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Communication

Protected paste volume in concrete
Extension to internal curing using saturated lightweight fine aggregate

D.P. Bentz*, K.A. Snyder

Building and Fire Research Laboratory, National Institute of Standards and Technology, 100 Bureau Drive Stop 8621, Gaithersburg, MD 20899-8621, USA

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Abstract

One difficulty in the field use of high-performance concrete is the extensive self-desiccation and autogenous shrinkage that may occur due to its low water/cement ratio and the addition of silica fume to the mixture proportions. Several researchers have proposed the use of saturated lightweight aggregates to provide "internal" curing for the concrete. In this communication, simple equations are developed to estimate the replacement level needed to ensure adequate water for complete curing of the concrete. Additionally, a three-dimensional concrete microstructural model is applied to determine the fraction of the cement paste within a given distance from the lightweight aggregate surfaces. The simulation results are compared with analytical approximations developed previously. This new concept for curing is similar to the protected paste volume concept conventionally applied to characterizing air void systems in air-entrained concrete.

Keywords: Aggregate; Concrete; Curing; Mixture proportioning

1. Introduction

As high-performance concrete (HPC) has moved from the laboratory to field use, one problem sometimes encountered is its propensity for undergoing extensive self-desiccation and autogenous shrinkage [1]. Due to the chemical shrinkage that occurs as the cement hydrates, empty pores are created within the cement paste, leading to a reduction in its internal relative humidity and a measurable shrinkage that may cause early-age cracking. This situation is intensified in HPC (relative to conventional concrete) due to its generally higher cement content, reduced water/cement (w/c) ratio, and the pozzolanic mineral admixtures incorporated, such as silica fume. The empty pores created during self-desiccation not only induce shrinkage stresses but also influence the kinetics of the hydration process, limiting the final degree of hydration, and thus strength, that can be achieved relative to that obtainable under saturated curing conditions [1].

This "curing" problem was recognized nearly 10 years ago by Philleo [2], who suggested incorporating saturated lightweight fine aggregate (LWFA) into the concrete mixture to provide an internal source of water necessary to replace that consumed by chemical shrinkage during hydration (curing). As the cement hydrates, this extra water will be drawn from the relatively "large" pores in the LWFA into the much smaller ones in the cement paste. This will minimize the development of autogenous shrinkage since the shrinkage stress is controlled by the size of the empty pores, via the Kelvin-Laplace equation [1]. Unfortunately, little was done to follow up on Philleo's idea until the mid-1990s when Weber and Reinhardt [3] once again proposed the use of saturated lightweight aggregates to support the curing of concrete. In their experimental program, replacing a portion of the fine aggregates by their saturated LWFA counterparts resulted in concretes that were "considerably less sensitive to the curing process" [3]. More recently, Bentur and his colleagues [4,5] have prepared high-strength concretes with a mixture of LWFAs and normal-weight aggregates and observed that the initial autogenous shrinkage measured for HPC can be eliminated by the judicious replacement of a portion of the fine aggregates with either saturated or air-dried LWFA. In this communication, equations are derived to estimate the replacement level necessary to avoid autogenous shrinkage as a function of mixture proportions. Additionally, a three-dimensional concrete microstructural model is applied to determine for various replacement levels and aggregate gradations the fraction of the hydrating cement paste within a given distance of

* Corresponding author. Tel.: 301-975-5865; fax: 301-990-6891.
E-mail address: dale.bentz@nist.gov (D.P. Bentz)

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the LWFA surfaces. We focus on replacement of the fine aggregate component as opposed to the coarse, due to both strength considerations and the fact that the much higher surface area of the fine relative to the coarse aggregate will result in a more uniform distribution of this additional curing water within the three-dimensional concrete microstructure. The results of the three-dimensional microstructural model are compared with an approximation based on the equations developed previously by Lu and Torquato [6] for the generic hard core/soft shell microstructural model. This paper only considers the availability and spatial proximity of the additional water introduced via the LWFA and does not address the processing (rheology) issues that may need to be addressed to offset the effects of the generally rougher surfaces of the LWFA on the flow properties of the concrete.

2. Modeling approach

In this section, we first derive an equation for determining the replacement level needed to ensure adequate water for "complete" curing of the concrete. In this case, complete curing means that the cement reaches the maximum degree of hydration that is possible, given the space limitations for forming hydration products in low w/c ratio systems. Then, we proceed to briefly describe the microstructural model of concrete that will be used to determine the relative proximity of the paste to the water sources (the LWFA surfaces).

The volume of water per cubic meter of concrete needed to be supplied by the LWFA depends on the mixture proportions of the concrete in the following manner. Let CS denote the chemical shrinkage occurring during the hydration of the cement; typically, this value is on the order of 0.06 kg H_2O per kg cement hydrated [7,8]. The amount of water necessary will depend on this quantity, as well as the cement content, C_f in kg cement/m^3 concrete, and the w/c ratio for the mixture proportions. For w/c ratios below 0.40 (typical of an HPC), complete hydration cannot be achieved and the maximum degree of hydration, α_{max}, can be estimated as (w/c)/0.40. Then, the volume of water, V_{wat}, that is "consumed" during hydration due to chemical shrinkage is given by Eq. (1):

$$V_{wat}(\mathrm{m^3\ water/m^3\ concrete}) = \frac{C_f \cdot \mathrm{CS} \cdot \alpha_{max}}{\rho} \qquad (1)$$

where ρ is the density of water (1000 kg/m^3). Denoting the porosity of the LWFA by ϕ_{LWFA} and its saturation (0–1) by S, the total volume fraction of LWFA necessary, V_{LWFA}, is given by Eq. (2):

$$V_{LWFA} = \frac{V_{wat}}{S \cdot \phi_{LWFA}} \qquad (2)$$

The ratio of this quantity to the volume fraction of fine aggregate in the original mixture proportions is the required fractional replacement by LWFA. This equation assumes that all of the water in the LWFA will be readily accessible to the surrounding cement paste, a topic addressed in more detail below.

For example, consider a typical HPC mixture with the following characteristics: cement content of 500 kg/m^3, w/c = 0.3, and fine aggregate volume fraction of 0.30. For w/c = 0.3, the maximum potential degree of hydration is 0.75. Substituting all the appropriate values into Eq. (1), 0.0225 m^3 water/m^3 concrete are needed to ensure that the capillary porosity in the cement paste is water-filled at the maximum degree of hydration. Assuming a porosity of the LWFA of 0.15 and complete saturation (S = 1.0), one calculates V_{LWFA} to be 0.15, so that 50% of the fine aggregate (on a volume basis) needs to be replaced by saturated LWFA.

In addition to providing the necessary volume of water, a further issue to be addressed is the proximity of the cement paste to the surfaces of the LWFA. Conceptually, this is similar to the "protected paste volume concept" for air-entrained concrete [9–11], where one is interested in the volume of cement paste within a given distance of an air void surface. For our purposes, this question can be addressed using a previously developed three-dimensional continuum microstructural model of concrete [12]. In this model, the aggregates are represented by impenetrable spherical or ellipsoidal particles and each aggregate particle is surrounded by a soft penetrable shell representing the interfacial transition zone. For the current study, we are not specifically interested in the interfacial transition zones, but instead adapt the code to surround only the saturated LWFA particles with a shell of variable thickness. Then, by systematic point sampling [12], we can determine the volume fraction of paste contained within these shells and hence the relative proximity of the cement paste to the additional water sources.

It should also be noted that analytical equations exist [6,13,14] for estimating these paste volume fractions directly from the aggregate particle size distribution. The complete equations for doing this have been provided elsewhere [13], based on the original development of Lu and Torquato [6]. Application of these equations to the case of partial replacement of the fine aggregate by LWFA considers only two components of the system: the cement paste with volume fraction V_{paste} and the saturated LWFA. Therefore, we correct the LWFA volume fraction used in the analytical equations by dividing it by the sum ($V_{LWFA} + V_{paste}$), thereby keeping the ratio V_{LWFA}/V_{paste} the same for both the measured system and the analytical calculation. These equations will thus only provide approximate values of the cement paste fraction within a given distance of a LWFA surface, as they effectively ignore the probability that a point within a given distance from the aggregate surface could lie within a normal weight aggregate, as well as within the cement paste. This approximation will worsen as more of the normal weight aggregates are of the same size as the LWFA. Here, the accuracy of this approximation will be evaluated quantitatively for the two systems (described below) considered in this study.

In this preliminary study, two aggregate gradations were investigated based on the limits of the ASTM C 33 [15] aggregate specification. In both cases, the coarse aggregate particle size distribution (PSD) followed the coarse limit curve for a nominal size range of 12.5 to 4.75 mm (maximum aggregate size of 19.0 mm) and a coarse-to-fine aggregate volume ratio of 1.5:1 was assumed. For the first study, the fine aggregate PSD followed the coarse limit of the ASTM C 33 specification and a volume fraction of aggregate (V_{agg}) of 0.75 was used. In the second case, the fine limit of the ASTM C 33 fine aggregate specification was used. In the latter case, because of the higher surface area of the aggregate (nearly twice that of the first case), the volume fraction of aggregate was reduced to 70%. Because of the fineness of the aggregate, over one million aggregate particles were needed to simulate a three-dimensional model concrete, 30 mm on a side (27,000 mm^3 in volume). In both cases, replacement of 25, 50, and 100% of the normal weight fine aggregate by its saturated LWFA counterpart on a volume basis was simulated by randomly assigning the desired proportion of the fine aggregate to be lightweight during the aggregate placement process. The fraction of the cement paste within a given distance of the LWFA surfaces was then determined for the two distributions for each of the following distances: (10, 20, 30, 40, 80, 100, 150, and 200) μm. As the capillary pore space in the cement paste depercolates during curing, the water transport will be effectively limited to distances on the order of 100 to 200 μm [8,16].

3. Results and discussion

Fig. 1 illustrates two-dimensional slices from the three-dimensional concrete microstructural model for the coarse and fine limits of the fine aggregate particle size distribution. In these images, one can clearly see that the system containing smaller aggregates contains much more paste (light gray) within 100 μm of a LWFA surface. In fact, the surface area of the LWFA in the right portion of Fig. 1 is about double that of its surface area in the left half of the figure, as is the volume of paste within 100 μm of the LWFA.

The two microstructures are evaluated quantitatively in Fig. 2, which shows, for the two aggregate PSDs and volume fractions, the fraction of the cement paste within a given distance of a LWFA surface. Clearly, to disperse the water uniformly throughout the microstructure at a low level of fine aggregate replacement, the surface area of the fine aggregate (or specifically the saturated LWFA) should be maximized. Thus, Eq. (2) provides only a determination of the bulk volume of water needed for curing, while the detailed simulation or the equations of Lu and Torquato [6]

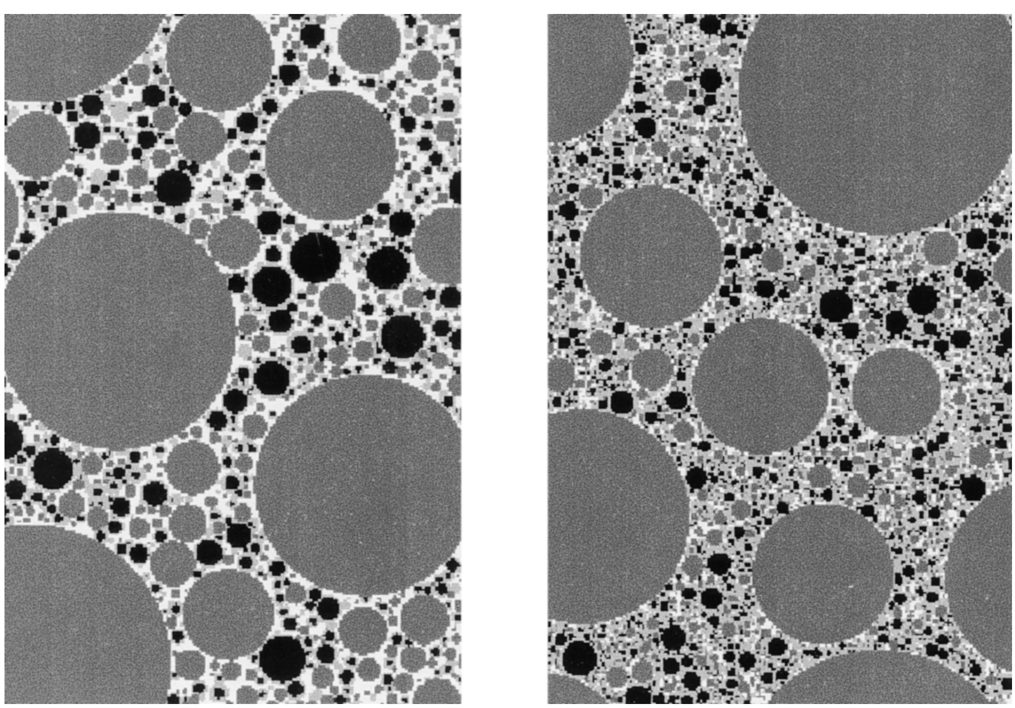

Fig. 1. Model two-dimensional images (20 $\times$ 30 mm, 1 pixel = 100 μm) from three-dimensional continuum concrete microstructures with 50% replacement of fine aggregate by LWFA. Colors are as follows: white, cement paste farther than 100 μm from a LWFA surface; light gray, cement paste within 100 μm of a LWFA surface; dark gray, normal weight aggregates; and black, saturated LWFAs. In the left image, $V_{agg} = 0.75$ and fine aggregate follows the coarse limit of ASTM C 33 specification. In the right image, $V_{agg} = 0.70$ and fine aggregate follows the fine limit of ASTM C 33 specification.

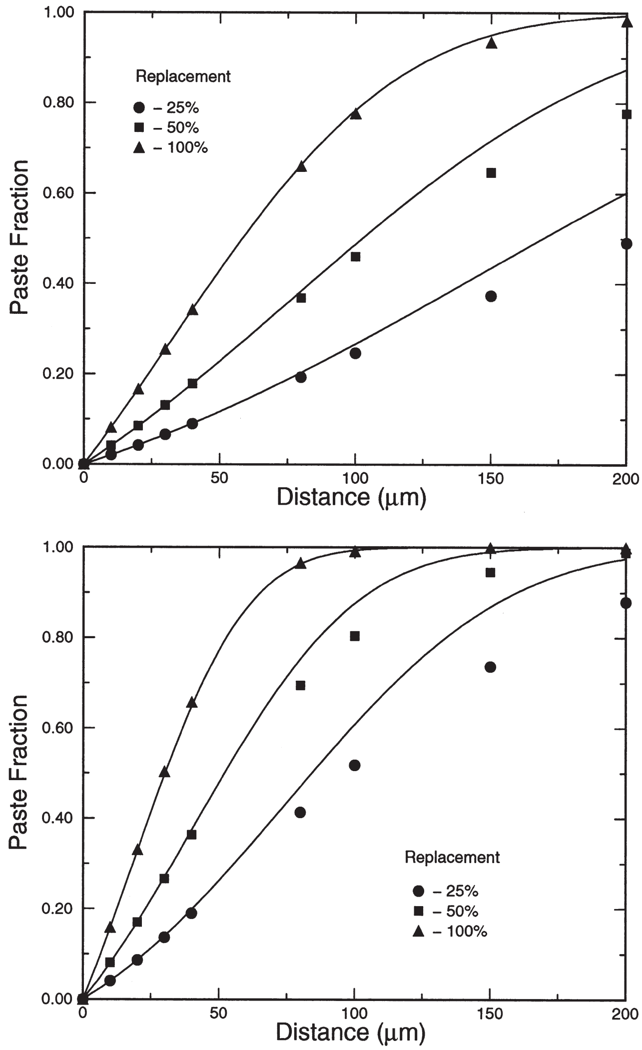

Fig. 2. Model results for fraction of cement paste within a given distance of the LWFA surfaces for three replacement levels and two aggregate gradations: (top) $V_{agg} = 0.75$ with coarse limit for fine aggregate; (bottom) $V_{agg} = 0.70$ with fine limit for fine aggregate. Symbols indicate simulation data and lines correspond to the estimations of the equations developed by Lu and Torquato [6] (modified by considering only the paste and LWFA components of the system).

are needed to ensure that the majority of the cement paste is near enough to a LWFA surface to benefit from the available water.

This result is in agreement with the protected paste volume concept for air voids, which suggests that a finely dispersed system of small air voids will be superior to one composed of larger air voids at equal air contents. In fact, once the water in the LWFA is consumed by hydration, a system of relatively coarse air voids should remain to aid in freeze/thaw protection. Past studies have indeed indicated a high durability for lightweight aggregate concrete exposed to freezing and thawing cycles [17].

For the three replacement levels and two aggregate gradations considered in this study, the approximations based upon the analytical equations of Lu and Torquato [6] are seen to estimate quite well the simulation results, especially at short distances and for complete replacement of the fine aggregates by their lightweight counterparts. The evaluation of these equations requires much less computer time than the full three-dimensional microstructural model simulation and conveniently provides the fraction of cement paste within all distances of interest to the user.

4. Conclusions

Equations have been developed to estimate the replacement level of saturated LWFA needed to provide all of the water necessary for the complete curing of a HPC. This calculation assumes that no water exchange occurs with the external environment (sealed curing). Computer simulations have demonstrated that the protected paste volume concept applies to characterizing the cement paste within any given distance of the LWFA particle surfaces. Simulation results suggest that a well dispersed system of small saturated LWFA particles would be most beneficial to the curing of field concrete, similar to the case of air voids protecting concrete from damage due to freezing and thawing. By applying a modification that represents the microstructure as a system of LWFAs randomly dispersed in cement paste, the analytical equations of Lu and Torquato [6] have been shown to provide a good estimation of the volume fraction of cement paste within a given distance of a LWFA surface. Thus, these equations may serve as a technical basis for the experimental optimization of the addition of LWFA to a given concrete mixture.

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