccation and autogenous shrinkage of the specimens [12]. Siliceous river gravel (SRG) and crushed limestone (CLS) were used as normal-weight coarse aggregates in the SRG and CLS specimens, respectively. Lightweight expanded shale and clay (ESC) aggregates were used in the ESC specimen. Blended coarse aggregates consisting of SRG and ESC aggregates were used in the BLD specimen. The unit weight of oven dry coarse aggregates is shown in Table 1. Most of ESC aggregates was in the range of 5–10 mm in size. All coarse aggregates used in the specimens were sieved to minimize the difference in their gradation. The aggregate particles that passed through a 9.5-mm sieve and were retained on a 6.4-mm sieve were used in the test.

Fig. 1 shows the variation in water absorption caused by immersion of lightweight coarse aggregates in the ESC specimen, as a function of time. The absorption of the aggregate was determined in accordance with ASTM C127. As soon as the aggregates are immersed in water, water absorption increases rapidly. Then, it gradually increases with time. The absorption of water by lightweight aggregates was 20.5% at 11 d. The test results indicate that lightweight aggregates can absorb a large amount of water, whereas normal-weight aggregates, such as SRG and CLS, absorb a small amount of water, as shown in Table 1.

2.2. Specimens and test methods

To compare the IRH and drying shrinkage of concrete containing lightweight and normal-weight coarse aggregates, two different types of specimens, one for measuring IRH and the other for measuring drying shrinkage, were fabricated using the same mixture as that shown in Table 1. Fig. 2(a) shows RH sensors installed in a $50.8 \times 50.8 \times 304.8$ mm prism mold. A capacitive-type RH sensor, SHT75, was used in the test to measure the IRH of concrete. The accuracy of RH of SHT75 is ±1.8% for $10\% < \text{RH} < 90\%$ and ±4% for other RH ranges. Existing studies [15,16] suggest that SHT75 can accurately measure the IRH of concrete. Seven SHT75 s, which were protected using tubes with Gore-Tex capped ends, were symmetrically installed at different distances, i.e., 3.2 mm, 6.4 mm, 12.7 mm, and 25.4 mm, from the side of the prism mold to measure the IRH distribution in a cross section of the specimens. Fig. 2(b) shows the vibrating wire strain gage (VWSG) installed at the center of the prism mold to measure the drying shrinkage of concrete. Each mixture had three companion IRH specimens and three drying shrinkage specimens. The values of IRH and drying shrinkage shown hereinafter are the averages of the values for the three companion specimens.

The specimens were fabricated in accordance with ASTM C192 using the mixture proportions shown in Table 1. By immersing lightweight coarse aggregates in water for 11 d prior to mixing materials, the amount of water absorbed in lightweight aggregates was controlled to reach the desired level of 20.5%. In addition, normal-weight coarse aggregates were immersed in water in advance for the same period as that for lightweight aggregates. Fresh mixtures were cast into prism molds. The top surfaces of the specimens were sealed with plastic wrap, and the specimens were cured under the standard curing condition at 23 ± 1 °C for 1 d. Wood formwork was removed from concrete casting at 1 d, and the specimens were placed in an environmental room at constant temperature and RH (21.5 ± 0.5 °C and 50%). To impose a symmetric drying condition on the specimens, only two side surfaces of the specimens were exposed to dry environmental conditions, and all other surfaces were sealed with aluminum foil tape. According to previous studies [15,16], the symmetric drying