Construction and Building Materials 98 (2015) 662–670

Contents lists available at ScienceDirect

Construction and Building Materials

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

Determination of the water content of fillerised fine aggregates in the saturated surface dry state

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HIGHLIGHTS

- We capture the water content of aggregates in saturated surface dry state W_{SSD}.
- Our improved experimental setup accounts for porous fine aggregates with fines.
- We derive a practical calculation procedure of W_{SSD} from the drying theory.
- We suggest an independent graphical assessment that yields similar W_{SSD} values.
- Our experimental setup may be automatized for in-laboratory routine use.

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form 24 August 2015
Accepted 25 August 2015
Available online 2 September 2015

Keywords:
Fine aggregate
Sand
Cement concrete
Water absorption
Test method
Experimental setup
Drying

ABSTRACT

An experimental setup designed to capture the saturated surface dry (SSD) state of porous fine aggregates incorporating significant amounts of fines is presented. This setup is validated upon testing fine aggregate sources with different water absorption values up to 5.6%, and at least 8% of fines. Test duration is found to lie in the 120-to-240-min-range, depending on test sample initial mass and water content. Several procedures for calculating the water content in SSD state are presented and discussed. One of these procedures uses the drying theory to fit curves depicting water content shift as a function of drying time and identify breakpoints. A more straightforward strategy is focused on the transition point between retained and free water on charts representing the variations of water content as a function of relative humidity. In both cases, fairly repeatable and discriminant water content values in SSD state are obtained. As expected, these values are found significantly higher than those determined in the absence of fines according to the usual cone test (CEN, 2014). Moreover the lack of reliability of water absorption values determined in the presence of fines according to the cone test procedure is verified. Eventually, several perspectives are pointed out to improve the setup which could easily be automated.

1. Introduction

Short term and long term performances of cement concrete are known to depend on effective-water-to-cement ratio (W_{eff}/C), where effective water refers to water available for cement hydration. Effective water may be defined as the total mass of water contained in the cement concrete (W_{tot}) less the mass of water retained by the aggregate fractions. For a given aggregate source, this 'retained water' is known to increase with decreasing size fraction, especially in the fine fractions 0/4 or 0/5 mm. The maximum retained water is routinely though disputably [2] assessed by the 'water absorption' value (WA) – mass of water penetrating the voids of particles during a prescribed period of time, routinely 24 h, expressed as a percentage of the oven-dried mass of the aggregate sample [1]. For a long time, the large quantities of fine aggregates needed for cement concrete production have been purveyed almost exclusively by natural fine aggregates (NFA) from alluvial or limestone deposits, whose WA values are

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.131
0950-0618/

known to be low (<1%). In the recent years, the shortage of alluvial sources and waste storage capacity limitations have given rise to a worldwide interest in abundant alternative fine aggregate sources such as recycled concrete fine aggregates (RCFA). However, their use is still limited due to high WA values in the range 6–10% [3,4].

Indeed, adjusting the W_{eff}/C ratio of fresh cement concrete becomes much more difficult when fine aggregates with high WA value are incorporated, since they may add or subtract water allotted for cement hydration, thus impact its short term workability as well as mechanical and durability performances in hardened state [5,6]. Khatib [7] reported the good workability of fresh cement concrete incorporating 100% RCFA with additional water to reach $W_{tot}/C = 0.5$ (no plasticizer); however, he also noted a compressive strength drop down to 35% after 28 days of curing and a drying shrinkage increase up to 50% when compared with a reference cement concrete incorporating NFA exclusively. Reducing the W_{tot}/C ratio upon using an admixture allows both to maintain sufficient workability and prevent compressive strength drop, but concrete properties in hardened state are still impacted: splitting resistance may decrease by 30%, water absorption and sorptivity may increase by 46% and 70% respectively with respect to corresponding values of the reference cement concrete. As a consequence, external fluids may penetrate the concrete microstructure and introduce deleterious substances such as carbon dioxide and chloride ions, causing concrete carbonation and steel corrosion respectively [8].

The water absorption of alternative fine aggregates such as RCFA having significant implication on W/C ratios for concrete mixtures, determining it accurately is critical [4]. Therefore, most test methods consist of drying a pre-saturated sample until achievement of the state under which particles surface is free of vaporizable moisture but their accessible pores remain saturated with water, called saturated-surface-dry state (SSD, see Fig. 1), then in promptly weighing the sample. To capture the SSD state, some methods focus on the visual detection of test portion color change when particles become free of surface vaporizable moisture [9,10]. Others track the slump of a cone-shaped test portion [1,11,12] or the flow of a test sample off a tilted masonry trowel [10] which occur when between-particles surface tension forces disappear. Others spot slope breakpoints on curves measuring physical characteristics of test samples as a function of drying time, such as electrical resistivity reflecting the presence of between-particles water bridges [13]. A few test methods attempt to detect the end of the saturation phase while soaking a dry test portion, either from direct measurement of the volume of absorbed water [14], or from detecting the reflection signal of infra-red light rays when particles surface becomes moist [15]. Unfortunately, most of these test methods are unsuitable for fine aggregates such as RCFA, which may incorporate up to 10–13% of fines (particles passing the 0.063 mm sieve) [16,17]. Indeed, Rogers et al. [18] have reported a 100% overestimation of WA values assessed from methods using the cone slump criterion [1,11,12], which they allotted to fines adhering to larger particles and forming clusters, thus trapping part of the formerly free water into their inner structure and causing earlier achievement of the sample 'SSD' state than in the absence of fines. Similarly, methods focused on test portion color change yield scattered results in the presence of fines, since homogenously drying a sample becomes delicate [19].

Promising WA values of fine aggregates were measured using test methods derived from thermodynamic [19,20] or industrial drying approaches [21]. The former consists in air drying a pre-saturated fine aggregate sample placed into a rotating drum closed at both ends by 0.075 mm square mesh screens, while recording the temperature gradient between drum inlet and outlet as well as relative humidity at drum outlet. The drying phase is stopped and the sample is weighed when the temperature gradient or relative humidity curves evidence breakpoints similar to those shown on Fig. 2, presumably representative of SSD state according to the authors. The latter assimilates the drying of soaked aggregates at rest in a chamber to the evaporation of water from a porous medium at constant air temperature. Fig. 3 depicts sample mass reduction through evaporation as a function of time, which consists of three well-known phases [22]:

- a transition phase corresponding to the drying chamber conditioning;
- then, a linear part depicting the evaporation of surface water at a constant rate monitored by environmental conditions (temperature and relative humidity) until achievement of the SSD state;
- eventually, a phase at decreasing mass reduction rate evidencing the evaporation of absorbed water from aggregate pores.

Though promising, these two test methods have drawbacks: the drum method is biased by a loss of fines through the screens and disassembly operations which delay the weighing once SSD state is achieved; the drying chamber is unsuitable for uniformly drying polydisperse fine aggregates at rest due to crusting effects [22].

In order to determine the water absorption of fine aggregates incorporating fines, the present paper introduces an improved experimental setup designed to capture the SSD state and measure the water content in this state. Section 2 describes the experimental setup and the test program designed for its validation. Section 3 investigates the presence of breakpoints on various curves representing recorded data and discusses methods for assessing the water content in SSD state.

2. Experimental setup and test program

2.1. Experimental setup

The experimental setup used to capture the SSD state is inspired from early development by Dana et al. [20] and subsequent development by Kandhal et al. [19]. As shown in Fig. 4, it is composed of a hair dryer that blows warm air at one end of a rotating drum, which is mounted on caster wheels and driven by a belt through a step motor. The drum incorporates flights to stir the test sample in order to achieve reasonably uniform drying, as well as screens at drum inlet (0.063 mm opening) and outlet to reduce aggregates loss. Temperature is measured by two probes located at either ends of the drum and relative humidity is captured by a hygrometry probe located at drum outlet. However, three major improvements have been implemented: first, both the screen blinding and loss of fines issues reported by Kandhal et al. [19] have been sorted out using respectively an outlet screen with a wider opening (0.5 mm), and a fines collector consisting of a simple vortex system equipped with a cup, in which fines will remain trapped till the end of the test (see Fig. 4); second, no more drum removal is needed for weighing as the full experimental setup is mounted on a balance, thus allowing continuous weight monitoring to ±1 g; third, the air dryer is fed by a voltage regulator to monitor the blown air temperature to roughly 70 °C, that is not too high to avoid removing crystallized water in the mortar attached to the aggregate [23,24] though sufficiently high to keep the drying time reasonable. The total mass of unloaded experimental setup mounted on the balance is 13.1 kg.

2.2. Test program

Tested materials were sampled from three different sources, crushed sand-lime alluvium, crushed limestone and recycled concrete. Fig. 5 depicts the mean grading curve of each material tested, all of them incorporating at least 8% fines. Table 1 summarizes the densities and water absorption values determined for each material according to EN 1097–6 clause 9. The selected materials cover a reasonably wide range of WA values, from 0.8 for NFA up to 5.6% for RCFA, and the corresponding densities vary conversely as already noticed elsewhere [7,25]. Although the test procedure depicted in EN 1097-6 clause 9 prescribes fines discarding, a second set of samples were tested with their fines, supplemented with methylene blue (MB) tests performed on 0/2 mm samples in accordance with EN 933-9 [26] to check the fines quality. As expected [18], water absorption values in the presence of fines are systematically higher than those measured without fines, although MB values suggest low clay contents.