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INFLUENCE OF ARTIFICIAL LIGHTWEIGHT AGGREGATE ON PROPERTY MODIFICATION OF UNFIRED BRICK WITH LOW ENERGY SUPER-SULFATED CEMENT

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Abstract

Rapid increase in concrete demand for infrastructural construction has been associated with depletion of natural resources, leading the urgent need to utilize manufactured materials substituting natural materials in concrete productions. This study proposes applying cold-bonded low calcium Class F fly ash (FFA) based artificial lightweight aggregate (ALWA) to partially replace natural fine aggregate in an ecological unfired brick with a low energy super-sulfated cement (SSC). To estimate the influence of ALWA on the brick properties, natural fine aggregate (FA) in the reference brick was substituted with ALWA at four different amounts of 25, 50, 75 and 100% by volume. Various properties including unit weight, flowability, dried density, compressive strength, water absorption, and drying shrinkage were investigated. Experimental results showed that ALWA addition as partial replacement of FA at all ratios resulted in the modified bricks with significantly increase in flowability and decreases in both unit weight and dried density. With neglecting minor reduction on compressive strength, the 75% ALWA substituting FA by volume was considered as the optimum value to manufacture the modified unfired bricks with remarkable enhanced performance.

Keywords: super-sulfated cement; artificial lightweight aggregate; unfired brick; engineering properties.

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1. Introduction

Aggregates have been the dominant materials in a vast number of industries, particularly the construction fields. For many past years, crucial dependence of construction material science on the aggregates led to depletion of the natural resources due to extreme exploitation. Thus, utilization of lightweight aggregate (LWA) for concrete productions has been urgently considered to resolve the abovementioned issue. Typically, the LWA was applied for manufacturing lightweight concretes with superior performance in terms of high thermal and acoustical insolation and better fire resistance when compared to those of the normal weight concretes. At present, cold-bonded fly ash based artificial lightweight aggregate (ALWA) has been extremely applied for concrete productions with desired

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properties. However, the existing issues associated with high water absorption and low mechanical strengths induced the extra costs for surface treatment and thus seemed to limit the application of ALWA for concrete productions [1, 2]. Therefore, exploring a potential applicability of the un-treated ALWA has been encouraged to increase the index of sustainable development.

During the past decades, brick has been one of the most crucial construction materials, and the worldwide demand for brick usage has gradually increased. Traditional brick has been typically manufactured by firing process of clay through high temperature kiln [3–8], hence possibly induced severe depletion of the virgin natural resources and released large amount of greenhouse gases [9]. Therefore, using cementitious binders for producing brick has become preferable for alleviating the environmental impacts [9]. In addition, application of binder based on alkali-activated material (AAM) with commercial strong alkalis of NaOH/KOH for practical brick productions has been reported [10–13]. For qualifying the requirements of safety, competitive cost, and ecological request, application of low alkali-sulfate activated pozzolanic material essentially based on the hydration mechanism of traditional super-sulfated cement has been proposed [14, 15], which was a fundamental principle for recycling the sulfate rich solid wastes in green brick productions [16, 17]. Besides the green binder, some current studies [18, 19] attempted to utilize rice husk ash and bottom ash to replace aggregate in ecological unfired brick productions.

Lightweight concrete (LWC) with distinguished characteristics of lower density and better acoustic and thermal properties when compared to the typical concrete has been envisaged to become the dominant construction materials efficiently applied for both load-bearing structures and non-load bearing walls [20]. Generally, the LWC categories consisted of no-aggregate, lightweight aggregate and cellular lightweight concretes, complying with the state-in-the-art principles of removal of heavy aggregates, incorporation of natural/artificial lightweight aggregate, and incorporation of foam created from mechanical and/or chemical methods, respectively. With an effort to minimize the concrete density, foamed concrete with addition of lightweight aggregate was interested. Among the LWC types, lightweight aggregate concrete (LWAC) and cellular lightweight concrete (CLC) with the superior engineering and durability performances were more efficiently than no-aggregate concrete when being applied for both concrete structures and non-structures [21]. Particularly for the building bricks, CLCs were probably the most appropriate due to the excellent insolation [22]. However, of the proper utilization of CLCs was typically associated with the unique awareness of the manufacturing and constructing techniques, which was possibly unavailable in some specific locations. According to the above literature review, utilization of LWAC for manufacturing building bricks seems to be still valuable. Moreover, influence of the cold bonded fly ash ALWA without surface treatment on the unfired brick performance has not been widely known. Therefore, the current study aims at exploring the effect of using the untreated cold bonded fly ash ALWA as natural fine aggregate replacement on the performance of the unfired brick produced with a low energy super-sulfated cement (SSC). Obviously, the attempt of this study is not only to visualize proper compatibility between these two ecological materials (i.e., the SSC binder and ALWA) but also to preliminarily propose such the innovative ecological unfired brick as one of the sustainable construction materials.

2. Experimental program

2.1. Materials

Commercial Type I ordinary Portland cement (OPC) and retrieved three industrial by-products of Class F fly ash (FFA), ground granulated blast furnace slag (GGBFS/slag), and flue gas desulfurization gypsum (FDG) all available in Vietnam were used to produce the ALWA and ecological

Table 1. Physical properties and chemical compositions of raw materials

	OPC	GGBFS/slag	FFA	FDG
Specific gravity	3.10	2.90	2.17	2.32
SiO_2, wt.%	22.45	38.01	58.77	-
Al_2O_3, wt.%	6.81	13.13	26.11	-
Fe_2O_3, wt.%	3.15	0.55	5.61	-
CaO, wt.%	60.03	36.80	2.07	-
MgO, wt.%	2.08	5.77	1.66	-
SO_3, wt.%	2.77	1.36	0.21	-
Na_2O, wt.%	0.55	0.13	0.27	-
K_2O, wt.%	0.79	0.78	1.48	-
TiO_2, wt.%	0.41	0.45	0.66	-
L.O.I, wt.%	0.95	3.01	3.11	-
$CaSO_4 \cdot 2\,H_2O$, wt.%	-	-	-	98.9

unfired bricks. 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, OPC mostly contained crystals of alite and belite rich in calcium oxide. On the other hand, the FDG was primarily comprised of gypsum. As being expected, FFA primarily contained mullite and quartz rich in alumina and silica while GGBFS mostly contained calcium and magnesia oxides and tremendous amount of amorphous silica and alumina (Table 1 and Fig. 1). As such, the reactivity of slag was possibly higher than that of FFA in reaction with the alkali solution supplied by OPC hydration. In addition, the features of the raw materials as shown in Fig. 2 illustrated that among four raw materials only FFA mostly contained the particles with spherical shapes. For producing the reference bricks, 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 [23] and shown in Table 2, showing that the FA contained rather high fraction of fine particles. In order to control the flowability of the fresh brick mixtures, commercial Type G super plasticizer (SP) was used.

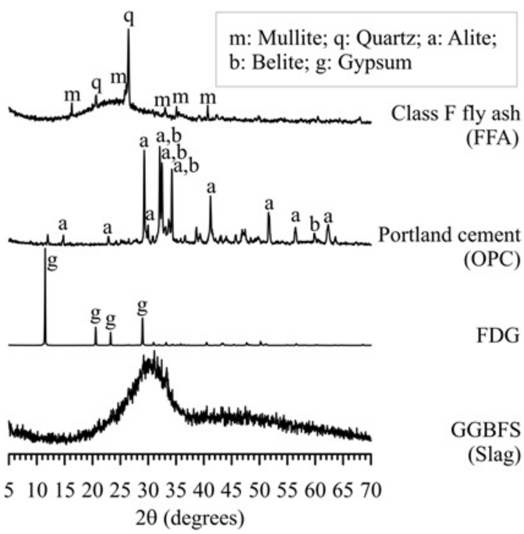


Figure 1. XRD patterns of three blended powders

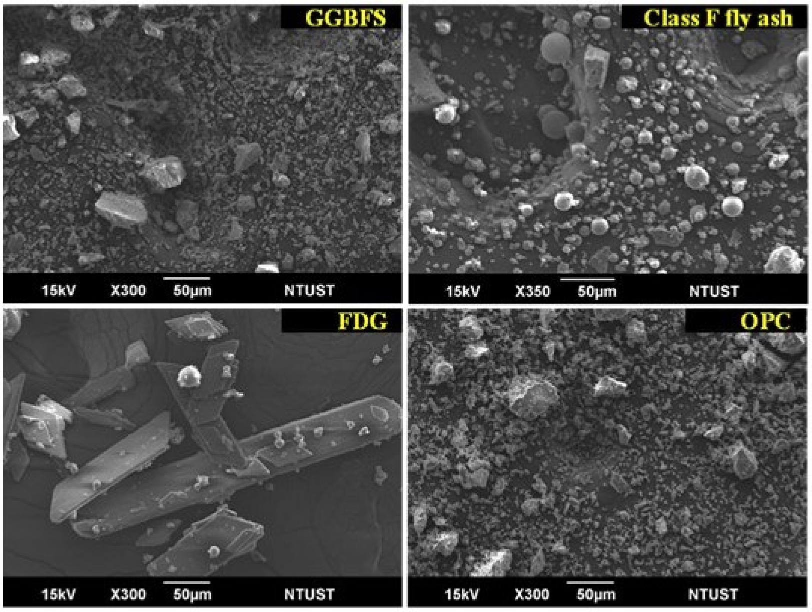


Figure 2. SEM images of three industrial waste particles

Table 2. Particle size distribution of natural fine aggregate

Sieve size (mm)	Percentage retained	Cumulative percentage retained	Standardized requirements	
			Coarse sand	Fine sand
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
Sieve bottom	3.25	100	90-100	65-100

2.2. *Preparation and characteristics of the ALWA*

The ALWA proportion included FFA and OPC mixture with a mass ratio of FFA:OPC = 90:10. The ALWA manufacture was based on the cold-bonded agglomeration process as described in the previous publications [1, 2] as shown in Fig. 3.

Figure 3. Manufacture process of ALWA

After being produced, the ALWA products were collected and cured at 27°C and 95% RH for 28 days, sieved to remove the particles with the sizes larger than 5 mm, and then used for the brick manufacture. Bulk dried density of the ALWA complying with TCVN 6221 [24] was 943 kg/m^3 which was in range of 500-1000 kg/m^3 and thus suitably applied for concrete productions as suggested by TCVN 6220 [25]. The particle size distribution of ALWA was conducted in accordance to TCVN 6221 [24] and shown in Table 3, which suggested its applicability for only nonstructural insolating concretes as defined by TCVN 6220 [25]. In this study, the FM and water absorption of the ALWA were 4.86 and 18%, respectively. Instead of being suffered surface treatment for enhancement of water absorption as suggested by the previous study [1], the untreated ALWA was directly used for brick manufacture for lowering the cost.

Table 3. Particle size distribution of ALWA

Sieve size (mm)	Percentage retained	Cumulative percentage retained	Standardized requirements		
			Structural concrete	Structural and insolating concretes	Nonstructural insolating concretes
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	-
Sieve bottom	0.5	100	-	-	-

2.3. Mix proportion, preparation, and test methods for bricks

In this study, the binder in bricks was produced with low energy super-sulfated cement (SSC) fabricated with 5% OPC, 10% FDG, and 85% slag by mass. The water-to-powder ratio (w/p) was fixed at 0.5. Four volume ratios of ALWA to FA of 25/75, 50/50, 75/25, and 100/0 were used for estimating the influence of the ALWA on the brick performance. 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 [1]. The mix proportions of the unfired bricks were detailed and shown in Table 4 whereas the superplasticizer (SP) dosage was used to maintain the equivalent flowability of the fresh brick mixtures. In this study, the flowability of the fresh bricks was investigated using the tube with diameter of 150 mm and height of 76 mm. For producing the fresh bricks with adequate flowability, the slump flow diameter of 250 ± 10 mm was achieved by adjusting SP dosage [26–28]. As such, during casting procedure, free vibration was applied to eliminate influence of vibrating energy on the brick performance. Immediately after being mixed, the fresh bricks were tested for the unit weight in accordance to TCVN 3108 [29]. In this study, the real-size bricks with dimensions of 40×85×160 mm^3 as shown in Fig. 4 were prepared for assessing the brick properties. After being cast and cured at ambient temperature for 24 hours, the hardened samples were removed and cured in air at 27±2 °C and 65% RH until the ages of tests. Compressive strengths of bricks were conducted in accordance to TCVN 6355-2 [30] using the manually modified specimens which were created by binding two halves, obtained by cutting the real-size specimens, with high strength mortar as shown in Fig. 4. The oven dried bulk density and water absorption of the brick samples were conducted using the real-size specimens in accordance to

TCVN 6355-4 [31] and TCVN 6355-5 [32], respectively. Moreover, drying shrinkage along the brick length was tested in accordance to TCVN 7959 [33].

Table 4. Mixture proportions of unfired bricks (kg/m^3)

Mixture designations	Slag	FDG	OPC	Water	FA	ALWA	SP
M0	563	66	33	331	1163	-	1.7
M25	563	66	33	331	872	184	0.4
M50	563	66	33	331	581	368	-
M75	563	66	33	331	291	551	-
M100	563	66	33	331	-	735	-

Note: FDG = Flue gas desulfurization gypsum; OPC = Ordinary Portland cement; FA = Fine aggregate; LWA = Lightweight aggregate; SP = Superplasticizer.

(a) Real-size brick sample

(b) Modified brick sample

Figure 4. Features of unfired brick specimens with real size of 40×85×160 mm (left), and combined two halves (right)

3. Results and discussions

3.1. Fresh properties

Influence of ALWA on fresh properties of the unfired bricks were visualized and summarized in Fig. 5 and Table 5, respectively. Fig. 5 showed that the modified unfired brick with ALWA illustrated a highly adequate flowability without impacts related to segregation and bleeding, which preliminarily indicated the resultant bricks with excellent consistency. In order to feature superb dispersal of ALWA in the modified unfired bricks, the cross sections of the hardened brick samples were also provided as shown in Fig. 5, in which a high homogeneity of the brick mixtures was obviously revealed. In addition, Table 5 showed that the target slump flow diameter, i.e., 250 ± 10 mm, was successfully achieved for all brick proportions. When compared with the reference brick without ALWA addition, the modified unfired bricks with ALWA replacing FA consumed less amount of SP, implying that the ALWA significantly improved the consistency of the fresh bricks. As shown in Table 5, the ALWA addition replacing for the FA at up to 50% by volume unremarkably affected the unit weight of the modified bricks when compared with the reference bricks without ALWA addition, possibly due to the structure of the ALWA modified bricks seemed to be more condensed. Further increase of the ALWA addition as FA substitution at 75-100% by volume induced the fresh modified bricks with reduced unit weight, which was due to the lower density of the ALWA than that of the FA. In this study, the improvement of fresh property of the ALWA modified bricks in comparison with that of the reference brick without ALWA addition was probably due to the optimized particle size distribution which was subsequently discussed. In addition, the mostly spherical sharp of ALWA particles (Fig. 6) was also attributed to reducing friction among the brick ingredients and thus increasing the flowability of the fresh modified bricks.

Figure 5. Flowing feature of the ALWA modified unfired bricks

Table 5. Fresh properties of unfired bricks

Mixture designations	ALWA:FA volume ratio	SP amount (kg/m^3)	Slump flow diameter (mm)	Unit weight (kg/m^3)
M0	0:100	1.7	260	2048
M25	25:75	0.4	240	2078
M50	50:50	-	255	1991
M75	75:25	-	260	1888
M100	100:0	-	250	1833

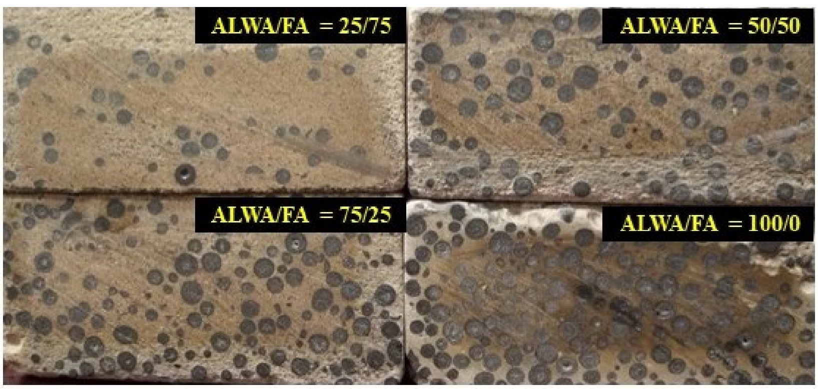


Figure 6. Cross section of the ALWA modified unfired bricks

3.2. *Compressive strengths*

Compressive strengths of the hardened unfired bricks with/without ALWA addition were shown in Fig. 7. Generally, the increment of the ALWA further decreased the 28-day compressive strengths of the hardened modified bricks when compared with the reference without ALWA addition, which was attributed to the lower strength of the ALWA. However, the ALWA addition substituting FA at up to 75% by volume insignificantly reduced the 28-day compressive strengths of the modified unfired bricks in comparison with the reference brick without ALWA addition. Indeed, the hardened unfired bricks modified with ALWA as FA substitution at values in range of 25-75% by volume had the 28-day compressive strengths reaching 89.91-98.06% of that of the reference unfired bricks without ALWA addition. Such result implied that utilization of ALWA as partial substitution of FA at appropriate level, i.e., 25-75% by volume, possibly resulted in the brick structure with high level of condensation and thus efficiently compensated the compressive strength reduction. In this study, the 28-day compressive strengths of the modified unfired bricks with ALWA addition replacing FA up to 100% by volume were in a range of 6.3-7.6 MPa which met the classification of M5.0-M7.5 for practical concrete bricks complying with TCVN 6477 [34].

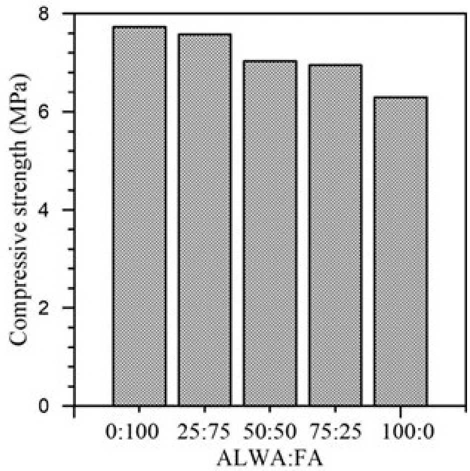


Figure 7. Compressive strengths of unfired bricks at 28 days of curing

3.3. Dried density

Effect of the ALWA addition on dried density of the hardened unfired bricks was investigated and illustrated in Fig. 8. According to the figure, the ALWA addition as partial replacement of FA at values beyond 50% by volume induced the modified unfired bricks with a significant reduction on the dried density. A quantitative comparison showed that the hardened unfired bricks modified with ALWA substituting FA at 25%, 50%, 75%, and 100% by volume had the dried densities equal to 95.71%, 86.84%, 83.81%, and 77.90% those of the reference unfired brick without ALWA addition. Obviously, such result was due to the lower density of ALWA as compared with FA. Obviously, the density reduction was a promising benefit of utilizing ALWA in unfired bricks due to the reduced self-weight of materials.

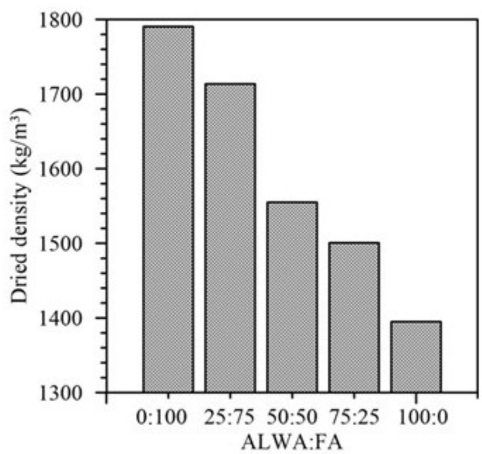
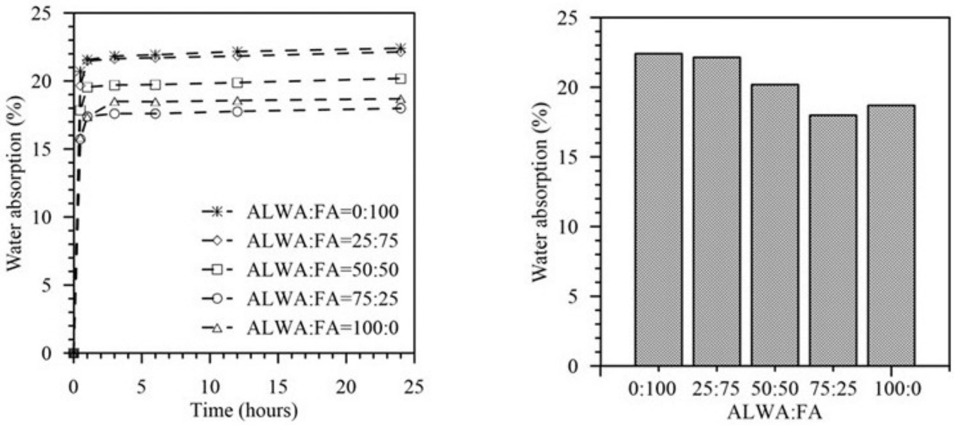


Figure 8. Dried density of unfired bricks

3.4. Water absorption

The water absorptions of the hardened unfired bricks were investigated and shown in Fig. 9. Accordingly, the ALWA incorporation significantly improved water penetration resistance of the modified unfired bricks due to the reductions on both water absorption rate and water absorption. Fig. 9

showed that the water absorptions of the hardened unfired bricks modified with ALWA replacing FA at 25%, 50%, 75%, and 100% by volume reduced at ratios of 1.18%, 9.91%, 19.73%, and 16.58% when compared with the reference unfired brick without ALWA addition. In this study, the unfired brick modified with ALWA replacing for FA at 75% by volume had the lowest water absorption of 17.99% which obviously satisfied the limits required for either typical clay or cementitious binder brick available in different locations [26, 27, 35]. The water absorption improvement of the ALWA modified unfired bricks as revealed in this study could be explained due to both the particle packing of aggregates and the refinement of interfacial transition zone (ITZ). The former could be attributed to the particle size distribution as subsequently discussed. On the other hand, the latter could be attributed to the internal curing effect induced by the pre-saturated ALWA [36].



(a) Water absorption rate after 24 hours

(b) Water absorption

Figure 9. Water absorption properties of unfired bricks

3.5. *Drying shrinkage*

Effect of ALWA addition on drying shrinkage of the modified unfired bricks was illustrated in Fig. 10. Generally, the drying shrinkage of the unfired bricks increased with the ages of curing due to the cumulative water evaporated from the brick samples into the atmosphere. Fig. 10 showed that the increase of the ALWA addition as partial replacement of FA significantly reduced the drying shrinkage measurements, inferring a high potential applicability of the ALWA modified unfired bricks for jobsite constructions where the high volume stability was seriously required. In this study, the ALWA

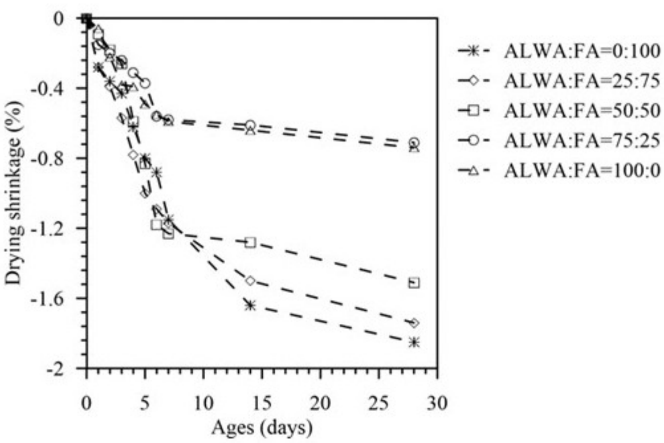


Figure 10. Drying shrinkage of unfired bricks

addition as partial replacement of FA at 75% by volume led to the modified unfired brick with the lowest drying shrinkage. The beneficial effect of using ALWA on drying shrinkage controlling was probably due to the high condensation of the brick structure induced by the dual effects of aggregate packing and pore refinement of the ITZ as aforementioned and particularly emphasized on the internal curing effect as suggested by the previous publications [36, 37]. Therefore, such innovative method should be proposed to efficiently stabilize the volume of the building bricks under improper curing regime as applied in this study.

3.6. Particle size distribution

With a paste-to-aggregate volume ratio fixed at a certain value as applied in this investigation, the particle size distribution of the aggregate fraction crucially influenced the macro-behavior of the bricks. Therefore, to facilitate the role of ALWA in modifying the brick performance, in this study, the particle size distribution of the aggregates with the sizes in range of 0.14-5 mm was investigated and shown in Fig. 11. Coinciding with the experimental results, three theoretical packing models proposed by Fuller, Andreasen and Andersen (A&A) for designing good performance self-compacting concrete (SCC), and another one obtained by analyzing the particle size distributions of the practical SCCs from China (Chinese grading) were also incorporated [38]. Fig. 11 showed that when compared with the bricks produced with sole usage of either FA or ALWA, the modified bricks with ALWA addition substituting FA at 25-75% by volume had the curves of aggregate particle size distributions shifted closest to those assigned to the better grading of aggregates. Such result apparently clarified that utilizing binary blending of FA and ALWA was more efficient for modifying particle size distribution of aggregate with poor grading as observed for FA or ALWA. Particularly, in this study, the optimized grain size distribution was primary factor alternating the engineering properties in both fresh and hardened stages as previously discussed.

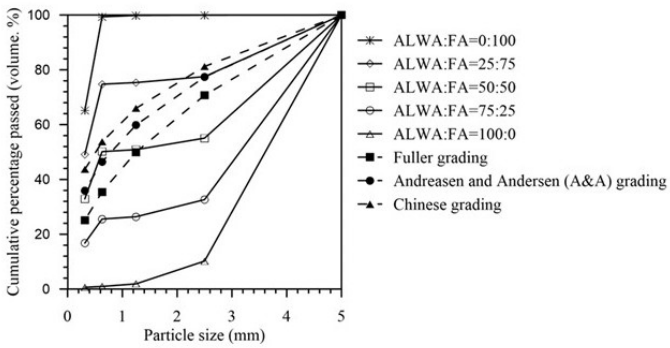


Figure 11. Effect of ALWA on particle size distributions of aggregates comprised of unfired bricks

4. Conclusions

The beneficial effects of using artificial lightweight aggregate (ALWA) as natural fine aggregate (FA) substitution on performance of an ecological unfired brick manufactured with tremendous amount of industrial by-products such as slag, fly ash, and flue gas desulfurization gypsum have been explored. According to the experimental results, the following conclusions could be drawn:

- The ALWA has been successfully manufactured by adapting the cold bonded agglomeration process using a mixture of Class F fly ash (FFA) and Type I ordinary Portland cement (OPC) with the mass ratio of FFA:OPC = 90:10. Although the ALWA had high water absorption, surface treatment has not been processed to minimize the cost.

- The flowability and unit weight of the fresh modified unfired bricks have been significantly improved with ALWA addition replacing for FA at values in range of 25-100% by volume.

- The 70% ALWA substituting FA by volume was considered as the optimum amount inducing the modified unfired bricks with significant reduction of dried density (16.19%), unremarkable reduction of 28-day compressive strength (only 10.09%), significant reduction of water absorption (19.73%) and extreme reduction of drying shrinkage (61.62%) when compared with the reference unfired brick without ALWA addition.

- Analysis on particle size distributions of the aggregates showed that the ternary blending of ALWA and FA with different ratios of ALWA:FA varied at 25:75, 50:50, and 75:25 by volume had the most optimum packing condition.

- In this study, the unfired bricks modified with ALWA addition as partial replacement of FA up to 100% were successfully produced to have the 28-day compressive strengths in a range of 6.3-7.6 MPa which met the classification of M5.0-M7.5 for the building concrete bricks complying with TCVN 6477.

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