ENGINEERING TRANSACTIONS • *Engng. Trans.* • **65**, 2, 371–389, 2017
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
National Engineering School of Metz (ENIM) • Poznan University of Technology

Research Paper

Preparation of a New AAC-Concrete Sandwich Block and its Compressive Behavior at Quasi-Static Loading

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Autoclaved aerated concrete (AAC) is an environmentally friendly material that has several advantages such as heat insulation, sound insulation, and light weight which reduce the energy consumption of a structure during its construction and when using it. However, the compressive strength of AAC is relatively low in comparison with concrete masonry units that are used as building blocks. This paper provides insight into a newly proposed AAC-concrete sandwich composite. The main aim of this research is to produce a lightweight eco-friendly loadbearing building block. Construction and demolition wastes including the cement and fine powder waste were utilized to generate the AAC-concrete composite.

The proposed sandwich composite was tested in a number of stages. Firstly, a preliminary test was conducted to test the proposed sandwiching technique. Three sets of plain sandwich specimens were prepared, each with a different combination of AAC thickness and concrete thickness. It was found that the proposed composite had a higher compressive strength than AAC and a lower density than the normal concrete. Secondly, different concrete and mortar mixes were prepared and studied to identify the mix that would yield the best sandwich composite. This best mix was identified and used throughout the experiment. Thirdly, different sandwiching techniques were applied to enhance bonding at the AAC-concrete interface. The proposed sandwiching techniques were as follows: (1) inserting grooves at the AAC-concrete interface and (2) wrapping the AAC block with wire mesh. Multiple cube specimens with 10 cm side length were prepared and tested for their compressive strength. It was found that the wire mesh provided a more effective bonding. Finally, additional grooved and plain sandwich cube specimens with 20 cm side length were prepared and tested under different quasi-static loading rates. Unlike plain sandwich block, the compressive behavior of grooved sandwich showed a slight increase in its capacity at higher quasi-static rate. Almost all specimens in this study failed in a similar manner that is, by debonding at the AAC-concrete interface, followed by crushing.

Key words: composite, AAC, quasi-static, sandwich block, recycled materials.

1. Introduction

Construction and demolition waste (CDW) constitutes a major portion of waste deposits in the United Arab Emirates (UAE), where millions of tons of heterogeneous CDW are produced each year. Since CDW is not recyclable, its management is considerably problematic. Moreover, little knowledge is available on feasible means of utilizing it. Thus, the CDW production sets major environmental, economic and social hazards. The proposed in this study AAC composite block offers an effective method of utilizing CDW [1, 2].

AAC is an eco-friendly construction material, largely favoured for its light weight, thermal insulation and sound absorption properties. It was first developed in Sweden in 1924 as a building material alternative to timber [3]. AAC has a wide range of load bearing as well as non-load bearing applications in industrial, residential and commercial projects. Load bearing applications include walls, floors, and roof panels in low-rise buildings.

The raw materials involved in the production of AAC are: cement, lime, sand, water and aerating agent (usually aluminium powder). Although we may observe minor differences in the production process of AAC depending on the manufacturer, this process generally consists of five key stages: (1) preparation and storage of raw materials, (2) batching, mixing and pouring, (3) curing, (4) cutting, and (5) steaming and packing. The reaction between an aerating agent such as aluminium powder and limestone results in the formation of gas bubbles, which produces the aerated concrete. The aerated concrete is then cured in a pressurized steam chamber to produce AAC.

With a growing demand for sustainable development, AAC has become a promising option for many construction and building companies, as well as a growing research area for researchers around the world. For example, F. Bisceglie *et al.* investigated the substitution of lightweight natural materials with the waste granular AAC in the construction of green roofs. The main incentive for their research was to reduce industrial waste and promote sustainable engineering practices in Europe. Physical and chemical tests were performed to ensure that the granular AAC is fit to replace lightweight natural materials. The results satisfied the appropriate 'Ente Nazionale Italiano di Unificazione' (UNI) standards and it was concluded that AAC is suitable to replace lightweight natural materials in green roofs [4, 5]. In another study by R. Drochytka *et al.* the use of waste fly ash as an alternative siliceous raw material for the AAC production was proposed to reduce industrial waste. It was concluded that the behaviors of fly ashbased AAC and sandbased AAC are very comparable; hence, fly ash can be used in the production of AAC in place of sand [6]. Another application of AAC was investigated in a study by Y. Yardim *et al.*, in which semiprecast slabs with ferrocement precast layer and AAC as in fill material were proposed. It was concluded that the proposed system behaves as a fully composite slab [7].

Further studies aimed to investigate the properties of AAC. For example, in a study by A. Ahmed and A. Fried, the flexural strength of AAC consisting of conventional mortar and thin layer mortar was verified. The effect of mix proportions and mortar type were studied separately. While strengths' values of specimens made from conventional mortar coincided closely with the values set by British standards described in [8, 9], the conventional mortar specimens were generally weaker than the thin layer mortar specimens [1]. In a different study by M. Jerman *et al.*, the hygric and thermal properties of three commercial types of AAC, with different bulk densities and compressive strengths, were studied. It was found that as the bulk density increased, the open porosity increased as well. Moreover, water absorption and apparent moisture diffusivity increased with an increasing bulk density. Water transport was the fastest in the sample with highest porosity. In addition, it was observed that thermal conductivity largely depended on temperature. Furthermore, all AAC samples demonstrated isotropy with respect to water and water vapour transport [10]. Furthermore, the microstructural properties and phase compositions of AAC produced by substituting lime with skarn-type copper tailings (SCT) and blast furnace slag (BFS) were studied by X. Huang *et al.* The incentive for substituting lime with SCT and BFS was to utilize the huge amounts of copper tailings existing in China and to reduce CO_2 emissions during the AAC production. It was concluded that BFS and SCT can be used in place of lime in the AAC production by providing CaO and MgO [11]. The thermal behavior of AAC exposed to fire was studied by K. Wakili *et al.* No spalling was observed; however, shrinkage was clearly visible [12]. In addition, the residual compressive splitting tensile strengths of AAC that contains perlite and polypropylene (PP) fiber, were studied at high temperatures by B. Ayudhya. It was found that the PP fiber did not significantly improve the unheated compressive strength and splitting tensile strength of AAC. Moreover, the 40% perlite sand replacement gave the highest strength and the addition of PP did not enhance the residual strength of AAC subjected to high temperatures [13].

The production of sandwich composites was studied by N. Memon *et al.* Their study investigated the applicability of lightweight sandwich composite produced by encasing lightweight aerated concrete with high performance ferrocement The obtained results were as follows: compressive and flexural strengths were remarkably enhanced, water absorption was reduced and the proposed unit behaved like a ductile composite [14]. A similar composite was proposed by S. Sumadi *et al.*, in which numerous composite characteristics were investigated. The obtained key results agreed with those obtained in the preceding study [15].

When studying the mechanical behavior of AAC, its low compressive and shear strengths stand out most notably. Unlike conventional concrete, AAC cannot sustain large compressive loads. It has a compressive strength in the range from 2. to 7.0 MPa (300 to 900 psi). Conventional concrete on the other hand, has a compressive strength in the range from 20 to 40 MP (3000 to 6000 psi). Moreover, the compressive strength of AAC depends on a number of characteristics, and these include: density, moisture content, size and shape of specimen, pore size distribution, direction of loading and age [16]. The compressive strength of AAC varies proportionally with density and inversely with moisture content [16]. The direct tensile to compressive strength ratio of AAC is between 0.15 and 0.35, as stated by Valore [17]. Legatski on the other hand, reported the tensile strength of AAC to be 10–15% of the compressive strength [18]. Furthermore, the drying shrinkage of AAC is significantly lower than that of non-autoclaved aerated concrete (NAAC), due to the presence of well-crystallized tobermorite mineral [19].

This paper aims to meet three main objectives, and these are: (1) to produce lightweight load bearing composite sandwich blocks made of AAC and concrete, (2) to optimize the proposed composite by optimizing the AAC-concrete interface as well as by optimizing the concrete skin mix, and (3) to investigate the behavior of the proposed composite at different loading rates. This research was prompted by the need to find adequate environmentally friendly building materials to promote more sustainable development. Moreover, this research contributes to waste utilization in the UAE. In effort to achieve the predefined objectives, a composite sandwich of AAC and lightweight concrete is proposed. The proposed solution is to be executed in two steps. Firstly, the composite sandwich, consisting of AAC and lightweight concrete sheets, is produced. Secondly, additive materials such as fly ash and micro-silica are introduced to enhance the product's compressive strength. In brief, the research methodology involves performing compression tests on cube samples at different quasi-static strain rates at room temperature. The results will include compressive strength values as well as descriptions of the modes of failure.

2. Materials

2.1. AAC

AAC blocks were readily provided by the manufacturer. Furthermore, they were modified into appropriate dimensions and tested in a university laboratory. Several samples were prepared using 5%, 10%, 15%, and 20% of two types of demolishing wastes (fine powder and G5 grade, classified by Bee'ah) by mixing them with cement, sand, water, quick lime, gypsum and aluminium powder.

Next, the mixture was poured into a block mold. Bee'ah is an environmental management company headquartered in Sharjah, UAE that aims to "catapult" this city to become the environmental capital of the Middle East and to make Sharjah reach zero waste to landfill vision. The molds were left for 6 hours to air dry and expand properly. Then the samples were taken out of the molds and placed in an autoclave for 12 hours at Al Jazeera Factory for Construction Materials in Abu Dhabi, UAE. The autoclave was programmed to heat the samples gradually up to 182°C in two hours. Then the temperature was kept constant for eight hours. Finally, the samples were allowed to cool down gradually for two hours to avoid sudden cooling which would cause cracking.

2.2. Concrete

Concrete was produced using type I standard Portland cement, crushed stone with a maximum size of 20 mm as coarse aggregate, dune sand as fine aggregate, and ground granulated blast-furnace slag (GGBS) as a partial replacement for cement and a superplasticizer. The concrete mix was prepared at four different water-to-cement (w/c) ratios to identify the optimum w/c ratio that would yield the maximum compressive strength and minimum density. Concrete specimens were cured in large water tanks at 21±2°C and tested for 3 days. The concrete mix proportions per a cubic meter batch are given in Table 1.

Table 1. Mix design for concrete used in the composite blocks.

Material	Weight [kg] per a cubic meter batch
Cement type	162.5
GGBS	162.5
10 mm aggregate	867
Crushed aggregates	800
Dune san	175
Wate	105, 120, 135, 150
Super plasticize	3.25L

2.3. Mortar

Mortar was produced using type I standard Portland cement, GGBS, sand and superplasticizer. As with concrete, the mortar mix was prepared at three different w/c ratios. The binder to sands ratio was 1 : 2 with 50% GGBS replacement and 0.5% superplasticizer. The mortar mix proportions based on ratios (not on a 1 m^3 batch) are given in Table 2.

Table 2. Mix design for mortar used in the composite blocks.

Material	Weight [kg] per a cubic meter batch
Cement type	5
GGBS	5
Sand	20
Wate	105, 120, 135, 150
Super plasticize	50 ml

3. Sample preparation/test specimens

3.1. *Concrete, mortar and AAC*

Concrete and mortar cubic specimens with 10 cm side length were prepared for the different concrete and mortar mixes. The specimens were left in the molds for one day then cured in water for 3 days. Next, the compressive strength and density tests were performed to determine the concrete mix and the mortar mix that would yield the maximum compressive strength whilst maintaining minimum density. Three specimens were tested for each mix and the average is reported in this paper. The selected mix of each of concrete and mortar was then used to prepare the composite block specimens for testing of the sandwiching technique. For AAC, two mix designs were prepared and tested and their corresponding average compressive strengths and density are reported.

3.2. *AAC sandwich blocks*

Cubic composite blocks with 10 cm side length were prepared by sandwiching the AAC blocks with two concrete (or mortar) sheets. Schematics of the test specimen are illustrated in Fig. 1 where 'a' represents the AAC thickness and 'b' represents the concrete thickness. Varying thicknesses of AAC and concrete were prepared to preliminarily test the sandwiching composite. AAC blocks

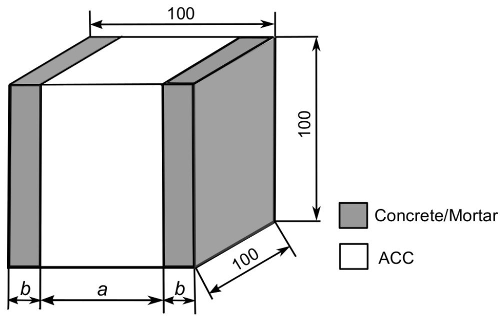

Fig. 1. 3D view of composite block.

were cut, placed in the molds and concrete was cast around them. These AAC plain sandwich specimens were cured after being left in the molds for one day. AAC plain sandwiching technique was examined in this preliminary stage by considering three different thicknesses of concrete sheets (b = 1.5 cm, 2.0 cm and 2.5 cm) to select the optimum size combination of AAC and concrete (or mortar).

Based on the results obtained in the preliminary tests, additional composite sandwich cubic specimens ($10 \times 10 \times 10$ cm) were prepared using three different sandwiching techniques: plain sandwiching, inserting grooves and inserting wire mesh. Compressive strength and density tests were performed. The tests were performed twice: the first test was at 7 days using 1.8 MPa AAC and the second test was at 3 days using 3.0 MPa AAC. For each test, the two sets of specimens were prepared: one using an AAC-concrete composite and the other using an AAC-mortar composite. Each set of specimens included control specimens (concrete or mortar), plain sandwich specimens, grooved specimens and wire mesh sandwich specimens (see Fig. 2). For the latter AAC composite, locally avail-

a) b) c) d)

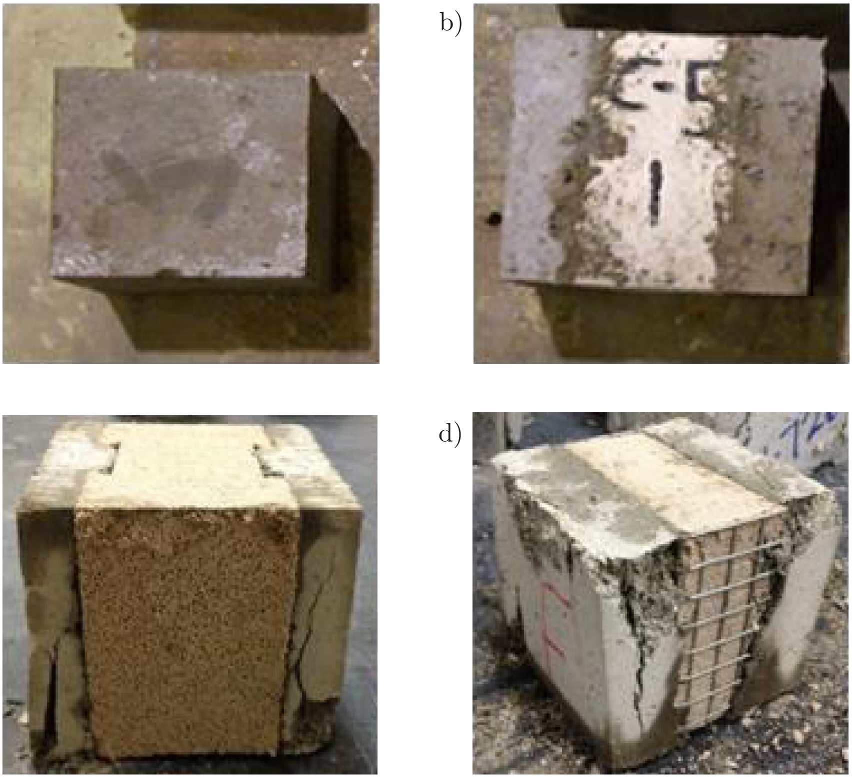

Fig. 2. A set of specimens used in the test program: a) control, b) plain sandwich, c) grooved sandwich, and d) wire mesh sandwich.

able non-structural galvanized steel wire mesh with the approximated diameter of 0.2 mm was used at 1×1 cm spacing.

4. Instrumentation and test setup

To determine the density, the cube specimens were simply weighed using a balance. The CNC milling machine was used to insert grooves onto the AAC's surface. An automatic saw was used to cut the AAC blocks into the required dimensions. A small concrete mixer was used to prepare the concrete and mortar mixes. To obtain the compressive strength, a concrete compression machine with 3000 kN capacity (see Fig. 3) was used to test all different composite specimens. Moreover, additional AAC plain sandwich specimens were prepared and tested under quasi-static loading conditions.

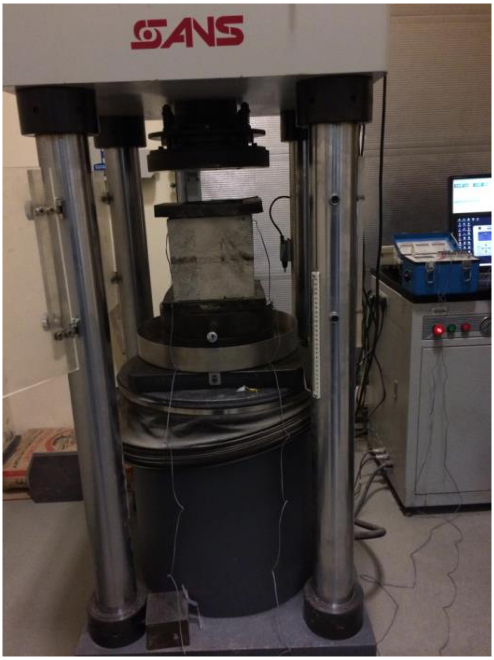

Fig. 3. Test setup consisting of compression machine, strain gauges and data logger.

5. Results and discussion

The strength of the AAC-concrete composite largely depends on the strength of the concrete itself. Thus, it is necessary to obtain the concrete mix that would yield the maximum compressive strength whilst maintaining the lightweight of the composite. In effort to do so, different concrete and mortar mixes were prepared and the corresponding compressive strength and density were measured and recorded (see Table 3). Based on these results (Table 3), the optimal w/c ratios for the concrete and mortar mixes were found to be 0.45 and 0.40 respectively. With that being considered, the mixes were prepared and cast around AAC with different sandwiching techniques (namely plain sandwiching, inserting grooves in AAC and wrapping AAC with wire mesh).

Table 3. Average compressive strength for different concrete, mortar and AAC mixes.

Concrete mixes		
w/c	Average strength [MPa]	Density [kg/m^3]
0.35	15.60	2253
0.40	22.21	2420
0.45	22.84	2436
0.50	20.24	2466
Mortar mixes		
w/c	Average strength [MPa]	Density [kg/m^3]
0.40	40.04	2261
0.45	34.80	2204
0.50	27.63	2142
AAC		
Mix	Average strength [MPa]	Density [kg/m^3]
1	1.80	539
2	3.00	554

5.1. Preliminary tests

The results from the preliminary tests are summarized in Table 4. The purpose of preliminary testing was to verify the hypothesis that a sandwiching of

Table 4. Preliminary compressive strength results for AAC-plain sandwich specimens.

AAC plain sandwich	Density [kg/m^3]	AAC thickness a [cm]	Concrete thickness b [cm]	Compressive strength [MPa]	Percentage decrease in density relative to concrete [%]	Percentage increase in strength relative to AAC [%]
Set	1305	5	2.5	7.9	34	182
Set	1160	6	2.0	6.1	41	118
Set	1030	7	1.5	3.2	48	14

AAC and concrete would result in the composite block with a lower density than concrete and a higher compressive strength than AAC. Different composite blocks were prepared by (a) varying the thickness of AAC and (b) varying the thickness of concrete. The combination of just mentioned (a) and (b), which yielded the best results was selected for the specimens in the following stage of the experiment. The results revealed a decrease in density relative to normal concrete reaching 48% and an increase in compressive strength relative to AAC reaching 182%. However, the highest strength-to-weight ratio was found for 10 cm cubic specimens with the concrete sheet thicknesses of 2.5 cm and 2.0 cm and these measurements were adopted in the next specimens.

In addition, it was noted that the failure cracks first appear at the interface between AAC and concrete. Hence, it was necessary to establish methods to enhance the bonding between these two materials. In this paper, two methods are proposed in to enhance the bonding at the interface, and these are: inserting grooves in AAC and wrapping AAC with wire mesh.

5.2. Compressive strengths of different AAC sandwiching techniques

The test results for the compressive strengths of the different sandwich composites are presented in Figs. 4 and 5. Two sets of compressive tests were performed under a static loading rate. The first set of tests was conducted after 7 days of curing using AAC with 1.8 MPa compressive strength. These tests did not yield very promising results as shown in Fig. 4, mainly due to the low compressive strength of AAC. The wire mesh resulted in a higher compressive strength than the grooved composite. Nevertheless, enhancing the bonding at

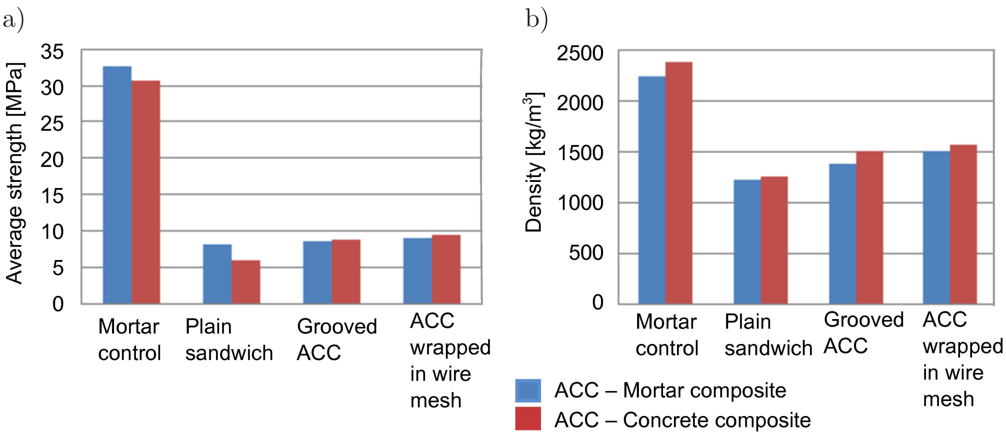

Fig. 4. Test results for the first set of composite block specimens at 7 days using a 1.8 MPa AAC: a) average strength, b) density.

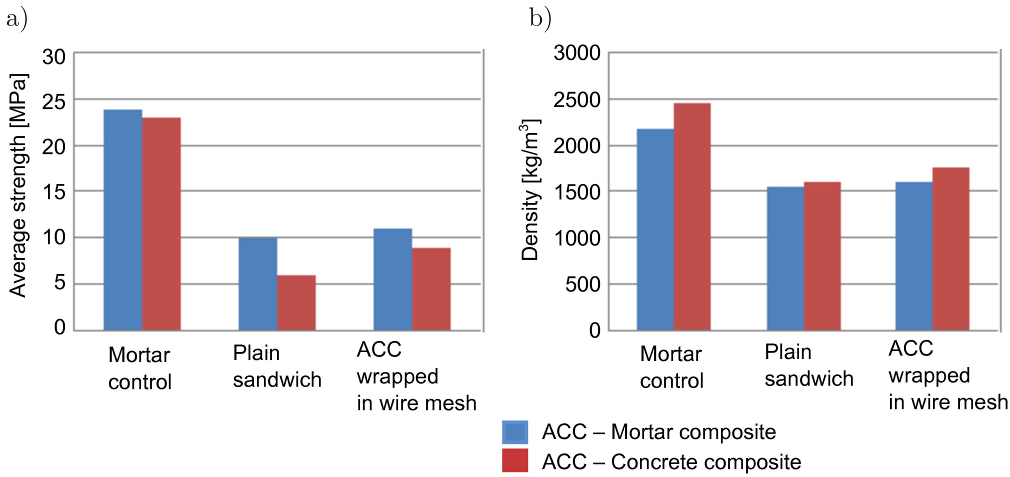

FIG. 5. Test results for the second set of composite block specimens at 3 days using a 3.0 MPa AAC: a) average strength, b) density.

the interface by either inserting grooves in the AAC block or wrapping it with wire mesh did not significantly increase the compressive strength.

A new set of specimens was then prepared using AAC with a compressive strength of 3.0 MPa and was tested at 3 days of curing as presented in Fig. 5. Compared to the plain sandwich, which yielded an average compressive strength of 5.92 MPa, the wire mesh sandwich composite had a higher average compressive strength of 8.92 MPa. However, when compared to the compressive strength of the control specimen, which was 22.91 MPa, the compressive strength of 8.92 MPa was considered insignificant.

The low compressive strength of the sandwich composites could have been due to the fact that specimens were cured in water only for 7 days and 3 days in the first and second test respectively. Thus, they did not attain their full 28-day strength. Also GGBS decreases the compressive strength of concrete in the short run, while it increases the compressive strength in the long run. Since all the tests were performed after a few days of curing, GGBS may have contributed to the decreased compressive strength.

5.3. Failure modes

It was observed that the failure cracks first appeared in the concrete sheet and then propagated diagonally to the interface between the two materials as illustrated in Fig. 6. It is worth noting that the cracks in the AAC block were not always visible due to its porous structure which allowed it to be compressed. Thus, to observe the cracks in AAC, the block had to be split open. Moreover, a)

b)

c)

Fig. 6. Failure modes for AAC-sandwich specimens:
a) plain, b) grooved, c) wire mesh.

the wire mesh composite exhibited perfect bonding, as illustrated in Fig. 6c, which shows the concrete tightly attached to the wire mesh.

5.4. Compressive strengths under quasi-static loading rates

Next, the specimens of plain and grooved sandwich composites were prepared to investigate their compressive behavior at higher (quasi-static) loading rates. A total of eight specimens: two grooved and six plain, were prepared in cubes with 200 mm side length as shown in Fig. 7. Two thick rubber plates were placed on the top and at the bottom of the specimen to ensure uniform stresses applied during the test. Strain gauges with 60 mm side length were also used and fixed laterally on both sides of all composite cubes, as illustrated in Fig. 8. The specimens were tested under two quasi-static loading rates: a high loading rate up to $V_2 = 60$ kN/min, and a lower loading rate of $V_1 = 6$ kN/min. The two grooved sandwich specimens were labelled as GS1 and GS2, where S1 and S2 referred to V_1 and V_2 loading rates, respectively. Likewise, the six plain sandwich specimens were labelled from PS1 to PS6, where S1, S3, and S5 referred to loading rate V_1 and S2, S4, and S6 referred to V_2.

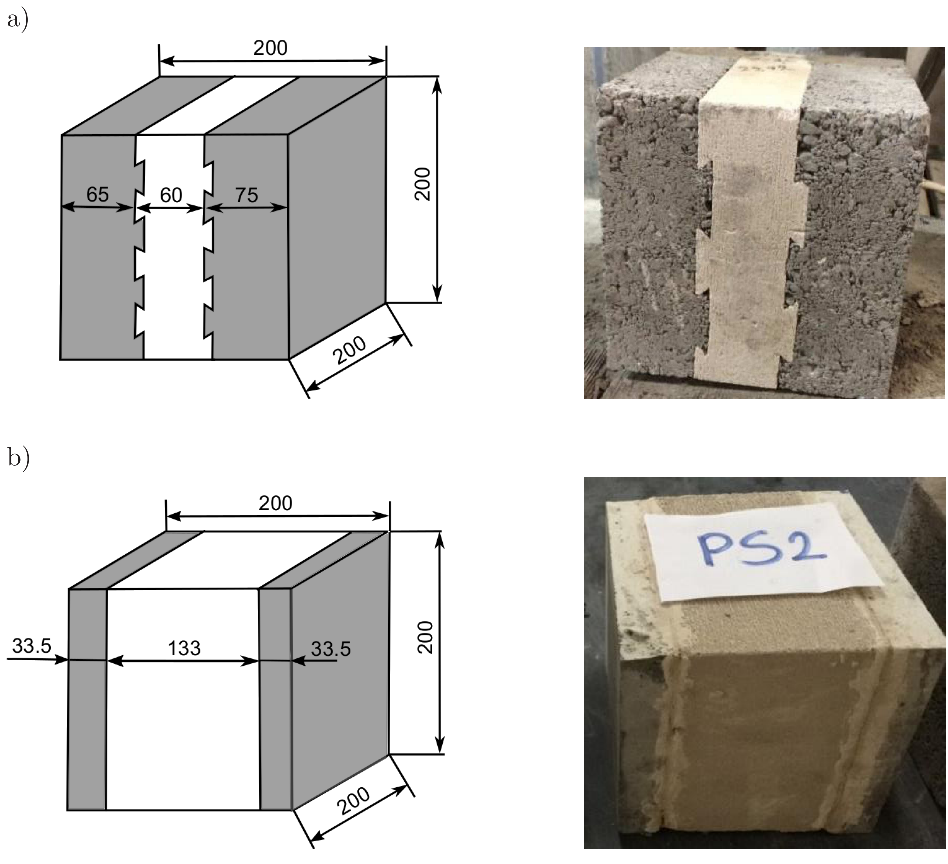

FIG. 7. Geometric description of: a) grooved sandwich, b) plain sandwich composites.

FIG. 8. Samples of grooved and plain sandwiches measured with 60 mm strain gauges.

The specimens were loaded until failure and the respective loads and deformation were recorded. Figure 9 presents the densities and the compressive strengths for all tested specimens. It is worth noting that grooved sandwich composites yielded a higher compressive strength at the higher loading rate and

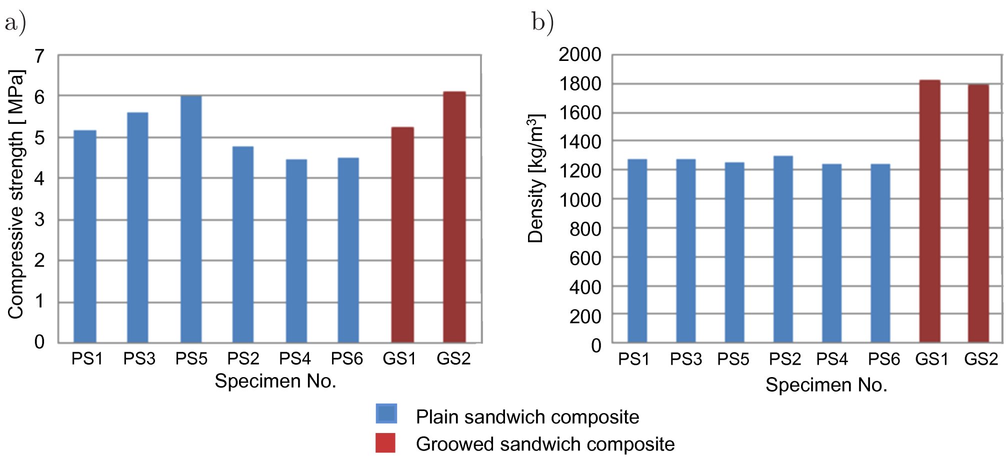

FIG. 9. Compressive strengths and corresponding densities of grooved and plain sandwiches at quasi-static loading rates: a) compressive strength, b) density.

a lower compressive strength at the lower loading rate when compared to the plain sandwiches. The compressive strength of the grooved sandwich showed more than 15% increase when tested at $V_2 = 60$ kN/min as compared to its capacity at the lower loading rate. By contrast, the compressive strength capacity of plain sandwich decreased by the same percentage (15% on average) when tested at the high loading rate. This could be attributed to the weak bond between the concrete sheets and AAC in the case of plain sandwiches. In other words, the plain sandwich was not exhibiting full composite behavior at higher loading rates. The low strain results recorded by the strain gauges confirmed such irregularities. The samples of the evolution of compressive stresses with time and the strain values measured using the strain gauges mounted on the concrete side of the composites are presented in Fig. 10.

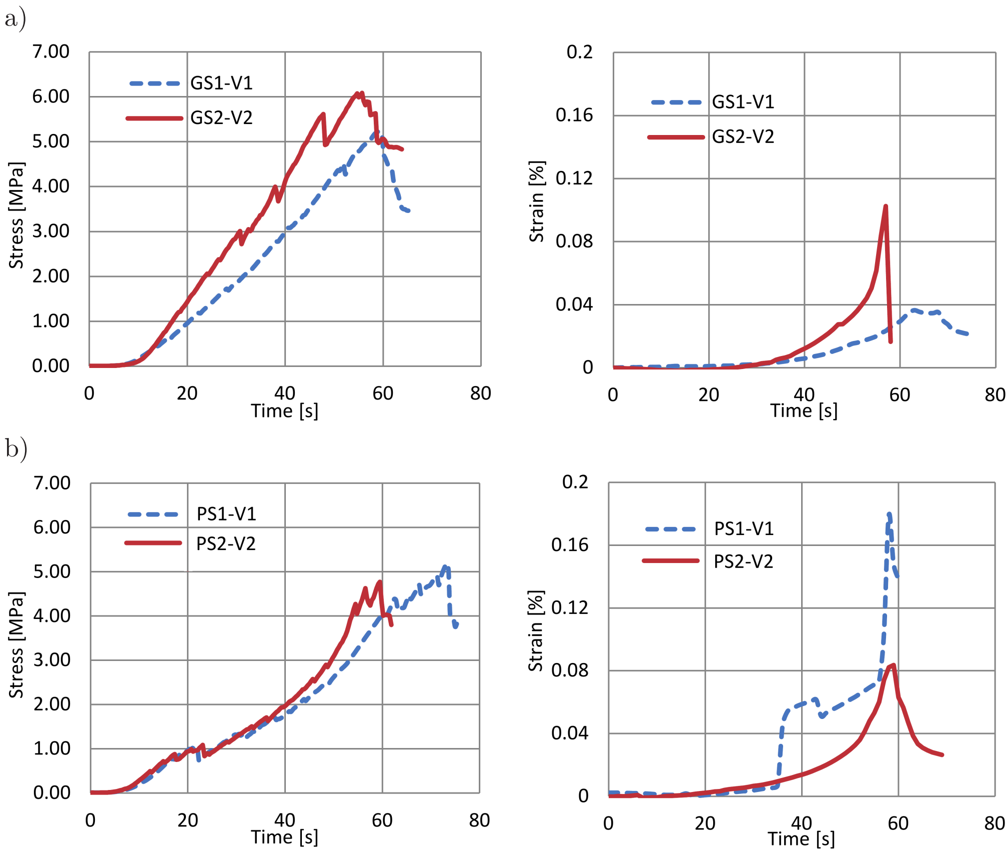

Fig. 10. Variation of stress and strains with time for grooved (a) and plain (b) sandwich composites at low and high quasi-static rates.

It was observed that bonding at the concrete-AAC interface was very weak, causing the two elements to separate readily when the load was applied. The failure mode of all specimens was characterized by composite failure followed by crushing of both AAC and concrete (Fig. 11). Most of the load was carried by the concrete skins in the grooved sandwich, which explains why the concrete failed more remarkably compared to the AAC block. On the contrary, failure was more evident in the AAC block of the plain sandwich composite after the initial debonding at the AAC-concrete interface.

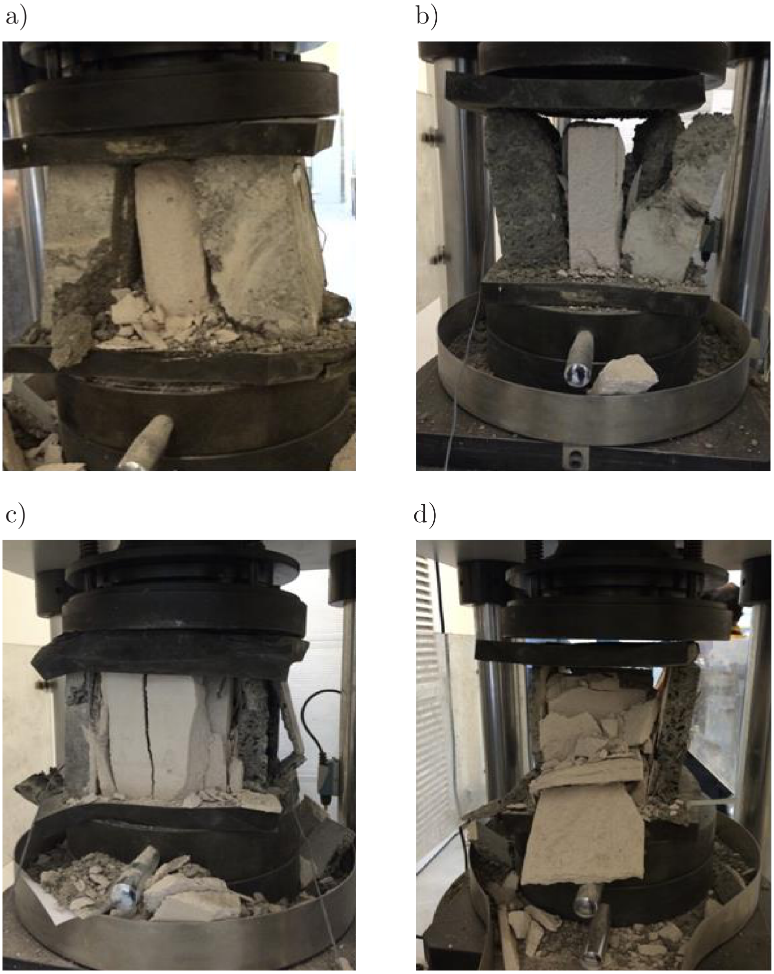

Fig. 11. Failure modes of plain and grooved sandwich specimens at different loading rates: a) GS1, b) GS2, c) PS1, d) PS2.

5.5. *Application of results*

The main aim of this research was to produce a lightweight eco-friendly load bearing building block. The above presented test results indicate that the compressive strength of AAC can be enhanced by a sandwiching with concrete. Nevertheless, the main limitation in recognizing the full potential of the proposed solution is the weak concrete-AAC interface. Amongst the three sandwiching techniques investigated in this research, wire-meshing and grooving proved to be the most promising. This prompts further research on using wire mesh or grooving to strengthen the AAC-concrete interface. Further research may investigate the use of shear connectors such as nails, crossbar bracing or z-shaped strips of welded wire mesh to enhance the composite. In addition, different grooving patterns, which may provide better interlocking, can be investigated.

The proposed composite can be compared to traditional concrete masonry units (CMUs) and AAC masonry units. In fact, the proposed composite is a compromise of these two structural elements. It aims to provide the sufficient compressive strength, which is attributed to CMUs, and the low weight, which is attributed to AAC. The compressive strength of the composite is less than that of traditional CMUs, which may limit its structural application. Nevertheless, as aforementioned, the capacity of the proposed composite can be increased by enhancing bonding at the concrete-AAC interface. Moreover, compared to traditional masonry units, the proposed composite has better fire resistance properties and lower weight.

6. Conclusions

This study was conducted to meet three main objectives: (1) to produce a lightweight load-bearing building block using AAC made of recycled materials (2) to optimize bonding at the AAC-concrete interface in the composite sandwich using different sandwiching techniques and (3) to investigate the behavior of the proposed composite sandwich under quasi-static loading. Based on the obtained test results, the following conclusions can be drawn:

- In the plain sandwich composite, failure cracks initiated and propagated at the AAC-concrete interface thus, prompting the need to find alternative sandwiching techniques.
- Both grooved and wire-mesh sandwiching yielded a higher compressive strength than the plain sandwich.
- Using wire mesh as a sandwiching technique yielded a higher compressive strength as compared to the grooved sandwich composite.
- Overall, sandwiching did not significantly enhance the compressive strength of AAC.
- In most specimens, failure occurred at the AAC-concrete interface. However, the wire mesh sandwich composite exhibited effective bonding.

- Different types of shear connectors such as steel nails, crossbars bracing between two wall faces and z-shaped strips of welded wire mesh to connect two faces of the wall can be used to enhance the composite action.
- Finally, the compressive behavior of grooved sandwich showed a slight increase in its capacity at higher quasi-static rate. On the other hand, the plain sandwich composites exhibited opposite behavior at higher rates.

Acknowledgment

The authors appreciate the support of the Gulf Ecosystems Research Center (GERC) and Bee'ah in Sharjah, UAE, Project No. GERC-14-01. The authors would also like to acknowledge the great efforts of Ms. Dina Saadi and Mr. Ali Fadhil who initially worked on this research as a part of their senior design project.

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Received December 27, 2015; accepted version May 14, 2016.