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Influence of internal curing on compressive strength and drying shrinkage of super-sulfated cement mortar

Tran Vu An, Nguyen Hoang Anh*, and Bui Le Anh Tuan

College of Engineering, Can Tho University, Viet Nam

**Correspondence: Nguyen Hoang Anh (email: hoanganh@ctu.edu.vn)*

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ABSTRACT

The current study aims at assessing the effect of using cold-bonded fly ash based artificial lightweight aggregate (ALWA) as an internal curing (IC) agent on the compressive strength and drying shrinkage of a typical super-sulfated cement (SSC) produced with a mixture of 85% slag, 10% gypsum, and minor amount of 5% blended Portland cement (PCB). The ALWA was used as partial replacement of fine aggregate (FA) at values of 25, 50, 75, and 100 vol.%. Experimental results showed that the ALWA partially replacing FA in range of 25–100 vol.% significantly decreased both the unit weight and dried density of the fresh and hardened IC-SSC mortars at average values of 13.9% and 20.0%, when compared with the reference SSC mortar, respectively. The ALWA increment continuously reduced the compressive strengths of the hardened IC-SSC mortars. But, at 28 days of curing, the hardened IC-SSC mortar containing the ALWA amount partially replacing FA up to 50 vol.% showed compressive strength reaching 89.3%, and comparable or slightly lower drying shrinkage in comparison with the reference SSC mortar without the IC agent.

1. INTRODUCTION

Super-sulfated cement (SSC) has been preferably applied for alleviation of environmental impacts induced by conventional ordinary Portland cement (OPC) manufacture (Dutta & Borthakur, 1990; Gruskovnjak et al., 2008; Midgley & Pettifer, 1971; Singh & Garg, 2002). Normally, for producing typical SSCs, mixtures of 80−85% ground granulated blast furnace slag (GGBFS/slag), 10–15% calcium sulfate, and only a minor amount of 5% OPC/lime are used (Dutta & Borthakur, 1990; Singh and Garg, 2002). Due to a quintessential requirement of using slag with the appropriate chemical composition, particularly including high alumina, for producing a product with adequate quality, most of the commercial SSCs have been superseded due to unavailability of high alumina containing slag (Imbabi et al., 2012). However, for persuading a concept of durability development, environmentally friendly SSCs including various industrial wastes rich in calcium sulfate have become research interests (Chen et al., 2015). Apparently, the mechanical performance of such kind of binder is lower than that of the OPC, which led to its' limit for widespread use in the construction fields (Nguyen et al., 2015; Nguyen et al., 2020; Nguyen et al., 2016). To achieve a proper modification on the SSC performance, reducing the water content in the resultant productions was seemly the most preferable cutting the cost (Nguyen et al., 2015). As such, an issue associated with increased risk of shrinkage induced by the self-desiccation phenomenon occurred.

The proper external curing (EC) regime by maintaining the appropriate temperature and humidity during necessary period of time is crucial for assuring good hydration of cementitious binder in concrete/mortar. By applying the external curing (EC), the water supply penetrated from the surrounding curing environment is primary. But, for high performance concretes which mostly contain low amounts of water, the water supply from the curing environment by penetration phenomenon has been insufficient for maintaining the long-term hydration of the binder. As such, the real continuity of the binder hydration normally tends to absorb the water from capillary pores and thus increased the risk of shrinkage induced by the increase in internal stress. For overcoming the problem, utilizing porous internal curing (IC) agents acting as the internal water reservoirs has been applied to mitigate the reduction of internal humidity in concrete/mortar. Therefore, the IC has been considered as an effective method for maintaining proper hydration processes and addressing the issue of high autogenous shrinkage of high performance concrete/mortar without impacts on the workability and hardened performance of the resultant concrete. Generally, IC agents included different types of porous materials with appropriate sorptivity, such as superabsorbent polymer (SAP) (Wang et al., 2016), wood fibers (Mohr et al., 2005), rice husk ash (RHA) (Van Tuan et al., 2010), demolished construction wastes (Liu et al., 2020), and lightweight fine aggregate (LWFA) derived from either natural (Alaskar et al., 2021; Zhutovsky et al., 2002), or artificial sources (Bentur et al., 2001; Cusson and Hoogeveen, 2008; Lura et al., 2014). Due to simple manufacturing and quality controlling processes, LWFA seems to be preferably applied. Indeed, since the 1950s, the improved performance of the concrete on utilizing saturated LWFA partially replacing fine aggregate (FA) was indicated (Bloem and GAYNOR, 1965; Klieger, 1969). Typically, commercially sintered clay based LWFAs have been widely used to reduce concrete shrinkage (Castro et al., 2011; Shen et al., 2021). In addition, LWFA made by applying compaction of alkali-activated bottom coal ash was also utilized in IC concrete (Balapour et al., 2020). Currently, cold-bonded fly ash based artificial lightweight aggregate (ALWA) with low energy consumption could be a promising alternative IC agent for ramping up sustainability development. However, the applicability of such innovative aggregate was seemly limited to partial substitution of the coarse aggregate in concrete productions (Hwang & Tran, 2015, 2016).

According to above review points, although beneficial effects of different IC agents on enhanced performance of concrete have been well-understood, an existing knowledge gap associated with impact of IC on the performance of SSC binder has been under researched. Particularly, the utilization of cold-bonded fly ash ALWA in the role of IC agent has been also unexplored. Therefore, this study attempts to initially evaluate influence of the cold-bonded fly ash ALWA compressive strength and drying shrinkage of the SSC mortars, which has not been previously studied.

2. EXPERIMENTAL PROGRAM

2.1. Materials

Four kinds of materials of blended Portland cement (PCB), gypsum, low calcium Class F fly ash (FFA) and ground granulated blast furnace slag (GGBFS/slag) were used for preparing the ALWA and SSC specimens. Their physico-chemical properties and mineral compositions are illustrated in Table 1 and Figure 1, respectively. In addition, the features of the raw materials' particles are shown in Figure 2. To produce the mortars, natural fine aggregate (FA) with specific gravity of 2.68 and water absorption of 1.5% was used. The particle size distribution of FA is illustrated in Table 2. For assessing the impact of the IC agent on the performance of the IC-SSC mortar, cold-bonded fly ash artificial light weight aggregate (ALWA) was also used. The manufacturing process and characteristic of the ALWA were just subsequently described.

Table 1. Physical properties and chemical compositions of the raw materials

	Slag	**FFA**	**PCB**	**Gypsum**
Specific gravity	2.86	2.13	3.05	2.68
SiO_2, %	38.01	58.77	22.45	-
Al_2O_3, %	13.13	26.11	6.81	-
Fe_2O_3, %	0.55	5.61	3.15	-
CaO, %	36.80	2.07	60.03	-
MgO, %	5.77	1.66	2.08	-
SO_3, %	1.36	0.21	2.77	-
Na_2O, %	0.13	0.27	0.55	-
K_2O, %	0.78	1.48	0.79	-
TiO_2, %	0.45	0.66	0.41	-
L.O.I, %	3.01	3.11	0.95	-

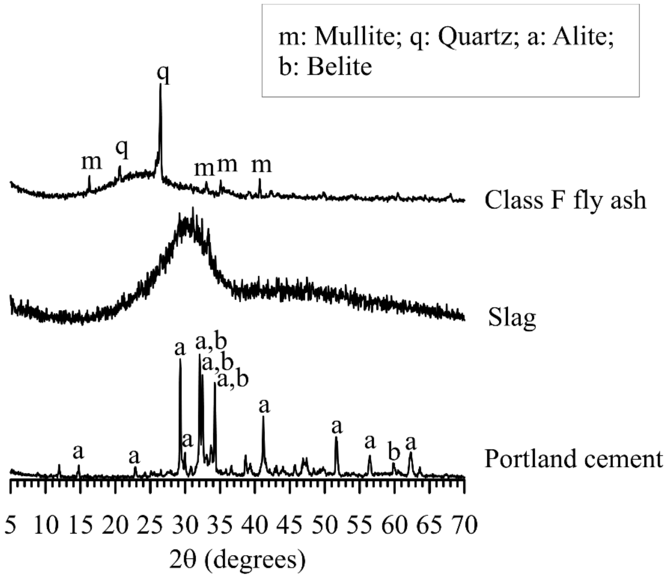

Figure 1. XRD patterns of three blended powders

Table 2. Particles size distributions of fine aggregate (FA)

Sieve size (mm)	Accumulated percentage retaining (mass.%)	Limit ranges suggested by TCVN 7572-2:2006	
		Coarse FA	Fine FA
5	0	-	-
2.5	0.05	0-20	0
1.25	0.15	15-45	0-15
0.63	0.65	35-70	0-35
0.315	34.8	65-90	5-65
0.14	96.75	90-100	65-90
Bottom	100	90-100	65-100

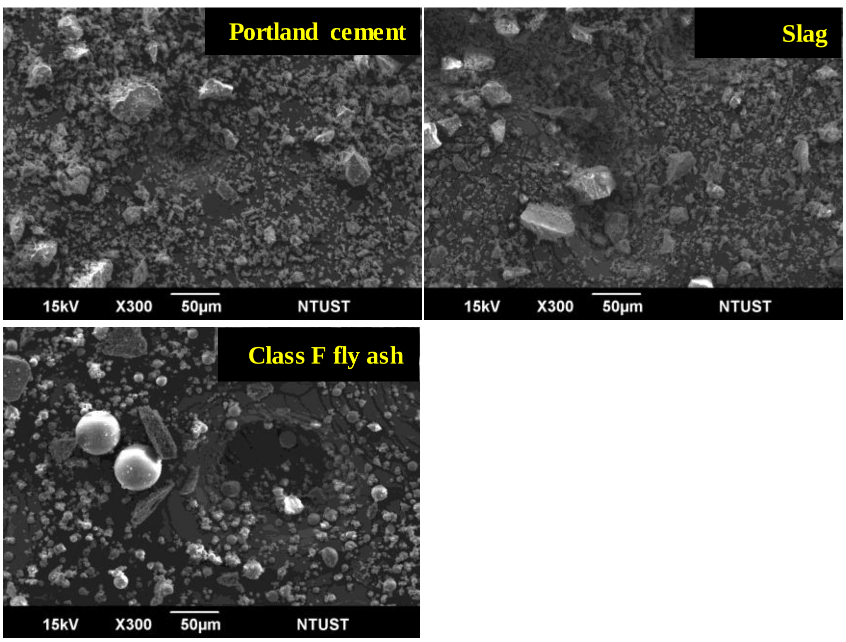

Figure 2. SEM images of the raw materials

2.2. Preparation and characteristics of the ALWA

The agglomeration process as shown in Figure 3 was applied for manufacturing the ALWA using a proportion being comprised of 90% FFA and 10% OPC, following the method of Hwang & Tran (2015; 2016). The two raw materials of FFA and PCB were firstly combined to become homogeneous mixture and used as the main precursor of the ALWA. The agglomeration process included three main periods: 1/ the feeding period in which the binary mixture of PCB and FFA was gradually fed in the rotating disc being set at the desired rotation speed and incline angle; 2/ the nucleation period where the water was sprayed on the powder mixture in the disc to initiate the spherical ALWA particles; and 3/ maintenance period in which the agglomerated ALWA particles were maintained in the rotating disc over a specific period of time. After being agglomerated, the ALWA particles were cured at temperature of 27°C and RH of 95% for 28 days before being sieved to remove the particles with of sizes larger than 5 mm. In this study, the bulk dried density of the ALWA was 943 kg/m^3 which was in range of 500–1000 kg/m^3 normally assigned to typical lightweight aggregates. The particle size distribution of the ALWA is illustrated in Table 3. Especially, the water absorption of the ALWA was 18% which was in range of 6–31% normally required for the appropriate IC agents (Castro et al., 2011).

Figure 3. Manufacture process of ALWA

Table 3. Particles size distribution of ALWA

Sieve size (mm)	Accumulated percentage retaining (mass.%)	Limit ranges suggested by TCVN 6220:1997 for different applications		
		Load bearing	Load bearing and heat and acoustic isolation	Heat and acoustic isolation
5	0	0–10	0–10	-
2.5	89.8	-	-	-
1.25	98.1	20–60	30–50	-
0.63	99.05	-	-	-
0.315	99.35	45–80	65–90	-
0.16	99.5	70–90	90–100	-
Bottom	100	-	-	-

2.3. Mix proportions, specimen preparation and test methods

The mortar binders contained 5% PCB, 10% gypsum, and 85% slag by mass. The water-to-powder ratio (w/p) was fixed at 0.4. For preparing the reference SSC mortar, a FA-to-powder mass ratio was fixed at 2.0. For evaluating the effect of IC agent on performance of the IC-SSC mortar, the saturated ALWA was used as partial replacement of FA at four values of 25, 50, 75, and 100 vol.%. The mix proportions of the SSC mortars are shown in Table 4. After being mixed, the flow table test in accordance with TCVN 3121-3:2003 was conducted to estimate the workability of the fresh mortars. On the other hand, the tests on compressive strength using the prisms with dimensions of 40×40×160 mm^3 according to TCVN 3121-11:2003 and drying shrinkage using the prisms with dimensions of 25×25×285 mm^3 according to TCVN 8824:2011 were conducted for assessment on the performances of the hardened mortars. After being cast, all mortar specimens were initially cured at ambient temperature for 24 hours before being removed and cured in air at 27±2°C and 65% RH until testing.

Table 4. Mix proportions of SSC mortars with different ingredients, kg/m³

	Slag	Gypsum	PCB	Sand	ALWA	Water
L0	566	67	33	1333	-	267
L25	566	67	33	1000	211	267
L50	566	67	33	667	421	267
L75	566	67	33	333	632	267
L100	566	67	33	-	843	267

3. RESULTS AND DISCUSSIONS

3.1. Workability

The workability results are shown in Table 5 and Figs. 4. As can be seen from Table 5, the fresh SSC mortars had flowing diameters in the range of 12–18 cm. The addition of ALWA-based IC agents partially replacing FA at values in range of 0–50 vol.% enhanced the workability of the fresh SSC mortars due to the increments of flowing diameters. Such results are due to both the improvement of the aggregate grading and the reduction on interfacial friction induced by spherical shapes of the ALWA particles. Further increasing the amounts of ALWA partially substituting FA at values in the range of 75–100 vol.% showed a slight decrease in the flowing diameters of the fresh IC-SSC mortars, which can be possibly attributed to excessive addition of ALWA significantly increased the fineness modulus (FA) of the aggregate and thus led to a lack of paste volume for achieving flowing ability of the fresh mortars. But, when compared with the reference SSC mortar without IC agents, the IC-SSC still showed the better workability, regardless of ALWA amounts. Such results are opposite to the effect of recycling aerated concrete blocks (ACB) and sintered clay bricks (SCB) as IC agents on the workability of the fresh mortars as previously reported (Liu et al., 2020). In this study, the ALWA additions partially replacing FA in the range of 25–50 vol.% resulted in the best workability of the fresh mortars.

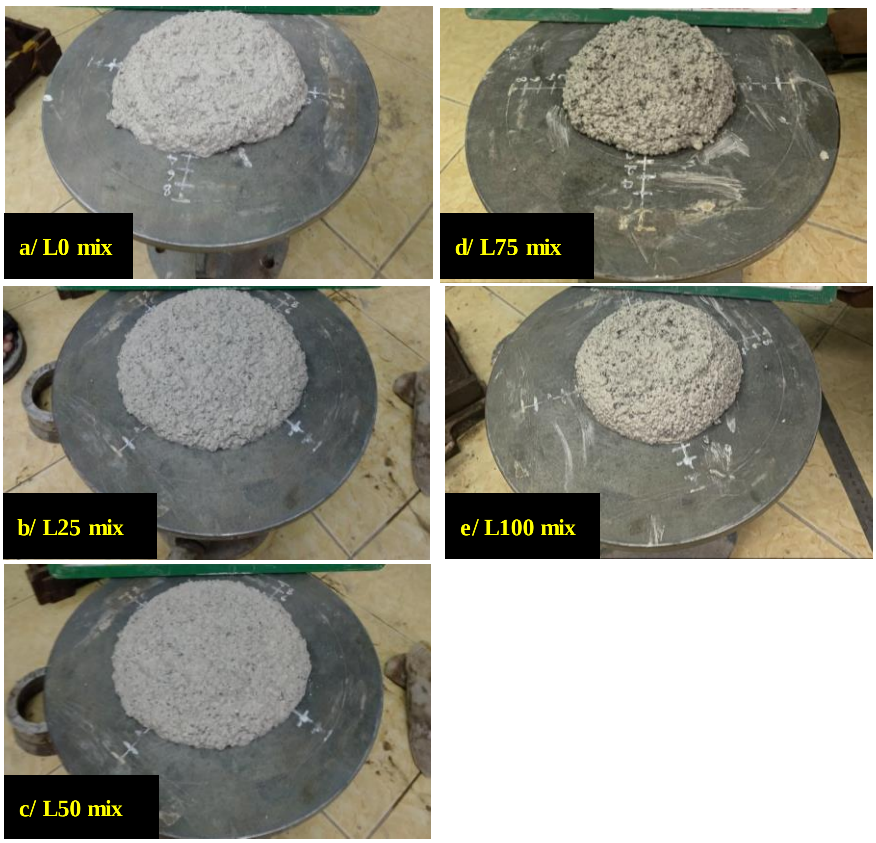

Figure 4. Effect of ALWA on the workability of fresh SSC mortars

Table 5. Workability of SSC mortars with different ingredients

	ALWA:Sand	Flow diameter, cm
L0	0:100	14
L25	25:75	16
L50	50:50	16
L75	75:25	14.5
L100	100:0	14.5

3.2. Unit weight and dried density

The unit weight and dried density of the SSC mortars are shown in Figure 5. Accordingly, the unit weight and the dried density of the fresh and hardened SSC mortars were in the ranges of 1637–2123 kg/m^3 and 1428–1926 kg/m^3, respectively. The ALWA addition as partial replacement of FA remarkably reduced both the unit weight and dried density of the SSC mortars when compared with the reference SSC mortar without ALWA addition. Such results are possibly due to the lower density of the ALWA, when compared with that of the FA. Obviously, this obtained result significantly confirmed the advantage of utilizing the ALWA based IC agent to reduce the self-weight of construction structures.

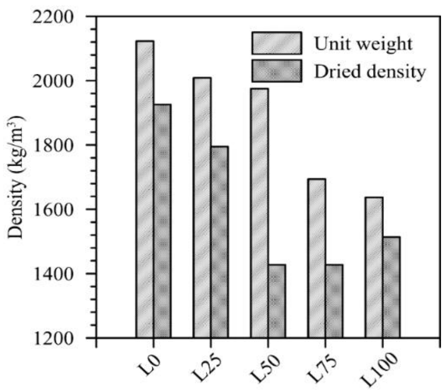

Figure 5. Unit weight and dried density of the SSC mortars

3.3. Compressive strength

The compressive strengths of the hardened mortar specimens were illustrated in Figure 6.

Accordingly, the compressive strengths increased with the increased ages due to the increased degree of hydration. In general, the compressive strengths of the hardened IC-SSC mortars reduced with the increment of the ALWA partially substituting FA at values in range of 0–100 vol.%. Such results are crucially due to the mechanical properties of the ALWA particles being lower than those of the FA particles. Yet, Figure 6 indicates that when compared with the reference SSC mortar, the IC-SSC mortar with ALWA partially replacing FA at 25 vol.% shows comparable compressive strengths at all days. At 28 days of curing, the compressive strength of the IC-SSC mortar containing up to 50 vol.% ALWA partially replacing FA, was unremarkably lower than that of the reference SSC mortar. Probably, the adjusted addition of the ALWA based IC agent crucially supplied the water for assuring the proper hydration of the binder and thus resulted in a certain compensation for the compressive strength reduction of the hardened IC-SSC mortar. However, further ALWA additions in the range of 75–100 vol.% resulted in a lack of binder volume to fill the voids generated by poorly packed aggregates as aforementioned. Obviously, the suggested amount of the IC agent, i.e., up to 50 vol.% replacing FA, as obtained in this study, was largely different from the optimal amount of 10 vol.% as previously reported (Liu et al., 2020). This is probably due to the varied properties of the materials used. On the other hand, when commercial ALWA based IC agent was applied (Shen et al., 2021), the optimum amount of IC agent replacing FA was seen to be as high as 60 vol.%, which was higher than the desired value of 50 vol.% in this study. These results are possible due to the better physical properties of the commercial ALWA.

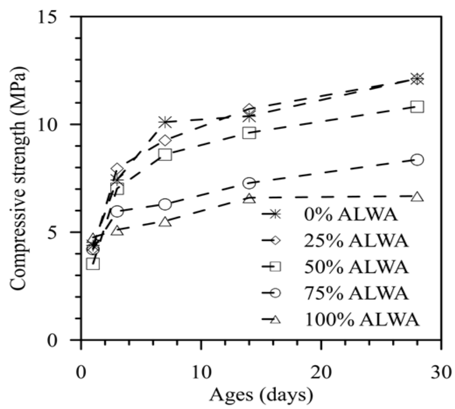

Figure 6. Compressive strengths of the hardened super sulfated cement mortars

3.4. Drying shrinkage

The drying shrinkage of the hardened SSC mortars is illustrated in Figure 7. Accordingly, the drying shrinkage increased with increase in age due to an accumulated evaporation of water from the mortar specimens. As expected, the addition of the saturated ALWA particles alleviated the self-desiccation effect, and thus decreased the early drying shrinkage of the hardened mortar specimens. At later ages, the increased amount of the ALWA partially replacing FA at values in the range of 25–75 vol.% capriciously influenced the drying shrinkage of the hardened IC-SSC mortars. But the shrinkage discrepancy between the reference and IC-SSC mortars remained minor. This is probably due to the self-assembling phenomenon of the aggregates (Liu et al., 2020). Further increases of ALWA totally replacing FA slightly improved the drying shrinkages of the IC-SSC mortars when compared with the reference mortar. This is probably due to the pozzolanic activity of the ALWA, reducing the porosity in the interfacial transition zones and thus lowering the shrinkage observations (Liu et al., 2020). Particularly, the IC effect is also a crucial factor attributed to lowering drying shrinkage of the IC-SSC mortars due to the decreased reduction on the inner humidity within the mortar specimens.

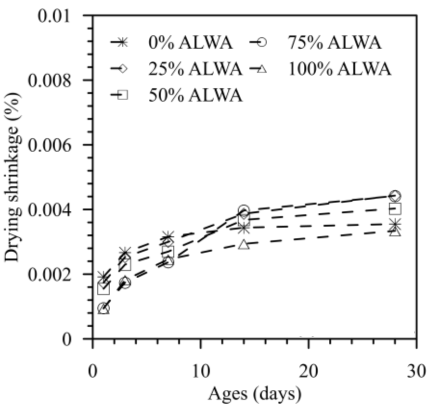

Figure 7. Drying shrinkage of the hardened super sulfated cement mortars

4. CONCLUSIONS

The effect of cold-bonded fly ash agglomeration based on the artificial lightweight aggregate (ALWA) as internal curing (IC) agent on the compressive strength and drying shrinkage of typical super-sulfated cement (SSC) mortars have been explored. According to the observed experimental results, the following conclusions should be drawn:

1. The workability of the fresh SSC mortars containing various amounts of IC agent, i.e., ALWA, partially replacing fine aggregate (FA) in the range of 25–100 vol.% was significantly improved.

2. The increased amount of ALWA decreased compressive strengths of the hardened SSC mortars. The hardened SSC mortars containing ALWA as partial substitution of FA up to 50 vol.% exhibited little reduction in 28-day compressive strength when compared with the reference mortar without IC agents.

3. The increase of ALWA additions replacing FA in the range of 0–100% had little impact or slightly improved drying shrinkage of the IC-SSC mortars due to the IC effect.

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