Journal of Science and Technology in Civil Engineering, HUCE (NUCE), 2023, 17 (1): 94–110

UTILIZATION OF ARTIFICIAL LIGHTWEIGHT AGGREGATE AND UNGROUND RICE HUSK ASH AS INTERNAL CURING AGENTS TO MODIFY PERFORMANCE OF SUPER-SULFATED CEMENT MORTAR

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Article history:
Received 13/01/2023, Revised 19/02/2023, Accepted 16/3/2023

Abstract

This study attempts to utilize cold-bonded fly ash based artificial lightweight aggregate (ALWA) and retrieved unground rice husk ash (URHA) as internal curing (IC) agents for improving performance of typical super-sulfated cement (SSC) mortar fabricated with ternary mixture of 85% slag, 10% gypsum, and only 5% blended Portland cement (PCB). The ALWA partially replacing fine aggregate (FA) at four values of 25, 50, 75, and 100 vol.% was used. For evaluating impact of using hybrid addition of IC agents on performances of SSC mortars, the ALWA amount after being optimized was partially replaced by URHA at four levels of 25, 50, 75, and 100 vol.%. Experimental results showed that, ALWA partially replacing FA up to 50 vol.% led to the SSC mortars with remarkably increased workability and uncompromised impacts on the strengths and durability. Addition of URHA partially replacing ALWA significantly improved the fresh properties and flexural strength but it negatively impacted the durability performances of the resultant SSC mortars in terms of increased water absorption, decreased UPV, and increased drying shrinkage.

Keywords: super-sulfated cement; unground rice husk ash; internal curing; engineering properties; durability

https://doi.org/10.31814/stce.nuce2023-17(1)-08

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1. Introduction

Super-sulfated cement (SSC), being typically produced with minuscule content of ordinary Portland cement (OPC) has been used as an alternative binder to the ordinary Portland cement (OPC) in Europe and India due to beneficial effects of simple manufacture, little consumption of natural material and energy and low carbon dioxide emissions [1–4]. In general, the proportions of the SSCs include 80–85% ground granulated blast furnace slag (GGBFS/slag), 10-15% calcium sulfate under different chemical formations and only about 5% OPC/lime serving as the alkaline activator [1, 4]. For formulating the commercial SSCs with adequately high quality, using primary powder, i.e., slag, with sufficiently large amount of alumina has been quintessential, which is possibly unavailable in

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widespread areas [5, 6]. Consequently, most of the commercial SSCs has been superseded due to a lack of slag with appropriate chemical composition as aforementioned and/or extra cost induced by advanced chemical treatment applied for raw material [7].

Recently, productions of environmentally friendly SSCs containing calcium sulfate derived from various industrial by-products such as flue gas desulfurization gypsum and circulating fluidized bed combustion ashes receive a serious consideration from the modern cement/concrete industries to persuade the sustainability development [8]. But, the mechanical properties of the low energy SSCs were obviously unsatisfactory to be widely applied for construction fields where the OPC has been properly used [9–11] For enhancing the SSC performance, instead of adapting physicochemical treatment, lowering water content in the SSC proportions seems to be the most preferable consideration to minimize the cost [11], which possibly led to increased risk of shrinkage issue induced by self-desiccation phenomenon as subsequently described [12].

Proper curing regime including appropriate temperature and adequate water supply over certain period of time is significant for hydration of cementitious binder in concrete. Traditional concrete is cured by applying external curing (EC) methods where the water supply coming from surrounding environment plays an important role in maintaining the hydration process of the binder. Currently, high performance concretes become gradually dominant in construction sectors due to a growing focus on durability. By using low water content accompanying with workability modifying chemical admixture, the concrete structure becomes more condensed, which resists water penetration from surrounding environment and thus lowers the efficiency of the EC. As such, continuous hydration of cementitious binder induces reduction of water from capillary pores and thus results in increased internal stress, which is known as self-desiccation phenomenon increasing risk of shrinkage. For overcoming the problem, mitigating reduction of internal humidity in concrete mixture is a quintessential consideration.

Internal curing (IC) has been developed to maintain proper hydration process of cementitious binder by supplying internal water reservoirs in concrete mixture without impacts on the workability and hardened performance of the resultant concrete. Therefore, IC is considered as an effective technique to resolve the issue related to high autogenous shrinkage of concrete, especially the high performance concrete. In general, tremendous types of appropriate porous materials such as superabsorbent polymer (SAP) [13], wood fibers [14], rice hush ash (RHA) [15], mixture of aerated concrete blocks (ACB) and sintered clay bricks (SCB) [16], and lightweight fine aggregate (LWFA) derived from either natural [17, 18], or artificial productions [19–21] have been successfully applied for IC concretes. Among the aforementioned IC agents, LWFA seems to be a preferable choice due to the specialized benefits of simple manufacture and easy quality control. Since the 1950s, excellent effect of utilizing saturated LWFA based IC agent as partial replacement of conventional fine aggregate (FA) has been identified [22, 23]. Apparently, commercially available expanded shale, clay, and slate based LWFAs have been widespread used for improving shrinkage of ultra-high performance concrete [24, 25]. In addition, LWFA produced with compaction of alkali-activated bottom coal ash [26] was also utilized in IC concrete. Currently, cold-bonded fly ash based artificial lightweight aggregate (ALWA) with low energy consumption could be a promising alternative IC agent to ramp up sustainability concept, but its' applicability seems to be limited as coarse aggregate fraction in concrete productions [27, 28].

According to above review points, although beneficial effects of different IC agents on enhanced performance of concrete have been well-understood, an existing gap associated with impact of IC on performance of modified green cement, particularly emphasizing on SSC, is still unaware. Moreover, applicability of simultaneous using of cold-bonded fly ash LWFA and URHA as the IC agents has been also unexplored. Therefore, this study attempts to initially evaluate comprehensive performance of the SSC mortars modified with hybrid utilization of these two IC agents in order to fulfill the database related to IC modified low energy binder. Alternately, the significance of the current study is also expanded to lay an essential foundation for persuading concept of sustainability development by maximizing additions of low energy materials such as cold-bonded fly ash LWFA and URHA in concrete/mortar productions which were effectively applied for construction fields where the superior resistance to sulfate attach was seriously required.

2. Experimental program

2.1. Materials

Commercial products of blended Portland cement (PCB) and gypsum and industrial by-products of low calcium Class F fly ash (FFA) and ground granulated blast furnace slag (GGBFS/slag) were used for manufacturing the ALWA and SSC binder. The physicochemical properties and mineral compositions of the raw materials were detected using X-ray fluorescence (XRF) and X-ray powder diffraction as shown in Table 1 and Fig. 1, respectively. Accordingly, PCB was primarily comprised of CaO rich alite and belite crystals. On the other hand FFA was mostly comprised of mullite and quartz crystals which were rather stable in low to mid concentration of alkali. Different from FFA, GGBFS mostly contained calcium and magnesium oxides and tremendous amount of amorphous silica and alumina, which was assigned to the high reactive pozzolanic material (Table 1 and Fig. 1). The features of the raw materials' particles were shown in Fig. 2. Accordingly, the FFA particles were mostly spherical shapes when compared with the irregular shapes of the others. For manufacturing control SSC mortar, natural fine aggregate (FA) with specific gravity of 2.68, fineness modulus (FM) of 1.32 and water absorption of 1.5% was used. The particle size distribution of FA was conducted based on TCVN 7572-2 [29] as shown in Table 2, illustrating that the FA contained rather high fraction of fine particles. For evaluating effect of internal curing (IC) on SSC mortar performance, both cold-bonded fly ash artificial light weight aggregate (ALWA) and retrieved unground rice husk

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

	Slag	Class F fly ash	Portland cement	Gypsum	URHA
Specific gravity	2.86	2.13	3.05	2.68	1.28
Water absorption, %					44
SiO_2, %	38.01	58.77	22.45	-	> 95%
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	-	

ash (URHA) were also used. The manufacturing process applied for ALWA was just subsequently described.

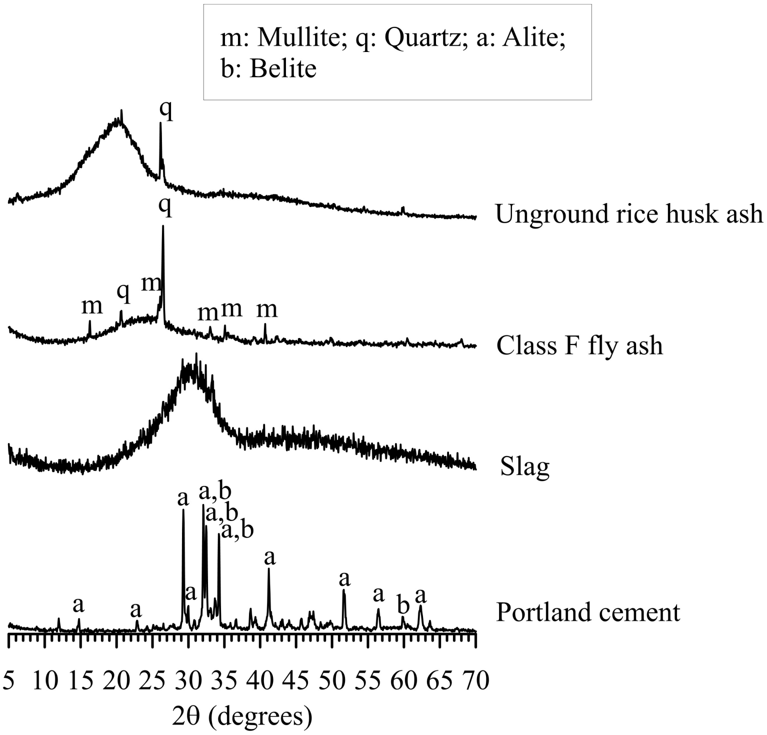


Figure 1. XRD patterns of raw materials

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

Sieve size (mm)	Retaining amount (%)	Accumulated retaining amount (%)	Limit ranges suggested by TCVN 7572-2	
			Coarse FA	Fine FA
5	0	0	-	-
2.5	0.05	0.05	0-20	0
1.25	0.1	0.15	15-45	0-15
0.630	0.5	0.65	35-70	0-35
0.315	34.15	34.8	65-90	5-65
0.140	61.95	96.75	90-100	65-90
Bottom	3.25	100	90-100	65-100

2.2. Preparation and characteristics of the ALWA

The ALWA proportion was comprised of 90% FFA and 10% OPC by mass. The fundamental manufacturing process of ALWA was based on the cold-bonded agglomeration as previously described [27, 28] as shown in Fig. 3. After being agglomerated, the ALWA products were suffered from a curing regime of temperature of 27°C and RH of 95% for 28 days. After that, the hardened

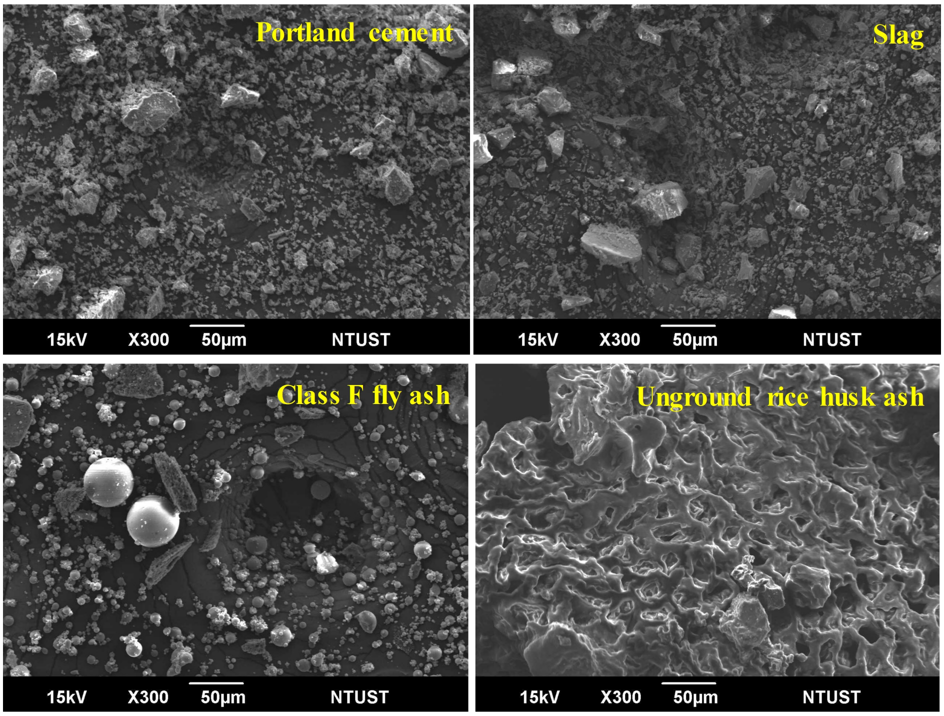


Figure 2. SEM images of the raw materials

ALWA particles were sieved to remove the particles with the sizes larger than 5 mm, and then used for producing mortars. In this study, the dried density of the ALWA being conducted according to TCVN 6221 [30] was 943 kg/m^3 which was in range of 500-1000 kg/m^3 normally assigned to the aggregates used for concrete productions as suggested by TCVN 6220. The particle size distribution of the ALWA was conducted in accordance to TCVN 6221 [30] and shown in Table 3, indicating its' applicability for only nonstructural insolating concretes as suggested by TCVN 6220. The fineness modulus (FM) of the ALWA was 4.86. In addition the water absorption of the ALWA complying with TCVN 7572-4:2006 [31] was 18% which was in range of 6-31% assigned to satisfactory IC agent as previously suggested [25]. As such, instead of being suffered a suitable surface treatment for improving water absorption as previously reported [27], the untreated ALWA was directly used for mortar manufacture in order to cut the cost.

Figure 3. Manufacture process of ALWA

2.3. *Mix proportions*

The binding powders of all SSC mortars were comprised of 5% PCB, 10% gypsum, and 85% slag by mass. The water-to-powder ratio (w/p) fixed at 0.4 was used for all SSC mortars. To produce the reference SSC mortar, mass ratio of FA to binder was fixed at 2.0. For evaluating effect of internal curing (IC) on SSC mortar performance, ALWA was used as partial replacement of FA at four values of 25, 50, 75, and 100% by volume. In this study, the dried density as mentioned in Section 2.2 was used to identify the volume of the ALWA. After being optimized based on mechanical strengths, the ALWA amount was partially replaced by URHA at four values of 25, 50, 75, and 100% by volume to assess the synergistic impact of binary addition of the IC agents on the properties of the SSC mortars.

In this study, ALWA was firstly soaked in water for 30 min to reach the stage of saturated surface dry before being used as previous suggestion [27]. The proportions of the SSC mortars are shown in Table 4.

2.4. *Specimen preparation and test methods*

Immediately after being mixed, the fresh SSC mortars were tested for the slump flow by applying flow table equipment and unit weight in accordance to TCVN 3121-3 [32] and TCVN 3108 [33], respectively. To estimate the hardened properties of the SSC mortars, the tests on dried density complying with TCVN 3121-10 [34], compressive and flexural strengths according to TCVN 3121-11 [35], UPV complying with TCVN 9357:2012 [36], and water absorption according to TCVN 3121-18 [37] using the prismatic specimens with dimensions of 40×40×160 mm^3. At the ages of testing, each mortar sample used for the dried density test was dried in oven to reach a so-called stable weight and identified the volume based on measuring the samples' dimensions. The dried density then calculated as ratio of the stable weight to the volume. For the test of water absorption, the stable weight of the sample under saturated state obtained by water immersion was used. The samples applied for testing on the flexural and compressive strengths were suffered from 3-point bending and compressing processes. The strengths were defined as the failure stresses acting on the cross sections of the tested samples. The UPV was identified by dividing length of tested sample by time detected by the commercial ultrasonic transducer. On the other hand, the prisms with dimensions of 25×25×285 mm^3 were cast for the test on drying shrinkage according to TCVN 8824:2011 [38]. After being cast and

Table 3. Particles size distribution of ALWA

Sieve size (mm)	Retaining amount (%)	Accumulated retaining amount (%)	Limit ranges suggested by TCVN 6220 for different applications		
			Load bearing	Load bearing and heat and acoustic isolation	Heat and acoustic isolation
5	0	0	0-10	0-10	-
2.5	89.8	89.8	-	-	-
1.25	8.3	98.1	20-60	30-50	-
0.630	0.95	99.05	-	-	-
0.315	0.3	99.35	45-80	65-90	-
0.160	0.15	99.5	70-90	90-100	-
Bottom	0.5	100	-	-	-

Table 4. Mix proportions of SSC mortars with different ingredients

Mixes	Slag	Gypsum	Portland cement	Sand	ALWA	URHA	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
L50R25	566	67	33	667	316	80	267
L50R50	566	67	33	667	211	159	267
L50R75	566	67	33	667	105	239	267
L50R100	566	67	33	667	-	318	267

Note: ALWA = Artificial lightweight aggregate; URHA = Unground rice husk ash.

cured at ambient temperature for 24 hours, the hardened mortar samples were removed and cured in air at 27±2 °C and 65% RH until the ages of tests.

3. Results and discussions

3.1. Workability

The workability of the fresh SSC mortars was summarized and feasibly illustrated in Table 5 and Figs. 5–5, respectively.

Table 5. Fresh properties of SSC mortars with different ingredients

Mixes	ALWA:Sand	URHA:Sand	Flow diameter, cm	Unit weight, kg/m^3
L0	0:100	-	14	2123
L25	25:75	-	16	2009
L50	50:50	-	16	1975
L75	75:25	-	14.5	1694
L100	100:0	-	14.5	1637
L50R25	-	25:75	18	1864
L50R50	-	50:50	16.5	1811
L50R75	-	75:25	17	1694
L50R100	-	100:0	17	1669

Note: ALWA = Artificial lightweight aggregate; URHA = Unground rice husk ash.

Accordingly, flowing diameters of the fresh SSC mortars with/without the IC agents consisting of ALWA and URHA were in range of 14-18 cm. Addition of ALWA partially replacing FA in range of 0-50 vol.% increased the flowing diameters of the fresh SSC mortars, which was possibly attributed to both the improved grading of particle size distribution and the reduced interfacial friction induced by spherical shapes of the ALWA particles. But, further increase of the ALWA partially replacing FA in range of 75-100 vol.%, slightly decreased the workability of the fresh SSC mortars due to minor decrease in flowing diameter. Such result was possibly due to excessive amount of coarser ALWA

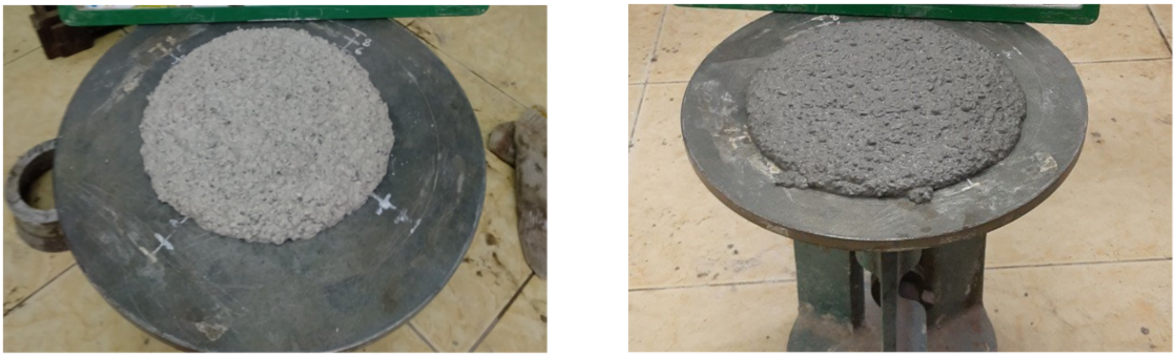
(a) L0 mix (b) L25 mix

(c) L50 mix (d) L75 mix

(e) L100 mix

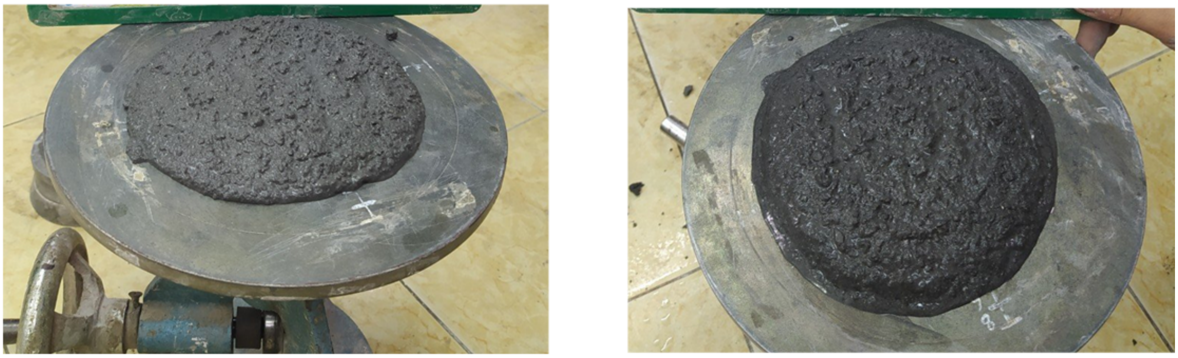
Figure 4. Effect of ALWA on workability of fresh SSC mortars

when compared with FA particles resulted in increasing paste demand for achieving the workability of the fresh SSC mortars. In this study, ALWA partially replacing FA in range of 25-50 vol.% induced the fresh mortars with the best flowing ability due to the highest flowing diameters. By fixing amount of ALWA at desired value of 50 vol.% as partial replacement of FA, addition of URHA partially replacing FA in range of 25-100 vol.% decreased the flowing diameters of the fresh SSC mortars. Such result was primarily attributed to the irregular shapes of the URHA in comparison with the spherical shapes of the ALWA. In addition, the severely rough surface of the porous URHA particles was also a considerable factor inducing the reduction on workability of the fresh SSC mortars due to an increased interfacial friction among ingredients. However, when compared with the reference SSC mortar without IC agents, the IC-SSC with various amount and ingredients of the IC agents still had the better workability due to the higher values of flowing diameters, which was just opposite to the performance of the fresh IC mortar containing recycling aerated concrete block (ACB) and sintered clay brick (SCB) as previously shown [16]. Accordingly, the incorporation of ACB and SCB agents resulted in the reduced workability of the fresh IC mortars, which was possibly due to irregular shapes of these two materials. In addition, as suggested by the authors, the reduced workability of the fresh IC mortars was also attributed to the fast initial absorption of the fine particles with increases in surface area and porosity.



(a) L50 mix

(b) L50R25 mix



(c) L50R50 mix

(d) L50R75 mix

(e) L50R7100 mix

Figure 5. Effect of URHA on workability of fresh SSC mortars

3.2. Unit weight and dried density

The properties including unit weight and dried density of the fresh SSC mortars are shown in Fig. 6. As illustrated from the figure, 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 1605-1926 kg/m^3, respectively. The ALWA partially replacing FA respectively significantly decreased the unit weight and dried density of the fresh and hardened SSC mortars. Such result was possibly due to the fact that the specific gravity of the ALWA was 0.943 as shown in Section 2.2 lower than the value of 2.68 of the FA as shown in Section 2.1. Especially, utilization of URHA as partial replacement of ALWA further decreased the unit weight and dried density of the fresh and hardened SSC mortars, respectively, which was primarily attributed to the porous structure of URHA particles. The obtained experimental result apparently indicated a beneficial effect of using the IC agents, particularly URHA, on reducing self-weight of the construction structures and thus reducing the construction cost. Obviously, the degrees of porosity of the IC agents was the crucial factor affecting the density of the resultant mortars, which was also mentioned in the previous publication [16].

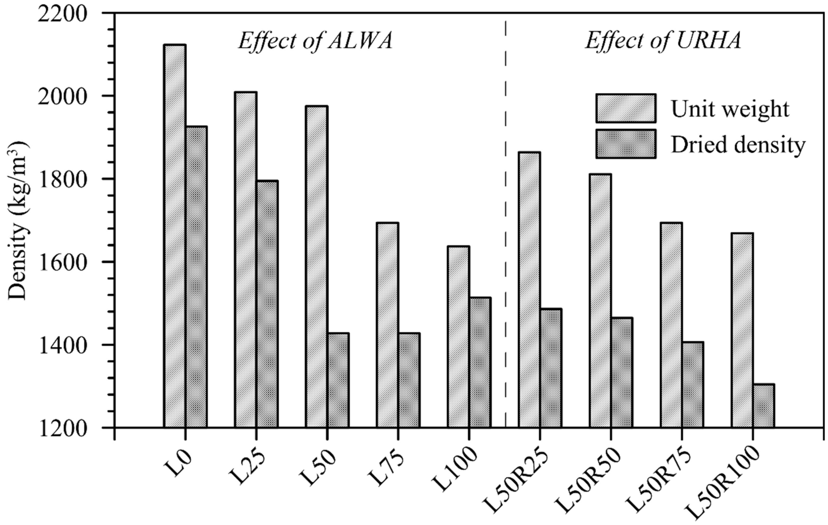
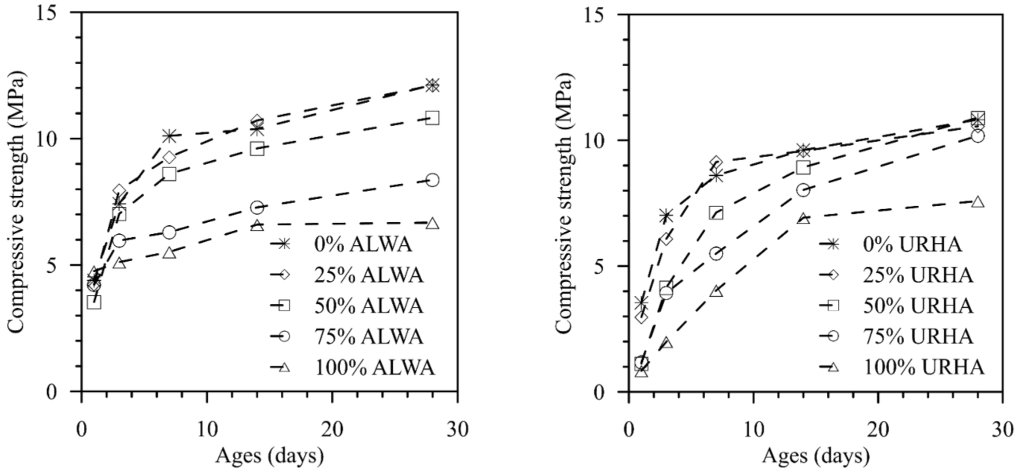


Figure 6. Dried density of the hardened super-sulfated cement

3.3. Compressive strength

The compressive strengths of the hardened SSC mortars was shown in Fig. 7. As being expected, the compressive strengths increased with the curing ages due to the enhanced degree of binder hydration. Generally, the compressive strengths of the SSC mortars decreased with the increased amount of ALWA partially replacing FA in range of 0-100 vol.%, which was primarily attributed to the lower mechanical performance of the ALWA particles in comparison with the FA particles. However, the observed result in Fig. 7 indicated that the SSC mortar containing ALWA partially replacing FA at 25 vol.% had the compressive strengths comparable to those of the reference SSC mortar without addition of IC agents at all ages of curing. At 28 days of curing, when compared with the reference SSC mortar, ALWA partially replacing FA at up to 50 vol.% insignificantly impacted the compressive strength of the IC modified SSC mortar due to minor strength reduction of 10.7%. Increased amount of ALWA addition at 75-100 vol.% replacing FA was associated with excessive amount of coarser

ALWA and thus resulted in lack of binder volume to fill the voids generated by poor packed aggregates. On the other hand, by fixing the ALWA amount at 50 vol.% as partial replacement of FA, using URHA as partial replacement of ALWA in range of 0-100 vol.% continuously decreased the compressive strengths of the hardened SSC mortars. Such result was attributed to the porous structure skeleton of the URHA particles.



(a) 0% URHA (b) 50% ALWA

Figure 7. Compressive strengths of the hardened super sulfated cement mortars

But, addition of URHA replacing ALWA at up to 75 vol.% unremarkably influenced 28-day compressive strength of the hardened SSC mortars as shown in Fig. 7(b), possibly due to the improved packing condition of the aggregates induced by filling effect of the URHA particles. Further increased addition of URHA replacing ALWA at 100 vol.% dramatically decreased the compressive strengths of the hardened SSC mortars, particularly at 28 days, due to excessive amount of fine particles led to lack of binding paste volume. As results, in this study, to produce the IC-SSC mortars with compromised 28-day compressive strength, the volume of IC agents replacing FA needed to be limited at 50 vol.% in which the volume ratio of URHA: ALWA was possibly varied at values from 0:100 to 75:25. Obviously, the suggested amount of the IC agents, i.e., up to 50 vol.% replacing FA, as obtained in this study was farther from the optimum around 10 vol.% of IC mortars containing aerated concrete block (ACB) and sintered clay brick (SCB) as suggested in previous studies [16], probably due to the differences in the binder and IC based aggregates usages. Probably, the SSC demanded more water for maintaining continuous hydration when compared with various SCM binders. However, as commercial ALWA was applied for IC concrete production [24], the optimum of IC agents replacing FA was even as high as 60 vol.% which was higher than value of 50 vol.% as obtained in this study, possibly due to the better physical properties of the commercial ALWA.

3.4. *Flexural strength*

The flexural strengths of the hardened SSC mortars with/without IC agents including ALWA and URHA at 28 days are shown in Fig. 8. In consistence with the compressive strength result, ALWA addition partially replacing FA at up to 50 vol.% insignificantly impacted 28-day flexural strength of the hardened IC-SSC mortar, but further increased amount of ALWA replacing FA at 75-100 vol.%

induced the IC-SSC mortars with significant fluctuation on the 28-days flexural strengths. On the other hand, when the ALWA amount was fixed at 50 vol.% as partial replacement of FA, the addition of URHA substituting ALWA at up to 100 vol.% gradually increased the 28-day flexural strengths of the hardened IC-SSC mortars. Particularly, the highest 28-day flexural strength of the hardened IC-SSC mortar was observed as URHA was set at 50 vol.% as a partial replacement of the ALWA. The result was possibly explained based on the improvement on interfacial transition zone (ITZ) attributed to the IC effect. As previously clarified [24], the presence of ALWA led to maintaining the internal relative humidity, which was favorable to the processing hydration of the binders and thus contributed to the pore refinement induced by higher polymerization degree of C-S-H precipitation.

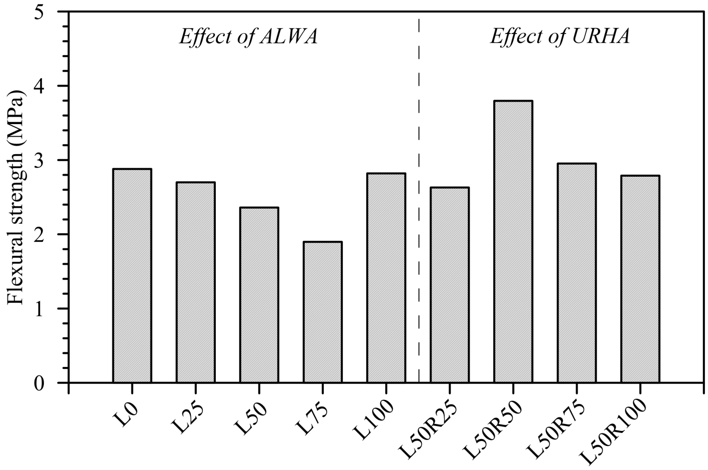
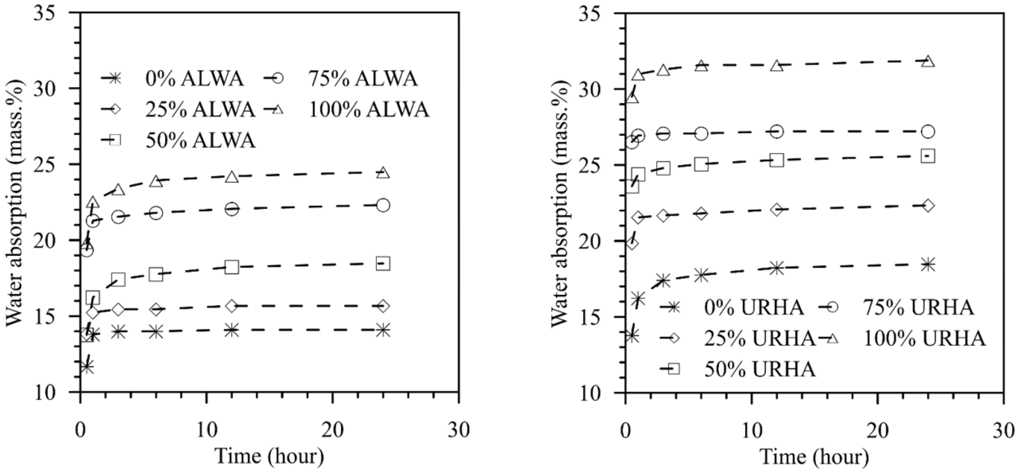


Figure 8. Flexural strengths of the hardened super sulfated cement mortars at 28 days



(a) 0% URHA

(b) 50% ALWA

Figure 9. Water absorption performances of the hardened super sulfated cement mortars

3.5. Water absorption

The water absorption performances of the hardened SSC mortars are shown in Fig. 9. The figure indicated that water absorption rates of the hardened SSC mortars with/without IC agents consisting of ALWA and URHA primarily gained during initial 6 hours. In general, addition of IC agents including either sole amount of ALWA or mixture of ALWA and URHA dramatically increased the water absorption of the hardened SSC mortars. Such result was possibly attributed to the high absorptivity of the IC agents. According to the previous study [16], incorporation of the porous IC agents resulted in the resultant mortars with increased porosity, which also corresponded to the mortar specimens with increased water absorption. As such, addition of the porous structure URHA particles was more favorable to the generation of porosity and thus more severely increased the water absorption of the IC-SSC mortars when compared with the effect of using ALWA in IC-SSC mortars. For alleviating the water absorption increment, the IC agent amount should be limited at 25 vol.% as partial substitution of FA. In addition, using URHA was improper for improving the water absorption of the IC-SSC mortars.

3.6. UPV

Effects of adding IC agents on the UPV of the hardened SSC mortars are illustrated in Fig. 10. Accordingly, the obtained UPV result was in good consistence to the observation on the water absorption performance as previously discussed. Indeed, the UPV values of the hardened SSC mortars significantly decreased with increased amount of the IC agents including ALWA and URHA. Such result was due to the decreased dried density of the mortar samples induced by the porous structures of the IC agents, which was clarified in the UPV-dried density relationship as shown in Fig. 11.

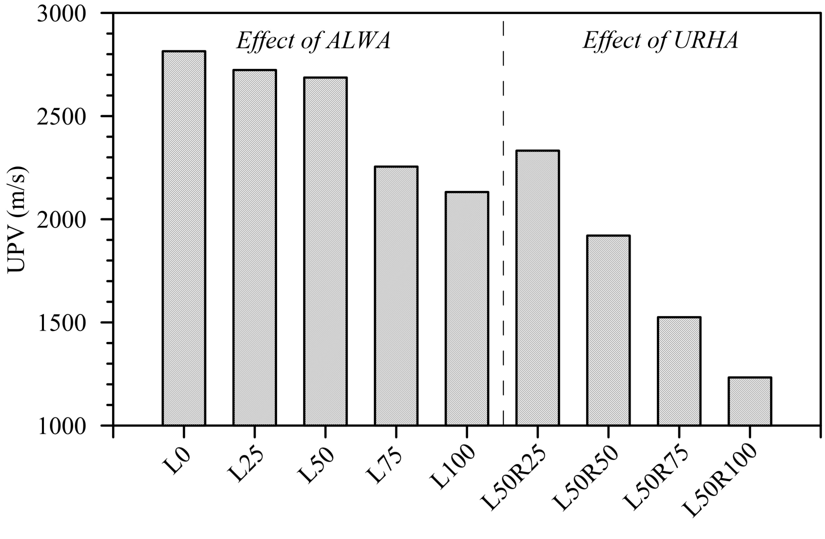


Figure 10. UPV of the hardened super sulfated cement mortars at 28 days

Accordingly, Fig. 11 showed that generally the higher value of dried density was associated with the specimen with the higher UPV value. Particularly, more negative impact on UPV of the hardened mortar samples on addition of URHA when compared with the ALWA addition was obviously obtained. Reasonably, the URHA particles owned porous structure being unfavorable to the ultrasonic

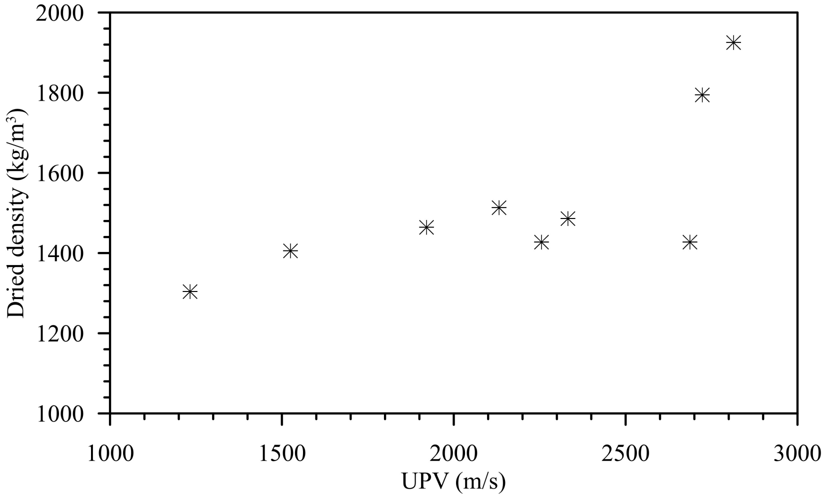
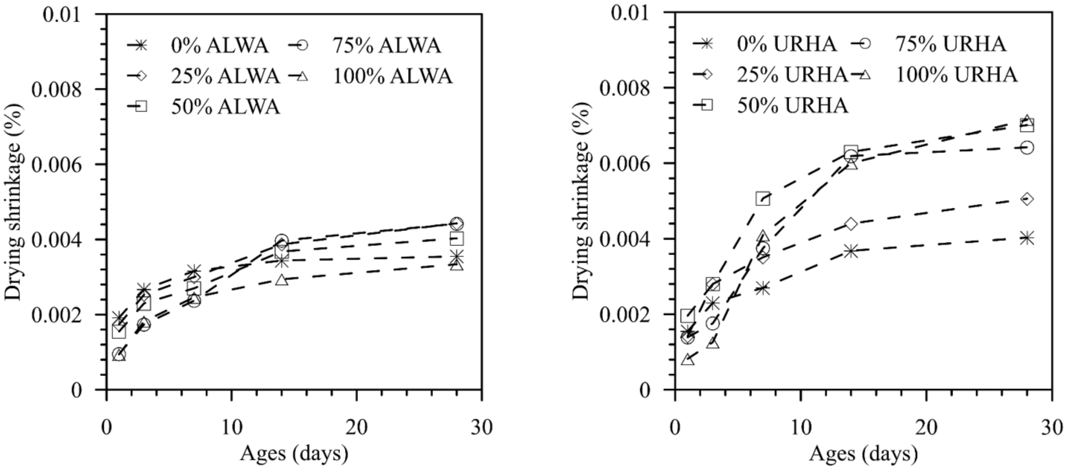


Figure 11. Relationship between UPV and dried density of the hardened super sulfated cement mortars

pulse transmission and thus illustrated a negative influence on the UPV value of the hardened IC-SSC mortars. For producing the IC-SSC mortars without compromised UPV values, sole addition of ALWA partially replacing FA at up to 50 vol.% should be considerably used. Such result was probably due to the pozzolanic reaction between the IC agents and alkali pore solution tended to reduce the porosity in the interfacial transition zones as previously suggested [16] and thus improved the UPV transmission.

3.7. Drying shrinkage

The drying shrinkage of the hardened SSC mortars with/without the IC agents is shown in Fig. 12. In general, the drying shrinkage values increased with increased ages of curing due to an accumulated evaporation of water from the mortar specimens into air. As being expected, the addition of the ALWA at saturated state alleviated the self-desiccation effect and thus decreased the drying shrinkage of the hardened SSC mortars at early. At later, increase of the ALWA replacing FA in range of 25-75 vol.% capriciously affected the drying shrinkage of the hardened IC-SSC mortars but the shrinkage discrepancy between the reference and IC-SSC mortars was just minor, which was probably attributed to self-assembling effect on aggregate mixture [16]. But, further increase of ALWA replacing FA at 100 vol.% slightly reduced drying shrinkages of the IC-SSC mortars when compared with the reference mortar, which was probably due to the pozzolanic activity of the ALWA tended to reduce the porosity in the interfacial transition zones and thus lowered the shrinkage observations [16]. On the other hand, when the ALWA amount was set at 50 vol.% as partial substitution of FA, increased addition of URHA partially replacing ALWA resulted in the hardened IC-SSC mortars with increased drying shrinkage, which was due to the lower elastic moduli and volume stability of the porous URHA in comparison with the ALWA [16]. In addition, the URHA with porous structures seemed to be vulnerable to the self-assembling effect. Moreover, the pozzolanic reactivity of URHA was normally too low, as clarified in the previous publication [39], to sufficiently compensate the long-term drying shrinkage of the mortar samples. For alleviating the drying shrinkage increment of the mortar specimens, addition of URHA as partial replacement of ALWA should be limited at 25 vol.%. In the previous study [16], aerated concrete blocks (ACB) and sintered clay bricks (SCB) with high water absorption were explored to serve as IC agents in mortars. Accordingly, hybrid addition of ACB and SCB considerably compensated the negative effect of sole addition of ACB on the drying shrinkage of the hardened mortars, which was obviously different from the result observed from the current study. Such result was possibly due to the stronger structural skeletons of the ACB-SCB mixture when compared with those of ALWA-URHA mixture.



(a) 0% URHA

(b) 50% ALWA

Figure 12. Drying shrinkage of the hardened super sulfated cement mortars

4. Conclusions

Effects of cold-bonded fly ash agglomeration based artificial lightweight aggregate (ALWA) and retrieved unground rice husk ash (URHA) acting as internal curing (IC) agents on the engineering and durability performances of a typical super-sulfated cement (SSC) mortars have been explored. According to the observed experimental results, the following conclusions should be drawn:

1. The workability, unit weight, and dried density of the SSC mortars containing various amount and ingredients of IC agents partially replacing fine aggregate (FA) in range of 25-100 vol.% were significantly improved, particularly as URHA was used.

2. The increased amount of the IC agents including ALWA and URHA decreased compressive strengths of the hardened SSC mortars. The hardened SSC mortars containing ALWA as partial substitution of FA up to 50 vol.% had the 28-day compressive strength unremarkably reduced when compared with the reference mortar without IC agents. Addition of URHA partially substituting ALWA gradually reduced the compressive strength of the hardened SSC mortars. The URHA addition was possibly considered at lower than 50 vol.% for alleviating the compressive strength reduction.

3. The flexural strengths of the hardened SSC mortars decreased with increased amount of ALWA partially replacing FA in range of 0-100 vol.%. By fixing amount of ALWA at selected value of 50 vol.% partially replacing FA, addition of URHA partially replacing ALWA in range of 25-100 vol.% positively improved the flexural strength of the hardened SSC mortars. 50 vol.% of URHA replacing ALWA was the optimum value due to the maximum flexural strength of the hardened IC-SSC mortars.

4. The increase of ALWA addition replacing FA in range of 0-100% unremarkably impacted or slightly improved drying shrinkage but significantly decreased the durability performances in terms of increased water absorption and decreased UPV. The URHA addition partially replacing ALWA

negatively impacted the durability performances of the hardened SSC mortars in terms of decrease in UPV and increases in drying shrinkage and water absorption. The utilization of URHA replacing ALWA should be limited at 25 vol.% for alleviating the durability issues.

Acknowledgement

The authors would like to acknowledge the financial aid from Can Tho University, through research grant of T2021-106, for this investigation.

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