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Quantitative Measurement of Water Absorption of Coarse Lightweight Aggregates in Freshly-Mixed Concrete

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Abstract

The high water-absorption of lightweight aggregate causes a high slump loss and poor workability of concrete. A prewetting process is usually recommended to compensate for the workability problem, but its application needs more delicate consideration in field. A method is proposed to measure the additional water absorption of lightweight aggregate, and its application in cement paste and concrete mixes confirms the absorption amount remaining unaffected by the mix proportion. The additional water absorption in cement-based materials can be considered as a material property, and its value is smaller than the water absorption measured by a standard test method (water-soaking). Compensating the additional water absorption finally allows to use dry lightweight aggregates for concrete, which is more robust and stabler than taking a saturated surface-dry lightweight aggregates.

Keywords: lightweight aggregate, prewetting, water absorption

1 Introduction

Lightweight aggregate concrete (LWAC) is beneficial to the design of structures and foundations. More than a 20% decrease in self-weight of structural components, that is, a lower dead load, allows us to save construction materials for a designed structure. Application of LWAC is therefore common these days (Walraven et al. 1995). Its implementation is not different from the placement of ordinary concrete, and various guidelines dealing with LWAC are available in the literature: ACI 213R-14 (American Concrete Institute 2014); JASS 5 14 (Architectural Institute of Japan 2009); and KCS 14 20 20 (Korea Construction Specification 2016). Nevertheless, workability control of LWAC requires more attention to the details than ordinary concrete when it is applied in the field (Videla and López 2000).

Lightweight aggregates (LWA) are porous, which results in a higher water absorption compared to normal aggregates. The water absorption of normal aggregates is generally restricted by less than 3% while the specific limit varies according to the standard in a specific region. For example, the water absorption of granite aggregates are generally 0.5% by mass. The water absorption of coarse LWA, however, ranges from 10 to 20% depending on the type of raw material and producing method (González-Corrochano et al. 2010; Kockal and Ozturan 2011; Shuguang et al. 2010). The high water absorption causes poor workability, significant slump loss and blockage of concrete pumping when the LWA is not adequately prewetted. Therefore, the prewetting needs to be carefully accomplished until the LWA reaches a saturated surface-dry (SSD) condition (the water absorption after 24 h water-soaking). Water-spraying on an LWA dump is the most preferred method in the field. However, water-sprayed LWA is usually drier than its SSD condition and absorbs more water in a mix. Water-soaking LWAs, prepared by immersing them in water longer than 24 h, may be an ideal method to obtain fully water-filled pores of

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LWA. The vacuum-soaking method, which involves evacuating air in a water container, accelerates the prewetting of LWA, which results in more complete prewetting and saves time for the process.

It is difficult to achieve a constant quality of the prewetting of LWA. An SSD condition of LWA is hardly defined because taking out surface water of water-soaked LWA is very prone to experimental error. Their water absorption measurements (after 24 h water-soaking) are not reliable giving a high variation even when experienced technicians follow a standard test method such as ASTM C 127 (ASTM International 2015). In addition, the degree of prewetting of the LWA is not consistently controlled, and so the properties of LWAC depends on the method and procedure of prewetting (Castro et al. 2011; Kabay and Aköz 2012; Paul and Lopez 2011). The aforementioned problems in practice make concrete producers to ask the use of dried or partially-saturated LWA. The dried or partially-saturated LWA absorbs additional water in a LWAC mix. The 'effective' water-to-cement ratio (*w/cm*) of the LWAC mix should consider the lost water due to the additional water absorption of the LWA. A precise measurement technique is therefore necessary to understand the additional water absorption of the LWA in a mix (Bello et al. 2017).

The water transport into the LWA reportedly continues during the early age of LWAC. Free mixing water fill the pore in LWA, and with cement hydration inward water is released to refill the empty pore created by the chemical shrinkage. Their desorption followed by the additional water absorption contributes to the high strength by internal curing mechanism (Henkensiefken et al. 2009; Punkki and Giørv 1993). As an example, the effect of internal curing was evaluated for 8 days after the mixing (Henkensiefken et al. 2009). Shrinkage of LWAC is also related with the additional water absorption up to 1 day (Ji et al. 2015; Wyrzykowski et al. 2015). Limiting the domain of a problem with the workability of LWAC allows to dissociate the additional water absorption of LWA from the cement hydration: Its measurement within 2 h after the mixing, which corresponds with the period of the casting process. This paper proposes a complementary measurement technique to evaluate the additional water absorption of coarse LWA in freshly mixed concrete within 2 h, and the measurement expectedly elucidate the workability loss of LWAC. The accuracy of the complementary measurement is verified with cement paste (of which water-to-cement ratio ranged from 0.4 to 0.6). Its reliability is also analyzed with multiple measurements. Finally, the additional water absorption of the LWA in freshly mixed concrete is discussed with various test results.

2 Methods and Materials

2.1 The Proposed Procedure

The water absorption of LWA in a mix is accompanied by loss of the mixing water. Measuring the loss of the mixing water in the mix allows us to evaluate the effective water absorption of the LWA. A specific procedure to evaluate the water absorption of coarse LWA in freshly mixed concrete is as follows:

i Take wet-sieved mortar from a concrete sample following ASTM C 172 (ASTM International 2017a). The use of a No. 4 sieve, 5 mm mesh opening, gets rid of all coarse LWA particles. Remix the wet-sieved mortar thoroughly by hand.

j Measure the moisture content of the mortar. We use a moisture analyzer commercially available for determination of moisture in plastics by loss in weight Refer ASTM D 6980 (ASTM International 2017b). Approximately 30 g (15 mL) of the wet-sieved mortar is spread onto a sample pan supported on a balance in a heating chamber. The sample is then heated to vaporize the moisture. A period of 30 min at 170 °C was sufficient for various mortar samples. The temperature higher than 105 °C accelerates the water evaporation to get rid of the effect of cement hydration.

k Obtain the moisture content, ϕ_w, which is defined by the percent of moisture with respect to the total mass of a sample.

l Calculate the water absorption of the coarse LWA by

$$Q = \frac{W-(W+B+S)\varphi_w}{G} \quad \text{or} \quad Q = \frac{W/B-(1+W/B+S/B)\varphi_w}{G/B}, \tag{1}$$

where *W*, *B*, *S*, and *G* are the mix proportion specified by the mass of the water, binder such as cement and fly ash, fine aggregates and coarse aggregates, respectively, required to produce a unit volume of concrete. Dividing the right-hand term by *B* in the first equation allows us to use the form expressed by the ratios. Note that *G* in the equation needs to be given in an oven-dry mass of lightweight aggregates because the water absorption of coarse aggregates is generally defined with the ratio of the oven-dried mass of lightweight aggregates (ASTM C 127).

The proposed method is based on the postulate that the water content of cement-based materials is constant within the time of measurement. The valid time of measurement is presumably less than 2 h after mixing because casting and placing of concrete is generally restricted to within that period. Such a time period is a dormant period of cement hydration, and its effect on the moisture content is negligible. No active consumption of mixing water is considered except the reaction of tricalcium aluminate together with gypsum, resulting in ettringite (AFt), $Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$, and monosulfate, $Ca_4Al_2O_6(SO_4)\cdot 14H_2O$, formation (Christensen et al. 2004). However, the quantity of the products is very limited compared to the total volume of a sample, and they are even dehydrated by low heat for the moisture vaporization. Those phases are generally decomposed at around 60 to 70 °C. The small amount of mixing water consumed for the reaction of tricalcium aluminate is then released by the moisture vaporization process. The measurement of the water absorption of LWA is therefore undisturbed. The postulate would be experimentally verified with cement paste and mortar samples before the other application tests were applied.

2.2 Measurement of the Amount of Mixing Water

2.2.1 Cement Paste

The verification of the postulate was accomplished by comparing the measured moisture content (φ_w) and the value calculated with a samples' mix proportion. The cement paste samples were produced by $w/cm = 0.4$, 0.5 or 0.6 by mass. Type I Portland cement was used with no admixture. Table 1 reports their mix proportions. The cement paste was produced by 5 min mixing with a planetary mixer. The moisture content of each sample was measured at 0, 0.5, 1 and 2 h after it was mixed. On the other hand, the moisture content could be predicted with the mix proportion (or *w/cm*) of a sample. The amount of water in a cement paste sample, relative to the total mass of a sample, could be calculated by

$$\varphi_{w\text{-}paste} = \frac{w/cm}{1 + w/cm}. \tag{2}$$

Table 1 Mix proportions of cement and mortar samples.

Sample	Water, kg	Cement, kg	Sand, kg
Paste $w/cm = 0.4$	0.4	1.0	–
Paste $w/cm = 0.5$	0.5	1.0	–
Paste $w/cm = 0.6$	0.6	1.0	–
Mortar $w/cm = 0.4$	0.4	1.0	3.0
Mortar $w/cm = 0.5$	0.5	1.0	3.0
Mortar $w/cm = 0.6$	0.6	1.0	3.0
Mortar $w/cm = 0.7$	0.7	1.0	3.0

2.2.2 Mortar

In addition, the mortar samples were also produced by $w/cm = 0.4$, 0.5, or 0.6, where the sand-to-cement ratio (*s/cm*) of all samples was fixed at 3.0 by mass (see Table 1). The sand is a standard sand conventionally used for measuring the cement strength, and ISO 679 (International Organization for Standardization 2009) provides its specifications including the gradation (0.1 to 1.5 mm). Its specific gravity was 2.62, and its water absorption was 0.79%. The mixing time for mortar was the same with that for cement paste: 5 min with a planetary mixer. The prediction for the moisture content of a mortar sample was also given with its mix proportion (*w/cm* and *s/cm* corresponding to *W/B* and *S/B*, respectively, in Eq. (1)):

$$\varphi_{w\text{-}mortar} = \frac{w/cm}{1 + w/cm + s/cm}. \tag{3}$$

2.3 Water Absorption of LWA in Cement Paste

The proposed procedure was applied for LWA-paste samples produced by mixing cement paste together with LWA. In cement paste, LWA was incorporated occupying 40% volume fraction. The weight of the LWA was 730, 830 or 930 g of the LWA was incorporated in Paste $w/cm = 0.4$, 0.5, or 0.6 mix, respectively. Their additional water absorption was calculated by a mass percentage, and that it was assumedly consistent even in a concrete mix. The LWA used for this study was an artificial LWA produced by sintering coal-combustion bottom ash and dredged soil, which is commercially available in Korea (KOENlite®). Its oven-dried density was an average of 1290 kg/m^3, where 3 experienced technicians provided ± 30 kg/m^3 (or ± 2.3% of the mean value) variation. The water absorption was also measured by ASTM C 127 (ASTM International 2015). Taking an SSD condition of 24 h-submerged LWA provided an average water absorption of 18.5% even though the variation according to the 3 technicians was as high as ± 12% of the mean value (16.3%, 18.6%, and 20.6%).

Figure 1 shows pictures of an LWA-paste sample, and the wet-sieved coarse LWA and cement paste to be tested are shown together. Further steps 2, 3, and 4 would be applied into the wet-sieved paste to measurement the water absorption of LWA.

In the first test, oven-dried LWA was used to get rid of the effect caused by the initial water content of LWA. The *w/cm* of cement paste was controlled as 0.4, 0.5, or 0.6 by mass. The paste were mixed for 5 min, the same with the previous measurements, and coarse LWA were incorporated in the paste. Additional 1 min was required to homogeneously distribute the LWA grains. The additional water absorption of LWA was measured for 2 h after the mixing.

Fig. 1 LWA-paste sample, wet-sieved coarse LWA and wet-sieved paste.

The second test analyzed the effect of the initial moisture content of LWA. The moisture content of LWA at an SSD condition was 18.5% (the water absorption) with a high variation. Drying 24-h submerged LWA until a target value allowed to obtain the LWA samples having the initial moisture content of $M_{initial}=8\%$ and 12%. The effect of the initial moisture content of LWA was then investigated with the LWA samples together with oven-dried LWA ($M_{initial} = 0\%$).

The third test was designed to identify the effect of the chemical admixture. The LWA-paste sample with $w/cm=0.4$ was reproduced, but here polycarboxylate-based HRWRA was incorporated to increase the fluidity of the cement paste. The dosage represented by the total solid content was 0.07% and 0.14% by cement paste. Air-dried LWA was used, and its initial moisture content was approximately 0.5%.

Finally, the reproducibility of the proposed test method was also investigated to show its application potential. A total of 15 LWA-paste samples were replicated with neat cement paste of $w/cm=0.5$ and air-dried LWA occupying 40% volume fraction. The additional water absorption at 0.1 h was measured with each replicated sample.

2.4 Water Absorption of LWA in Concrete

The water absorption of LWA in concrete mixes was evaluated by the proposed procedure. Table 2 reports the mix proportion of the tested concrete samples. Type I Portland cement and class F fly ash were used for binder, and crushed sand was used as fine aggregates. A control sample was produced with normal aggregates, which was labeled N55. Two series of samples labeled W and D used wet and dried LWA, respectively. The samples were designed to have various *w/b* and consequently various strengths. Keeping the water content of the samples decreased the binder content with a higher *w/b*, and consequently the LWA content slightly increased for a higher *w/b* sample.

Table 2 Mix proportions of concrete samples.

Sample[a]	Water	Cement	Fly ash	Fine aggregate	Coarse aggregate[b]
N55	180	245	82	846	927
W45	180	300	100	679	609
W50	180	270	90	693	622
W55	180	245	82	705	633
W60	180	225	75	715	642
W65	180	208	69	723	649
D45	180	300	100	679	528
D50	180	270	90	693	539
D55	180	245	82	705	548
D60	180	225	75	715	556
D65	180	208	69	723	563

[a] N55 was produced with normal-weight aggregates. W and D samples used wet and dried lightweight aggregates, respectively. The last two digits are *w/b* in percentage.

[b] LWA content accounts for the weight of the water absorbed in them (15.4% by mass) while the mixing water content is constant for all mixes.

Wet LWA was prewetted by water-soaking prior to the test. They were submerged for 24 h in water, and then for SSD condition they were slightly dried to get rid of surface water. The initial moisture content of wet LWA was therefore $M_{initial}=15.4\%$, which was lower than the water absorption of 18.5% as reported in the previous section. The W and D samples needed 609 to 649 kg of wetted LWA and 528 to 563 kg of dried LWA, respectively. Their averages were 631 and 547 kg, respectively. The dosage of polycarboxylate-based HRWRA was controlled for each sample to have a target slump of 220 mm. The dosage primarily controlled the workability of freshly mixed concrete while the additional water absorption of LWA increased the slump loss.

The moisture content (ϕ_w) of the wet-sieved mortar of each concrete sample was measured following the proposed method. The comparative analysis of the water absorption in a mix was accomplished by evaluating the remaining percentage of the water content in a mix. The remaining water content of each mix was then simply calculated by $\phi_w/\phi_{w\text{-}mortar}$ using Eq. (3). Each measurement of the moisture content was divided by the theoretical prediction of each mix, where the content of water, binder (cement and fly ash), and fine aggregates, W, B and S, respectively, are given in Table 2.

3 Results and Discussion

3.1 Measurement of the Amount of Mixing Water

A total of 10 measured moisture contents of the cement paste samples within 2 h were almost constant as expected. The moisture content of the 2 h-old sample was not even lower than the initial measurement (at 0 h) of the same sample. The mortar samples also provided the constant moisture contents within 2 h measurements. Therefore, it could be said that no significant water consumption occurred within 2 h.

Figure 2 shows the measurement results for the cement paste and mortar samples, where the circular points are the mean values of the 2 h-long measurement of each cement paste sample and the triangular points are those of each mortar sample. In addition, the blue dashed line in the figure is the theoretical prediction by Eq. (2) for cement paste, and the orange solid line is that by Eq. (3) for mortar. The measured moisture contents of the cement pastes and mortars lied on the prediction line by Eqs. (2) and (3), respectively. The measured moisture content precisely indicates the amount of mixing water in the cement pastes and mortars at least up to 2 h. The small variation in the measurements of both the cement paste and the mortar samples was within ±0.5% of the calculation, and it was presumably caused by sampling errors rather than the time effect. Therefore, we concluded that the proposed method is valid for the cement-based materials given that the time of measurement is limited to within 2 h after the completion of mixing.

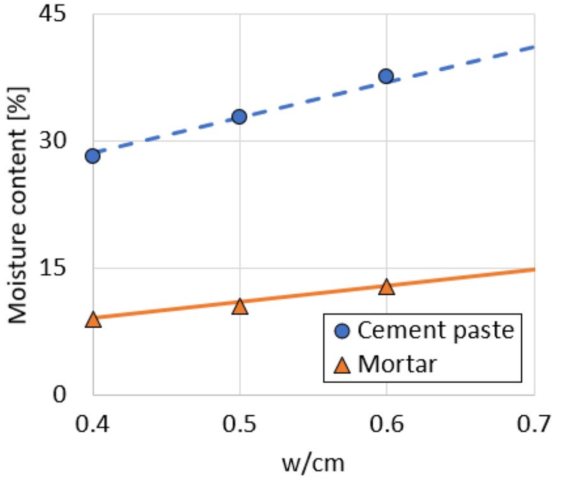

Fig. 2 Moisture content measured with cement paste and mortar samples (the variation of the measurement is less than 1% at each point).

3.2 Water Absorption of LWA in Cement Paste

Figure 3 shows the water absorption of oven-dried LWA over time, where the hollow points are the measured moisture content of the surrounding cement paste. The initial measurement, at 0 h, of each sample proportioned by $w/cm = 0.4$, 0.5, or 0.6 sample was 27.4%, 31.9%, or 36.4%, respectively, which was smaller than the measurement with the neat cement paste reported in Fig. 2 (28.3%, 33.0%, or 37.5%, respectively). The moisture content of the surrounding cement paste decreased over time because of the additional water absorption of the LWA. The additional water absorption was then calculated by Eq. (1), and the results are depicted by solid points in Fig. 3. The water absorption of the LWA clearly showed its increasing trend with time: from 2 to 5% within 2 h. However, the effect of *w/cm* was hardly concluded here and it would be discussed with the following figure.

Figure 4 shows the effect of the initial moisture content of LWA. The relatively dry LWA with $M_{initial} = 0\%$ or 8% showed gradual water absorption after a rapid increase in a flash. The rapid increase in the moisture content of the dry LWA occurred in the mixing process, as shown in Fig. 4a. The first measurement (at $t = 0$ h) consequently jumped to a higher value than $M_{initial}$, and the gradual increase was followed for 2 h. The gradual increase in the additional water absorption can be compared in Fig. 4b, where its increments at each sample were calculated by $\Delta Q = Q(t) - M_{initial}$. The effect of *w/cm* of

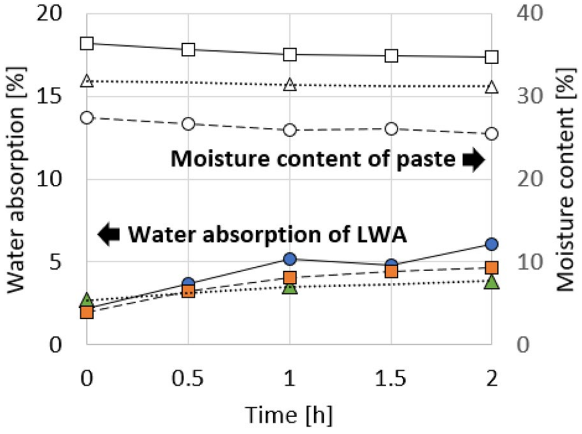

Fig. 3 Water absorption of LWA and moisture content of surrounding cement paste.

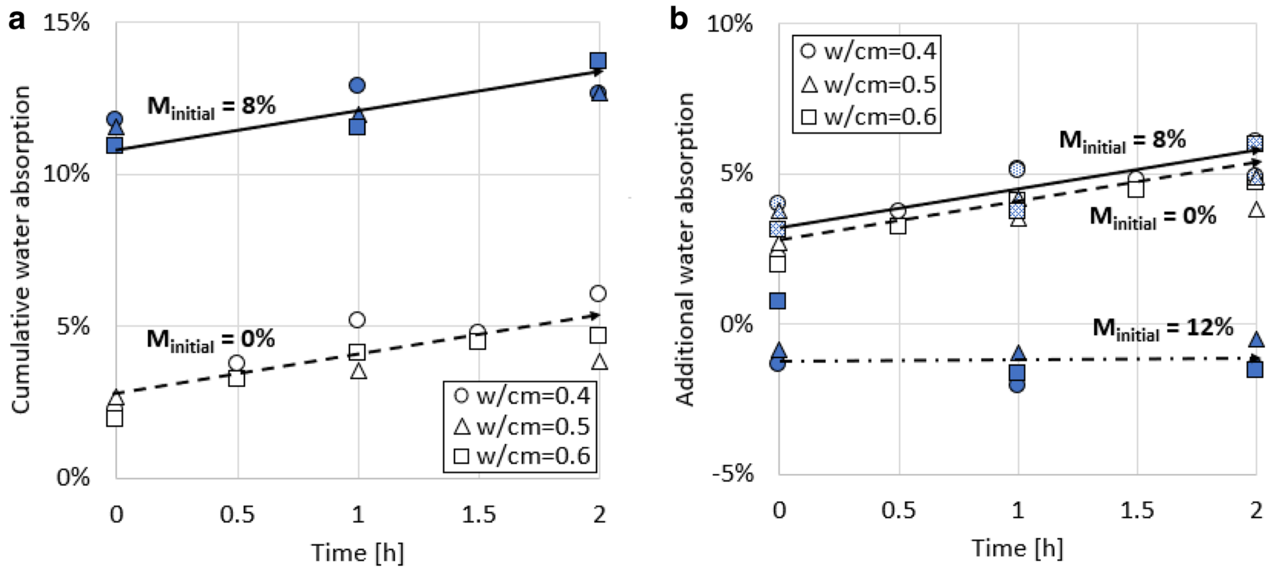

Fig. 4 Effect of the initial moisture content: **a** cumulative or **b** additional water absorption of LWA.

the surrounding cement paste was marginal compared to the effect of the initial moisture content. The gradual increase in the additional water absorption was identical for the dry LWA with $M_{initial}=0\%$ or 8%. The early water absorption in a mix is described by $\Delta Q_{0.5}=Q(t=0.5)-M_{initial}$, and a full capacity of the additional water absorption in a mix is $\Delta Q_2=Q(t=2)-M_{initial}$. $\Delta Q_{0.5}$ and ΔQ_2 for oven-dried LWA ($M_{initial}=0\%$) were 4.1% and 4.5%, respectively. Those values were the same as the LWA with $M_{initial}=8\%$. As a result, regardless of the initial moisture content, dry (unsaturated) LWA expectedly have the same amount of additional water absorption in a mix. On the other hand, in the case of $M_{initial}=12\%$ no additional water absorption occurred for 2 h. The LWA indeed released slight amount of water in the mixing process, on the contrary: Approximately − 1% additional water absorption as shown in Fig. 4b, and then the moisture content was kept constant for 2 h. Therefore, LWA having $M_{initial}=12\%$ could be said over-saturated in cement-based materials. The level of the saturation was lower that of LWA saturation in air. Note that the water absorption measured by 24-h water-soaking was 18.5% as previously reported.

A critical state of full saturation of LWA depends on the medium where they were distributed. Their saturation in water, in air (on the process of the measurement of water absorption), or in cement-based materials is delineated with a physically different condition for water transport. The absorption of LWA is also in discord with their desorption, which indicates that the SSD condition for LWA is unstable. Therefore, limiting the range of $M_{initial}$ up to a certain level is better to control the additional water absorption by using dry LWA. The current test with the given LWA indicated $M_{initial}$ less than 8% can be the criterion for taking their stable dry state providing the consistent additional water absorption in a mix.

The finding on the additional water absorption would be more robust if its quantity is regardless of the mix proportion. The effect of *w/cm* was marginal as confirmed in Figs. 3 and 4. Figure 5 reports the effect of chemical admixture. As can be seen in the result graphs, incorporating HRWRA did not change the additional water absorption of LWA in a mix. For reference, following a rheological protocol for cement paste (Choi

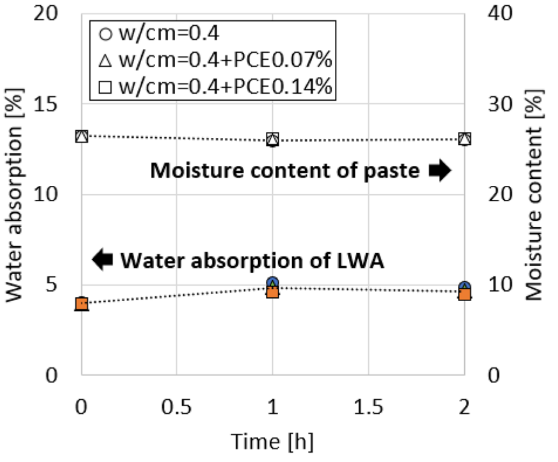

Fig. 5 Effect of chemical admixture.

et al. 2019), the infinite viscosity of each cement paste sample was measured as 0.79, 0.33 and 0.15 Pa·s for the control, 0.07% and 0.14% samples, respectively. The viscosity slightly increased over time, which was attributed to delayed consumption of polycarboxylates (a majority component of HRWRA) in cement suspensions (Yoon and Kim 2018; Yoshioka et al. 2002). The viscosity of the cement paste was measured using a DHR rheometer (TA Instruments, Inc.). Independence on the HRWRA dosage is equivalent to independence on the viscosity of the surrounding cement-based materials.

On the other hand, the reproducibility test with 15 LWA-paste replicated samples reported that the mean and standard deviation of $\Delta Q_{0.1}$ (the additional water absorption for 0.1 h) were 3.00% and 0.204%, respectively. The measurements varied from 2.63 to 3.48%, The variation was acceptable considering the characteristics of LWA. Note that as reported in the previous section, its water absorption by ASTM C 127 varied on 18.5 ± 14%.

3.3 Water Absorption of LWA in Concrete

Table 3 reports the slump and air content of the concrete samples, where they were measured at 0 and 1 h after mixing. The cylinder samples were then casted for the unit weight and strength measurement. The unit weights of the freshly mixed concrete samples were measured at 1 h after mixing. The compressive strengths measured using 100 mm-diameter 200 mm high cylinders at 28 days were also recorded for reference.

The additional water absorption measurements are given in the list of Table 3, and the remaining water content in each mix is plotted by Fig. 6. First of all, the result of the control sample N55 is depicted with the blue triangular points at $w/b = 0.55$. A control mix using normal aggregates at an SSD condition maintained approximately 100% water content at 0 and 1 h, as expected. The additional water absorption of wet LWA was not significant either. Only 2.5% mixing water (4.5 kg out of 180 kg) was absorbed even at 1 h after the mixing (red dashed lines in the figure). The additional water absorption of wet LWA in the concrete mixes was then 0.8% (4.5 kg divided by 547 kg) approximately. However, it needs to be compared with the fact that the LWA having the initial moisture content of $M_{initial} = 12\%$ slightly released water in the cement paste as reported in the previous section. The wet LWA having $M_{initial} = 15.4\%$ showed the opposite phenomenon in the concrete. This mismatch is attributed to the unstable state on full saturation of LWA as discussed in the previous section. Their $M_{initial}$ was higher than the state of full saturation in cement paste, but it was still lower than that in water (water absorption of 18.5%).

When dry LWA having $M_{initial}$ lower than the criterion for the stability (8% which is smaller than a half of the water absorption) was used, their additional water absorption on the D samples was predictable. The average of the remaining water content at 0 h was 90% (green dashed lines in the figure), which means that approximately 547 kg of dried LWA absorbed 18 kg of mixing water (10% of the initial water content 180 kg). An hour later, the remaining water content decreased to 88.2% (green dashed line in the figure), and a total of the additional water absorption attained 21 kg (11.8% of 180 kg). The additional water absorption was then computed as 3.8% by 21 kg over 547 kg.

The water absorption of dried LWA in the concrete mixes was comparable with the previous measurements for the LWA-paste samples. Note that those values of $\Delta Q_{0.1}$, $\Delta Q_{0.5}$ and ΔQ_{2} were 3.0%, 4.1% and 4.5%, respectively, as reported in the previous sections. The water absorption in the concrete mixes, 3.8% at 1 h, was in the

Table 3 Properties and test results of the concrete samples.

Sample	Slump, mm		Air content, %		Moisture content, %		Water absorption, %		Unit weight, kg/m^3	Strength, MPa
	at 0 h	at 1 h	at 0 h	at 1 h	at 0 h	at 1 h	at 0 h	at 1 h		
N55	225	165	5.5	3.6	13.1	13.1	0	0	2258	28.3
W45	245	155	3.8	3.8	14.4	14.2	0	1	1891	37.5
W50	235	130	3.8	2.6	14.4	14.3	1	2	1889	33.4
W55	230	100	4.8	3.8	15.1	14.4	0	3	1855	28.2
W60	220	100	4.3	3.2	14.7	14.3	2	5	1874	27.1
W65	230	85	4.5	3.8	14.9	15.0	2	2	1842	22.5
D45	240	175	4.7	2.7	12.9	12.6	10	12	1826	39.5
D50	245	105	3.6	2.6	13.2	13.2	10	10	1830	36.4
D55	245	95	3.8	2.7	13.5	–	9	–	1823	35.5
D60	220	75	4.6	3.7	13.6	13.2	10	12	1800	31.5
D65	235	90	4.4	3.2	13.4	13.2	12	13	1778	28.1

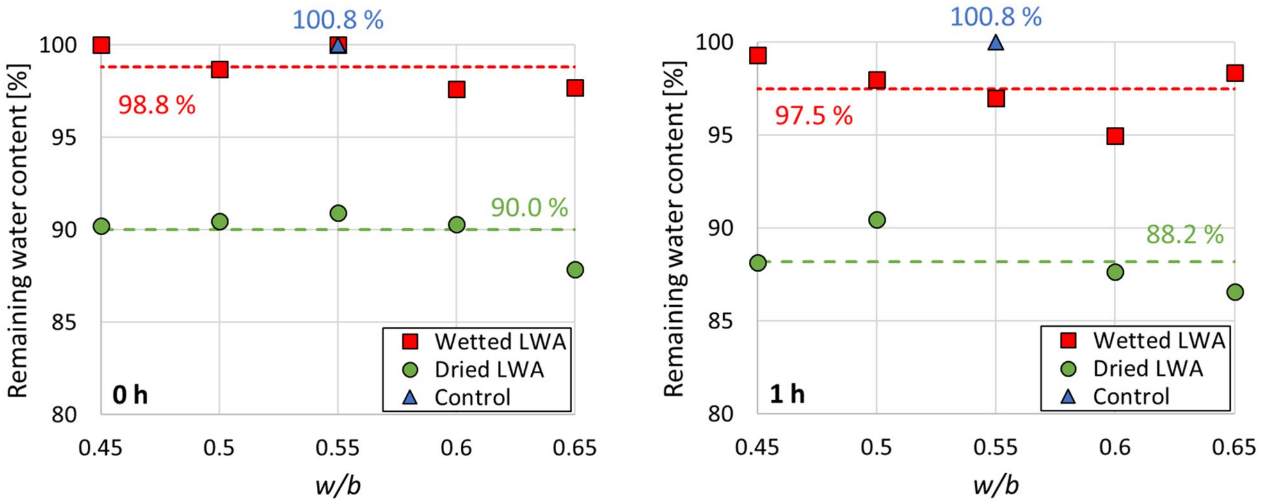

Fig. 6 Remaining water content in concrete mixes.

period of its gradual increase considering the trend of the water absorption in cement paste (see Fig. 4). Comparing it with $\Delta Q_{0.5}$ (4.1%) provided only − 7% in relative error, which was within the measurement variation of the reproducibility test. In other words, the water absorption of dried LWA in a concrete mix was predicted by a small-scale lab test using the LWA-paste samples. Here, it should be again noted that the additional water absorption in the concrete mix was much smaller than the water absorption measured by 24 h submersion (18.5%). The additional water absorption was independent of the mix proportion such as *w/b* and HRWRA dosage of LWAC, and therefore we consider it as a material property of LWA. Its measurement allows us to estimate additional mixing water, thus compensating for the effect of additional water absorption of LWA in a mix.

4 Conclusions

LWAC is an efficient construction material for decreasing the dead load of structures. The porous microstructure of LWA is good for the low-density LWAC, but it increases the water absorption. The additional water absorption of LWA in a concrete mix brings a high slump loss and poor workability retention. Its prediction is therefore helpful for quality control of fresh LWAC. Limiting the time of consideration into 2 h after mixing allowed to consider its effect on the workability of LWAC. The effect of cement hydration and mix proportion including the water-to-cement ratio could be disregarded. A complementary measurement technique was then proposed to measure the additional water absorption of LWA in a concrete mix. As a result, the additional water absorption of dry LWA in a cement paste was different from the conventional measurement of water absorption by 24 h water-soaking. For example, a typical LWA used in this study showed the additional water absorption of 4.5% only while its typical water absorption by 24 h water-soaking was 18.5%. More importantly, the additional water absorption of dry LWA was independent of their initial moisture content as well as the mix proportion (such as *w/b* and HRWRA dosage). Comparative experiments with LWA produced using dry LWA and wet LWA at an SSD condition showed the additional water absorption of dry LWA in a concrete mix was still consistent. In contrast, the additional water absorption or water release of wet LWA in the concrete mixes was hardly predictable due to the instability on their full saturation (in terms of the water absorption measurement and absorption–desorption equilibrium). Therefore, the use of dry LWA, of which initial moisture content is lower than a critical value (smaller than a half of the water absorption), can be one way to obtain a consistent and homogeneous mix of LWAC.

Authors' contributions

Y-HK and JHK conceived and designed the experiments; C-BP, BIC and TYS performed the experiments; YJ and JHK analyzed the data; Y-HK and JHK wrote the paper. All authors read and approved the final manuscript.

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References

American Concrete Institute. (2014). *Guide for Structural Lightweight-Aggregate Concrete, ACI 213R-14*.

Architectural Institute of Japan. (2009). *Japanese Architectural Standard Specification for Reinforced Concrete Work, JASS 5 14*.

ASTM International. (2015). *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate, ASTM C 127-15*.

ASTM International. (2017a). *Standard Practice for Sampling Freshly Mixed Concrete, ASTM C 172-17*. https://doi.org/10.1520/C0172.

ASTM International. (2017b). *Standard Test Method for Determination of Moisture in Plastics by Loss in Weight, ASTM D 6980-17*. https://doi.org/10.1520/D6980-17.

Bello, L., Garcia-Diaz, E., & Rougeau, P. (2017). An original test method to assess water absorption/desorption of lightweight aggregates in presence of cement paste. *Construction and Building Materials, 154,* 752–762. https://doi.org/10.1016/j.conbuildmat.2017.07.236.

Castro, J., Keiser, L., Golias, M., & Weiss, J. (2011). Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures. *Cement & Concrete Composites, 33*(10), 1001–1008. https://doi.org/10.1016/j.cemconcomp.2011.07.006.

Choi, B. Il, Kim, J. H., & Shin, T. Y. (2019). Rheological model selection and a general model for evaluating the viscosity and microstructure of a highly-concentrated cement suspension. *Cement and Concrete Research, 123*(May), 105775. https://doi.org/10.1016/j.cemconres.2019.05.020.

Christensen, A. N., Jensen, T. R., & Hanson, J. C. (2004). Formation of ettringite, Ca(6)Al(2)(SO$_4$)3(OH)(12)·26H$_2$O, AFt, and monosulfate, Ca(4)Al(2)O(6)(SO$_4$)·14H$_2$O, AFm-14, in hydrothermal hydration of Portland cement and of calcium aluminum oxide—Calcium sulfate dihydrate mixtures studied by in situ synchrotro. *Journal of Solid State Chemistry, 177*(6), 1944–1951. https://doi.org/10.1016/j.jssc.2003.12.030.

González-Corrochano, B., Alonso-Azcárate, J., Rodas, M., Luque, F. J., & Barrenechea, J. F. (2010). Microstructure and mineralogy of lightweight aggregates produced from washing aggregate sludge, fly ash and used motor oil. *Cement & Concrete Composites, 32*(9), 694–707. https://doi.org/10.1016/j.cemconcomp.2010.07.014.

Henkensiefken, R., Castro, J., Bentz, D., Nantung, T., & Weiss, J. (2009). Water absorption in internally cured mortar made with water-filled lightweight aggregate. *Cement and Concrete Research, 39*(10), 883–892. https://doi.org/10.1016/j.cemconres.2009.06.009.

International Organization for Standardization. (2009). *Cement—Test methods—Determination of strength, ISO 679:2009*.

Ji, T., Zhang, B. B., Zhuang, Y. Z., & Wu, H. C. (2015). Effect of lightweight aggregate on early-Age Autogenous shrinkage of concrete. *ACI Materials Journal, 112*(3), 353–363. https://doi.org/10.14359/51687229.

Kabay, N., & Aköz, F. (2012). Effect of prewetting methods on some fresh and hardened properties of concrete with pumice aggregate. *Cement & Concrete Composites, 34*(4), 503–507. https://doi.org/10.1016/j.cemconcomp.2011.11.022.

Kockal, N. U., & Ozturan, T. (2011). Characteristics of lightweight fly ash aggregates produced with different binders and heat treatments. *Cement & Concrete Composites, 33*(1), 61–67. https://doi.org/10.1016/j.cemconcomp.2010.09.007.

Korea Construction Specification. (2016). *Lightweight Aggregate Concrete, KCS 14 20 20*.

Paul, Á., & Lopez, M. (2011). Assessing lightweight aggregate efficiency for maximizing internal curing performance. *ACI Materials Journal, 108*(4), 385–393.

Punkki, J., & Giørv, O. (1993). Water absorption by high-strength lightweight aggregate. In *Proceedings of Congress on High Strength Concrete* (pp. 713–721).

Shuguang, H., Tingting, Y., & Fazhou, W. (2010). Influence of mineralogical composition on the properties of lightweight aggregate. *Cement & Concrete Composites, 32*(1), 15–18. https://doi.org/10.1016/j.cemconcomp.2009.10.001.

Videla, C., & López, M. (2000). Mixture proportioning methodology for structural sand-lightweight concrete. *ACI Structural Journal, 97*(3), 281–289. https://doi.org/10.14359/4623.

Walraven, J., den Uijl, J., Al-Zubi, N., Gijsbergs, J., & Naaktgeboren, M. (1995). Structural lightweight concrete: Recent research. *Heron*, *40*(1).

Wyrzykowski, M., Trtik, P., Münch, B., Weiss, J., Vontobel, P., & Lura, P. (2015). Plastic shrinkage of mortars with shrinkage reducing admixture and lightweight aggregates studied by neutron tomography. *Cement and Concrete Research, 73,* 238–245. https://doi.org/10.1016/j.cemconres.2015.03.013.

Yoon, J. Y., & Kim, J. H. (2018). Evaluation on the consumption and performance of polycarboxylates in cement-based materials. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2017.10.004.

Yoshioka, K., Tazawa, E. I., Kawai, K., & Enohata, T. (2002). Adsorption characteristics of superplasticizers on cement component minerals. *Cement and Concrete Research, 32*(10), 1507–1513. https://doi.org/10.1016/S0008-8846(02)00782-2.

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