INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 9 (2024) 108-117
https://publisher.uthm.edu.my/ojs/index.php/ijie

Effect of Direct Fire Exposure on the Physical and Mechanical Properties of Autoclaved Aerated Concrete (AAC) Based on Ceramic and Gypsum Waste (CGW) as Partial Substitution for Sand

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DOI: https://doi.org/10.30880/ijie.2024.16.09.008

Article Info

Received: 31 January 2024
Accepted: 31 October 2024
Available online: 4 December 2024

Keywords

Direct fire exposure, work density, compressive strength, autoclaved aerated concrete, ceramic-gypsum waste, sand replacement

Abstract

Autoclaved aerated concrete (AAC) containing ceramic-gypsum waste (CGW) as a partial substitution for sand and pure AAC were fabricated in this study. The compressive strength ranged from 1.64 MPa to 2.13 MPa, and work density ranged from 594 kg/m^3 to 605 kg/m^3. All AAC samples were exposed to direct fire at 923.8°C for 300 seconds. The maximum surface temperature (T_1) and opposite surface temperature (T_2) were 930.1°C and 31.7°C, respectively. The average T_1 of the sample was around 169.88°C, and the average thermal storage was around 10.36% after cooling for 900 seconds. Meanwhile, the average T_2 was 31.3°C, almost similar to the workshop temperature. Except for pure AAC, the samples did not crack, burn, or melt during exposure to direct fire at a temperature of 920°C for 300 seconds. Direct fire testing also positively affected the work density and compressive strength of AAC-CGW. The average work density decreased by 10.69%, and compressive strength increased by 12.39%. The maximum work density was reduced by 14.57 % for AAC-1, and compressive strength increased by 39.15% for pure AAC. This study demonstrated that the AAC-CGW is suitable for thermal and fire resistance walls due to their excellent durability and strength after exposure to direct fire.

1. Introduction

Currently, smart cities are one of the priorities for urban development. Technological advances for the safety and comfort of users must accompany urban development. In general, smart cities are identical to smart buildings and smart transport. An ideal smart building must be made of smart materials as the construction cycle produces municipal solid waste (MSW) and greenhouse gas (GHG). According to Ayilara et al. [1], improper management of MSW in landfills adversely affects the ecological system and human health, depletes the ozone layer when burnt, and increases the impact of climate change and GHG emissions. Building construction and operation also use 36% of global energy, accounting for 39% of energy-related carbon dioxide (CO_2) emissions

[2]. The emissions from building operations arise from the energy used for heating or cooling, hot water supply, ventilation and air conditioning, and lighting, accounting for 28% of energy-related GHG emissions worldwide [3].

The urban areas encounter MSW generation, GHG emissions, and fire attacks. A fire attack is mainly considered an accidental action in building construction that causes considerable loss, including building collapse and fatalities. Approximately 10,233 fire-attack cases occurred in Malaysia from 2018 to 2020 [4]. According to Babrauskas et al. [5], flashover will typically occur within 3 to 6 minutes in a flammable room. This means that a material that resists fire for more than 3 minutes allows the firefighter team to extinguish it. Therefore, the wall's resistance to direct fire in extreme environments is also crucial for buildings in large cities. An ideal material for building construction must exhibit the highest resistance and the best possible response in the event of fire, and the material must be recyclable. The construction material should be highly thermally insulating, not contribute to fire load and spread between compartments, and can be used as escape routes and structural integrity during fire. Based on the literature review, autoclaved aerated concrete (AAC) is suitable for solving all these problems. AAC is a smart material for building applications due to its advanced characteristics. The challenge for AAC is compensating for its reduced density while maintaining sufficient strength properties and fire resistance.

2. Literature Review

AAC is a family member of green building constructions [6], non-combustible material and Euroclass A1 reaction to fire [7], good sound insulation material [8], and excellent fire resistance [9]. According to Huang et al. [10], AAC is the only type of wall material that can save building energy, thereby reducing energy consumption by 70% compared to normal concrete and 40% compared to conventional bricks. The main ingredients of AAC are cement, fly ash or quartz sand, lime, gypsum and aluminium powder [11], [12]. Several researchers have successfully employed MSW to partially replace AAC raw materials: quartz sand [13], cement, and lime [14]. This approach could reduce the amount of MSW in landfills, consumption of natural resources, production costs, and GHG emissions. MSW has demonstrated positive outcomes as pozzolanic materials to enhance the engineering properties of AAC [15], [16]. Ceramic waste, constituted in MSW, has also been recognized as pozzolan materials [17]. The effect of the pozzolanic activity of ceramic waste on the mechanical and fire resistance performance of concrete has been reported by [18], [19].

According to Jerman et al. [20], the compressive strength of AAC blocks is generally less than 5 MPa with bulk densities of 300–500 kg/m^3. The compressive strength can be increased to 7 Mpa using additives [21]. Calcium carbonate ($CaCO_3$) and phosphogypsum (PG) are two types of additives often used to improve the physical and mechanical properties of concrete, including foamed concrete (FC) and ultra-lightweight cellular concrete (ULCC) [22]. According to Tian et al. [23], PG was more effective in improving the compressive strength of FC and ULCC. This may be due to the effect of calcium sulfate in gypsum. In the AAC production process, gypsum can promote the progress of the hydrothermal reaction and convert CSH(I) to tobermorite [24]. Furthermore, PG or gypsum waste (GW) is an attractive building material due to its good fire resistance, sound absorption, lightweight, and excellent moldability [25]. Untreated PG has been used as a raw material to fabricate AAC [26].

In addition, the incorporation of gypsum as an additive in AAC has been reported by [27]–[32]. Due to the abundance availability and good properties of ceramic and gypsum waste (CGW) in Malaysia, it is of great interest to study the effect of direct fire exposure on the physical and mechanical properties of AAC containing this waste. Thus, this study aims to determine the physical and mechanical properties of AAC-CGW after exposure to direct fire at a temperature of 923.8°C for 300 seconds. Six types of AAC were prepared, including pure AAC and AAC-CGW, according to ASTM C1693 [33].

3. Methodology

3.1 Preparation of AAC-CGW with Different Compositions

Two series of AACs were prepared by combining ceramic and gypsum to partially substitute sand. The compressive strength was similar at around 1.64 MPa to 2.13 MPa, and work density ranged from 594 kg.m^{-3} to 605 kg.m^{-3}. Table 1 shows the composition of raw materials for each AAC sample in kilogram (kg) and their compressive strength (f_c) and work density (ρ_w). To produce AAC, the composition of sand, cement and lime mixture was 70:12:18, with 45 to 70% sand, 0 to 23% CW, 2% GW, 12% cement, 18% lime, 0.1% Al, and 0.58% water. The AAC-CW1 mold dimensions were 378 mm in length, 237 mm in width and 177 mm in depth. The target density of AAC-CW1 was 520 kg.m^{-3}. The particle sizes of CGW were in the range of 0.5 to 1 mm.

Table 1 *Raw material composition, compressive strength and work density of AAC-CGW*

Samples	Raw material (kg)							f_c	ρ_w
	Ceramic	Gypsum	Sand	Cement	Lime	Al	Water	(MPa)	(kg.m^{-3})
Pure AAC	0	0	5.7718					1.64	594
AAC-1	0.1732		5.4833					1.92	597
AAC-2	0.4617		5.1947					2.04	601
AAC-3	0.7503	0.1154	4.9061	0.9895	1.4842	0.0082	4.7823	2.13	605
AAC-4	1.0389		4.6175					1.96	603
AAC-5	1.3275		4.3289					1.74	600

For AAC-1, 5.483 kg sand, 0.1732 kg ceramic waste, 0.1154 kg gypsum waste and 4.7823 kg water were mixed for 900 seconds. Then, 0.9895 kg cement and 1.4842 kg lime were added to the mixture and stirred for 60 seconds. Finally, some Al paste (0.0082 kg) was added and stirred for 30 seconds. The resulting slurry was poured into 2/3 box mold, shaken slowly and pre-cured for 3-4 hours at workshop temperature. Finally, all AAC samples were autoclaved at 200°C and 12 bar pressure for 12 hours at Kim Hoe Thye Industries laboratory.

3.1 Fire Resistance Testing

Fig. 1 shows the fire tool used in the direct fire testing for the first series of AAC samples. The dimensions of the AAC sample were 100 x 100 x 100 mm. The test was conducted at average temperature of 764.4°C, with maximum temperature of 930.1°C for 300 seconds. After 300 seconds, the test ceased, and the samples were cooled for 900 seconds in the workshop environment (27.5°C temperature and 68% humidity). The physical surface of the sample was visually examined during and after exposure to direct fire, and the changes were recorded. The thermal load temperature of the specimen was detected by two thermocouples, T_1 (surface) and T_2 (opposite surface). The temperature range of the type-K thermocouple was -50°C to 1300°C, with the accuracy of ±3°C. The direct fire testing was conducted according to the BS-7974, 2019 [34].

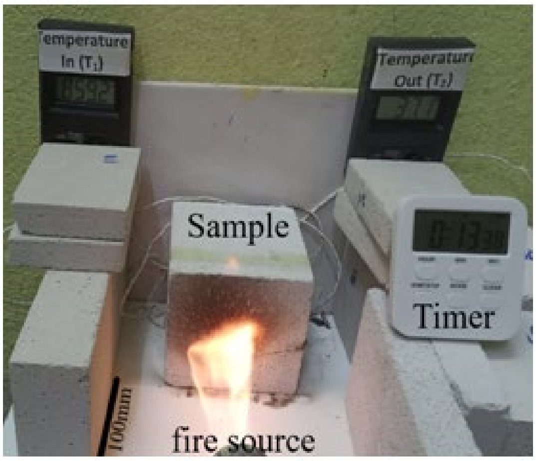

Fig. 1 *Fire tool used in direct fire testing of AAC samples*

The work densities of pure AAC and AAC-GCW were calculated according to ASTMC1692-11 [35], as expressed by Eqn. 1. The samples were weighed before and after direct fire testing using AND GF-6100 electrical balance at Concrete Laboratory, UTHM Pagoh.

$$\rho_w = \frac{M\,(\mathrm{kg})}{V\,(\mathrm{m}^3)} \tag{1}$$

where, M is the weight of the AAC-CGW sample, and V is the AAC-CGW sample volume.

Meanwhile, the compressive strength of pure AAC and AAC-CGW before and after direct fire testing was determined using Victor-automatic material testing equipment coupled with Vepro 8 V5.58(C) software at Material Technology Workshop, UTHM Pagoh.

4. Results and Discussion

4.1 Thermal Analysis

Fig. 2 shows the thermal analysis of pure AAC and AAC-CGW. The AAC samples were exposed to direct fire at 923.8°C for 300 seconds. The maximum surface temperature(T_1) of the sample was 930.1°C. Except for the first 60 seconds, T_1 increased by 100°C every 60 seconds. After extinguishing the fire source, T_1 slowly reduced to 170°C. The average T_1 of the samples was 169.88°C at 900 seconds. The average thermal storage was around 14.39% after cooling for 900 seconds.

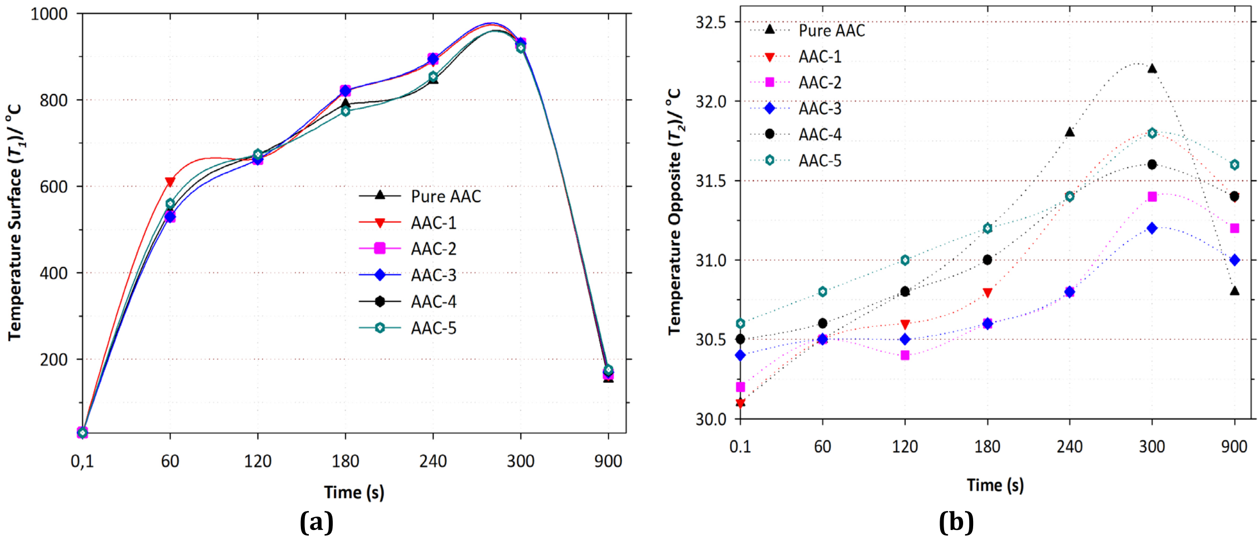

Fig. 2 *Thermal analysis of pure AAC and AAC-CGW: (a) Surface temperature (T_1); and (b) Opposite surface temperature (T_2)*

The opposite surface temperature (T_2) referred to the surface temperature of the opposite side of the same block. The distance of T_2 to T_1 was 100 mm, far from the exposed surface. The maximum T_2 was 32.4°C even though T_1 was 923.8°C. The average temperature was 31.7°C. The average T_2 increased by 1.4°C compared to the workshop temperature (30.3°C) but was insignificant. The T_2 decreased with increasing compressive strength for pure AAC and AAC-1 to AAC-3. This may be due to the positive effect of ceramic and gypsum waste on AAC, which could reduce the open pores of the sample. Similar results were reported by Narayanan and Ramamurthy [36]. After cooling for 900 seconds, the average T_2 of the samples was around 31.3°C or an increase of 0.9°C from the workshop temperature.

4.2 Surface Analysis

The surfaces of pure AAC and AAC-CGW before, during and after the direct fire testing are shown in Fig. 3. Except for pure AAC, the AAC-CGW samples showed normal color appearance, i.e., grey, before and after being exposed to direct fire. All samples also exhibited some black color. The fire source temperature below 1000°C may cause this color difference. Ahmed et al. [37] also obtained similar results for high-performance self-consolidating concrete. Despite exposure to direct fire at 923.8°C for 300 seconds, the surface of the samples remained crack-free and unburnt, visibly discernible to the naked eye. Moreover, the pure AAC was slightly molten. This may be due to the absence of non-combustible materials such as ceramic and gypsum. Meanwhile, the AAC sample containing CGW did not melt after exposure to direct fire at 923.8°C for 300 seconds. It was possible that the CGW contained in the AAC improved the sample's melting point. In general, the melting point of ceramic waste is 2000°C [38]. These results contradict previous research [39].

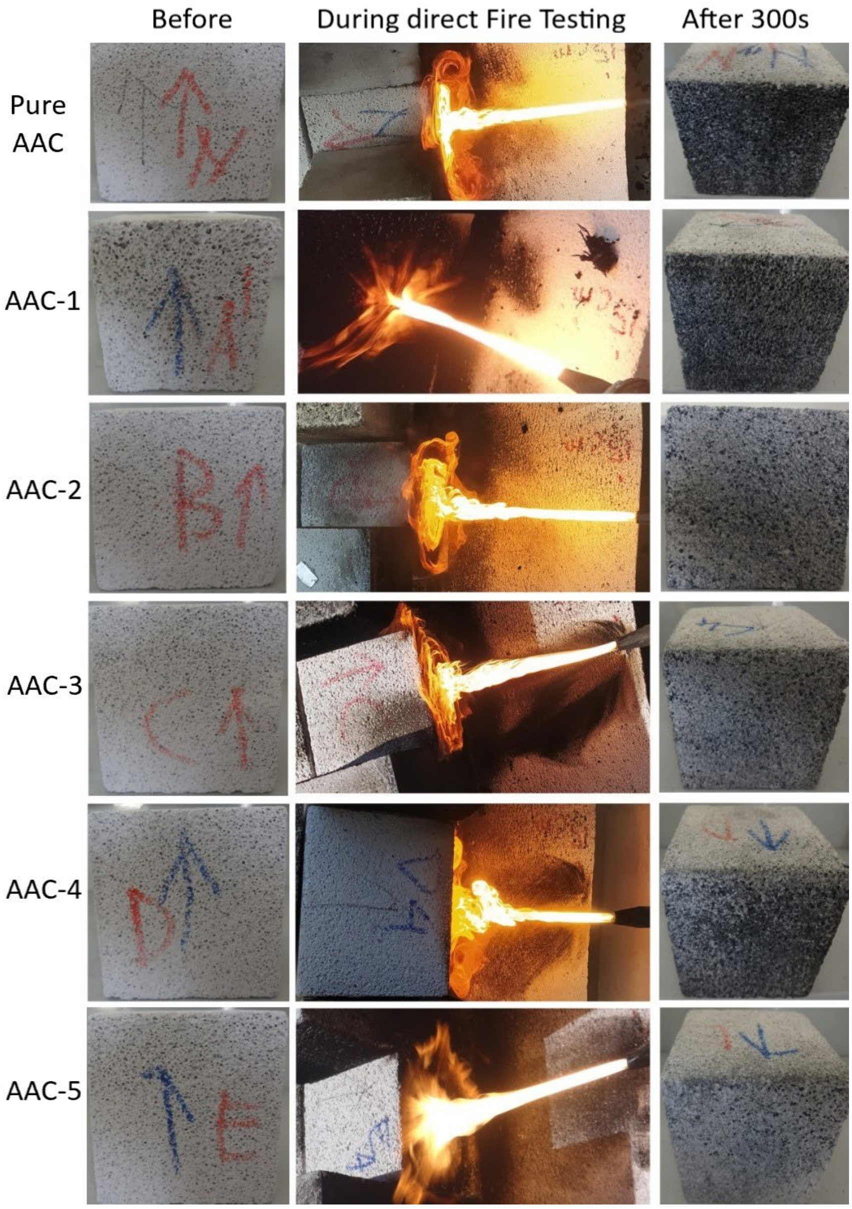

Fig. 3 *Pure AAC and AAC-CGW surfaces before, during and after exposure to direct fire testing*

4.3 Work Density

Fig. 4 shows the work densities of pure AAC and AAC-CGW before and after exposure to direct fire at more than 900°C for 300 seconds. The result showed that the work density decreased from 7.27 to 14.57%. The AAC-1 recorded the best work density reduction of 87.05 g.cm^{-3}. The lost work density may be due to the evaporation of the water content in the sample after exposure to direct fire. According to Gupta et al. [40], moisture loss decreases work density. The work density derivation is similar to the mass loss. Furthermore, the work density may also decrease due to the departure of free water and decomposition of C-S-H gel and aluminate hydrates [41].

The weight loss of the AAC-5 sample was only 7.27%. The sample may contain higher CW and consume a considerable amount of water during the slurry process. Exposure to extreme conditions, such as direct fire, has had a positive impact on the work density of AAC-CGW.

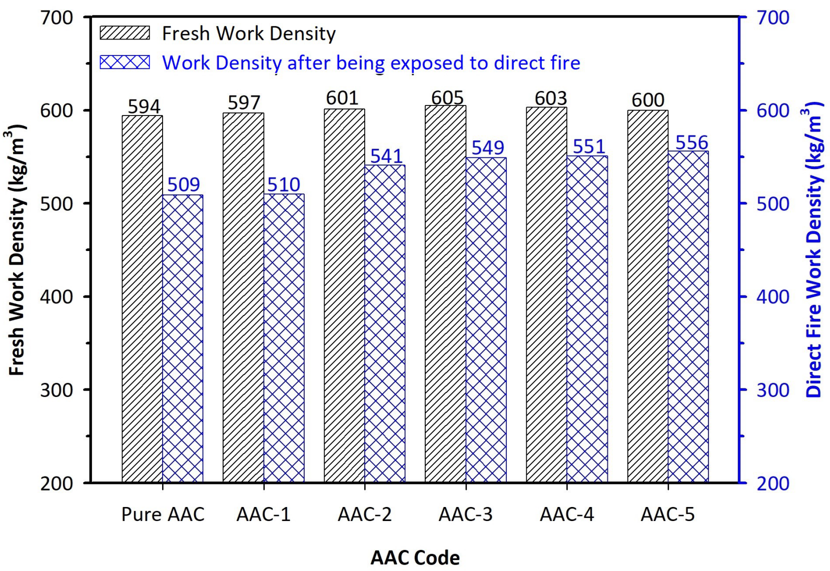

Fig. 4 *Work density of pure AAC and AAC-CGW before and after direct fire testing*

4.4 Compressive Strength

Fig. 5 shows the compressive strength of pure AAC and AAC-CGW before and after direct fire testing at 923.8°C for 300 seconds. After testing, the compressive strength increased by 39.15% (pure AAC), 25.52% (AAC-1), 21.03% (AAC-2) and 0.42% (AAC-3). The pure AAC had the best increase in strength value. The strength value increased by 2.28 MPa or 0.64 MPa. The condition may be the result of the melting of pure AAC sample. According to Zhou et al. [42], water causes the decomposition of hydration products, allowing for the rehydration of anhydrous cement and increasing the amount of C-S-H gel. Similar results have been reported in [43]–[46] that the compressive strength of AAC samples was influenced by direct fire exposure. On the other hand, the durability of AAC-CGW was not affected by extreme conditions such as direct fire of less than 5 minutes. Based on the strength results obtained after testing, the AAC-CGW could be used as non-loadbearing partition in Malaysia. The minimum strength requirement for non-loadbearing partition in Malaysia is 1.4 MPa [47].

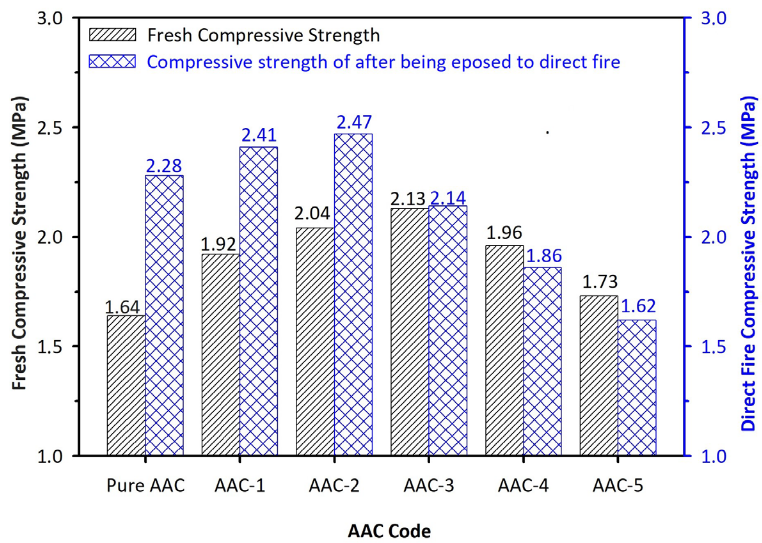

Fig. 5 *Compressive strength of pure AAC and AAC-CGW before and after direct fire testing*

Meanwhile, extreme fire exposure had a worse impact on the strength of AAC-4 and AAC-5. However, the decrease in strength values of both samples were less than 10%. The strength values of AAC-4 and AAC-5 were around 5.05% and 6.72%, respectively, which did not significantly affect the durability of the samples. The surfaces of AAC-4 and AAC-5 were also crack-free, and their strength values were higher by 32.93% and 15.93%, respectively, than 1.4 MPa. The decrease in compressive strength of AAC-4 and AAC-5 may be owing to the deterioration of paste under elevated temperatures. This phenomenon has been explained by [48].

5. Conclusions

This study successfully produced pure AAC and AAC containing CGW as partial replacement of sand with distinctive compressive strength values. The compressive strength ranged from 1.64 MPa to 2.13 MPa, and the work density ranged from 594 kg.m^{-3} to 605 kg.m^{-3}. All AAC samples were exposed to direct fire at 923.8C for 300 seconds, with maximum temperature of 930.1°C. Regarding fire resistance, all AAC-CGW samples, except for pure AAC, exhibited robust performance, showcasing the absence of cracks, burning, or melting even under direct fire exposure exceeding 920°C for 300 seconds. Additionally, the partial replacement of sand with CGW in AAC fabrication demonstrated a commendable 14.39% enhancement in thermal insulation compared to pure AAC. The direct fire resistance test substantiated the material's resistance to extreme conditions and positively impacted various physical and mechanical properties of the AAC samples.

After direct fire testing, the average work density decreased by 10.69%, and the compressive strength increased by 12.39%. This demonstrated direct fire exposure's efficiency in enhancing the AAC samples' overall performance. Direct fire contributed to a remarkable 39.15% increase in compressive strength compared to the initial sample. In conclusion, AAC-CGW exhibited promising characteristics that are highly suitable for applications in wall constructions, particularly in thermal walls demanding high fire resistance. This study verified the material's ability to withstand direct fire at elevated temperatures and highlighted the significant improvements in thermal insulation and mechanical properties of AAC containing CGW. These findings contributed valuable insights to the field of construction materials, particularly in developing AAC with enhanced fire resistance and thermal insulation properties.

Acknowledgement

This study was supported by a Ministry of Higher Education (MOHE) grant through the Fundamental Research Grant Scheme (FRGS/1/2021/STG08/UTHM/03/1).

Conflict of Interest

The authors declare no conflict of interest regarding the content of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Noraini. M;* ***data collection:*** *Izzati A. M, Hafizuddin H. S;* ***analysis and interpretation of results:*** *Efil. Y, Noraini. M;* ***draft manuscript preparation:*** *Efil. Y. All authors reviewed the results and approved the final version of the manuscript.*

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