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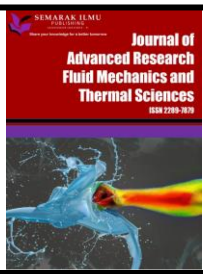


# Physical and Mechanical Properties of Autoclaved Aerated Concrete (AAC) with Ceramic and Gypsum Waste (CGW) Addition Before and After Exposure to Direct Fire at Temperatures up to 920°C

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**ABSTRACT**

This research endeavors to comprehensively explore the physical and mechanical properties of Autoclaved Aerated Concrete (AAC) with ceramic and gypsum waste (CGW) addition before and after exposure to direct fire at temperatures up to 920°C. The investigation focuses on determining the effects of CGW addition on AAC properties before and after exposure to direct fire at temperatures reaching 920℃ for 300 seconds. The main objective of this research was to determine the work density and compressive strength of AAC-CGW on the surface of direct fire exposure. In pursuit of this goal, various compositions of AAC with CGW, ranging from 5% to 30% wt/wt, were accurately prepared. The physical and mechanical were conducted before and after subjecting to direct fire testing. Important parameters such as work density, ranging from 593.71kg/m$^3$ to 672.70kg/m$^3$, and compressive strength from 1.64MPa to 2.39MPa, were analyzed. The findings demonstrated that the compressive strength exhibited an increase with CGW addition, particularly within the 5% wt/wt. The high point compressive strength value recorded was 2.39MPa for a 5% wt/wt CGW addition, reflecting a 45.73% increase in compressive strength compared to the reference sample (RS). The study also revealed convincing fire resistance results. Indicating for the reference sample (RS), the samples exhibited surfaces devoid of cracks, burns, or melting during direct fire exposure exceeding 920℃ for 300 seconds. Furthermore, CGW addition contributed to a remarkable 20.1% improvement in thermal insulation compared to the RS. Direct fire resistance testing had a positive influence on the physical and mechanical characteristics of AAC-CGW samples. The average work density experienced a 9.9% reduction, while compressive strength exhibited an 18.8% increase. Direct fire exposure led to an outstanding 53.30% enhancement in compressive strength compared to the sample.

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## 1. Introduction

In metropolitan areas, the regular growth of the population exhibits a direct correlation with the advancement of development, industries, and technology. Unfortunately, the repercussions of this growth include the generation of municipal solid waste (MSW) and the occurrence of fire incidents, both of which pose adverse effects on the urban environment. Notably, in major cities, the quantities of MSW and instances of fire attacks have been steadily increasing annually. For instance, on a global scale, an estimated 3.5 million tonnes of MSW are generated daily [1]. Regrettably, these waste materials are often inadequately managed, being haphazardly sent to landfills. Ayilara *et al.,* [2] point out that improper landfill management not only negatively impacts the ecological system and human health but also contributes to ozone layer depletion when burned, exacerbating climate change and greenhouse gas emissions. Concurrently, Malaysia reported 10,233 fire incidents during 2018-2020, where fire attacks, typically accidental actions leading to building contractions, resulted in significant losses, including building collapses and fatalities [3]. Consequently, ensuring the durability of walls in the face of direct fire in extreme conditions becomes imperative for building resilience.

To address these multifaceted challenges and foster sustainable development, the ideal concrete for construction should not only incorporate measures to manage MSW but should also possess robust fire resistance capabilities. Autoclaved Aerated Concrete (AAC) stands out as an exemplary construction material falling under the category of non-flammable and fire-resistant materials, classified as Euro class A1 [4]. AAC not only provides fire resistance but also belongs to the lightweight, porous concrete family, contributing to green building practices [5]. It serves as an effective sound insulation material and exhibits exceptional fire resistance [6]. As highlighted by Huang *et al.,* [7], AAC emerges as the sole wall material capable of significantly reducing building energy consumption by 70% compared to conventional concrete and 40% compared to traditional bricks. The hypothesis of this research potential that AAC with CGW addition is well-suited for various wall applications, particularly for thermal walls and, fire-resistant walls. The significant incorporation of AAC with CGW gives promising properties, positioning it as a viable and advantageous material in construction perspectives requiring strength and thermal efficiency.

## 2. Literature Review

AAC primarily comprises cement, fly ash or quartz sand, lime, gypsum, and aluminum powder [8,9]. Researchers aiming to curtail municipal solid waste (MSW) in landfills, minimize the use of natural resources like sand, reduce production costs, and lower greenhouse gas emissions have successfully incorporated MSW as a partial substitute for AAC raw materials, including quartz sand, cement, and lime [10,11]. Literature reviews highlight that MSW with elevated silica contents, such as fly ash and rice husk ash, proves to be the most effective method for enhancing the mechanical and physical properties of AAC [12,13]. MSW containing a cumulative concentration of silica, alumina, and iron exceeding 70% (87.41% in this study) is categorized as pozzolanic material [14].

To enhance the mechanical properties of AAC, researchers have successfully introduced supplementary materials like organic and inorganic fibers [15,16]. A recent study by Zhang *et al.,* [17] in 2022 investigated the mechanical properties and interface enhancement of autoclaved aerated concrete reinforced with bamboo cellulose nano-fibers. Their findings indicated an increase in flexural and compressive strength with an escalating content of bamboo cellulose nano-fibers (BCNF), showcasing a viable approach for utilizing renewable materials and waste in producing high-performance, green AAC. Concurrently, Huang *et al.,* [18] explored AAC reinforced with dopamine-modified polyethylene terephthalate waste fibers, revealing enhanced mechanical properties such as compressive and flexural strength. However, the impact of direct fire exposure at temperatures up to 900°C on the physical and mechanical properties of AAC has not been studied. The addition of waste materials in AAC gives improvement in physical and mechanical properties such as ceramic waste, gypsum waste, glass waste, biomass waste, and others.

Ceramic waste, a type of MSW recognized as pozzolanic material, constitutes nearly 30% of total ceramic production, leading to significant waste in landfills and approximately 0.15 billion tons of carbon dioxide emissions from ceramic tile production [19,20]. Studies have reported positive effects of ceramic waste on the mechanical and fire resistance of concrete [21,22]. In addition, the ceramics have also been used as insulator material in high voltage transmission systems [23]. Gypsum waste, another form of MSW, with almost 94% disposed of in landfills, stands out as an attractive building material due to its fire resistance, sound absorption, lightweight nature, and excellent moldability [24,25]. According to Kamarudin *et al.,* [26], gypsum is also a good addictive material because of chemical stabilization. Given the favorable properties of ceramic and gypsum waste (CGW) and the abundance of landfills in Malaysia, this study investigates into the physical and mechanical properties of AAC with additional CGW after exposure to direct fire at temperatures up to 920°C for 300 seconds. The main objective is to determine the work density and compressive strength of AAC-CGW before and after direct fire exposure.

## 3. Methodology

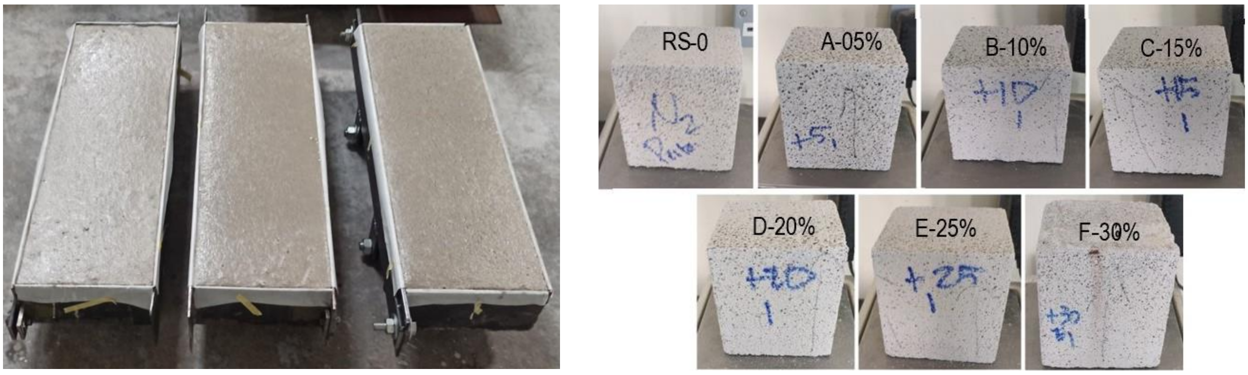
### *3.1 Preparation of Autoclaved Aerated Concrete based Ceramic Gypsum Waste (AAC-CGW)*

This investigation utilized sand and Portland cement procured from Pekan Pagoh, Johor, for the preparation of AAC samples. The lime and aluminum powder employed in the AAC sample preparation were provided by a chemical industry supplier in Malaysia. The AAC slurry, created as a pre-preparation step, utilized water sourced from the laboratory of Kim Hoe Thye Industries in Johor, Malaysia. Gypsum waste, serving as both a partial substitute for sand and an additional component, was obtained from Prudent Deals Sdn. Bhd., situated at 18 Lorong SS 1/11A, Petaling Jaya, 47301, Selangor, Malaysia. To ensure its purity, manual sorting was conducted on the gypsum waste to eliminate any extraneous materials such as plastic, rubber, and paper. Subsequently, a Ball Mill Machine was employed to manually grind the gypsum waste, resulting in gypsum waste powder (GWP) with particle sizes ranging from 0.5 to 1mm. Ceramic waste was sourced from Terengganu Recycle, a recycling center located in Hulu Terengganu. A manual sorting process was implemented to remove non-essential materials such as plastic, rubber, textiles, wood, and paper from the ceramic waste. Following this, a Ball Mill Machine was utilized to grind the ceramic waste, yielding ceramic waste powder (CWP) with particle sizes falling within the range of 0.5 to 1mm.

Table 1 tabulated the composition of AAC based on CGW addition components in the mixed design. The composition includes Sand (70%), Gypsum Waste (2%), Ceramic Waste (0 – 28%); Gypsum Waste (2%); Lime (18%); Cement (12%); Aluminium Paste (0.1%); and Water (0.58%). The mixed design for AAC based on CGW (AAC-CGW) entailed adjusting the sand composition, specifically increasing the proportion of ceramic waste, considering its impact on the strength performance of the resulting AAC-CGW. The mixing process involved utilizing Allefix’s 2100W Electric Mixer for 15 minutes, followed by the addition of aluminum powder (0.1%) and stirring for 15 seconds to form a slurry. The prepared slurry was poured into a 2/3 box mold, and gently shaken to allow air bubbles to rise to the top, as depicted in Figure 1(a). The expansion of the mixed slurry into the full mold required approximately 30 minutes and was repeated for various sample compositions. The slurry underwent pre-curing at room temperature for 3 hours, followed by curing in an autoclave machine under hydrothermal conditions at 200°C and 12-bar pressure for 12 hours.

**Table 1**
The mixed design composition for AAC based on CGW addition (AAC-CGW)

| Sample | Siliceous (%) | | | Calcareous (%) | | Al Powder (%) | W/R (%) |
|---|---|---|---|---|---|---|---|
| | Sand | CWP | GWP | Lime | Cement | | |
| RS-0 | 70 | 0 | 0 | 18 | 12 | 0.1 | 0.58 |
| A-05% | 70 | 3 | 2 | 18 | 12 | 0.1 | 0.58 |
| B-10% | 70 | 8 | 2 | 18 | 12 | 0.1 | 0.58 |
| C-15% | 70 | 13 | 2 | 18 | 12 | 0.1 | 0.58 |
| D-20% | 70 | 18 | 2 | 18 | 12 | 0.1 | 0.58 |
| E-25% | 70 | 23 | 2 | 18 | 12 | 0.1 | 0.58 |
| F-30% | 70 | 28 | 2 | 18 | 12 | 0.1 | 0.58 |




(a) (b)

**Fig. 1.** (a) The slurry of in-box mold of AAC-CGW addition (b) The specimen's dimension for physical and mechanical testing

## *3.2 Physical and Mechanical Testing*

All AAC specimens, as depicted in Figure 1(b), were dimensionally tailored to sizes of 100 x 100 x 100 mm for subsequent engineering tests encompassing parameters such as work density, compressive strength, and direct fire resistance. The work density measurements for the AAC samples were conducted utilizing an electrical balance, specifically the GF-6100 model, at the Concrete Lab UTHM Pagoh. Work density values were determined following ASTM C1692-11 [27]. The calculation of work density followed the formulation presented in Eq. (1) where *M* is the weight of the AAC-CGW sample and *V* is the AAC-CGW sample volume.

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

The evaluation of compressive strength for all samples was conducted using a Universal Testing Machine (UTM) of the VEW 2308 model, adhering to the compressive strength test standard ASTM D695. The specific strength of AAC samples was subsequently calculated to facilitate compressive comparisons among samples with varying work densities [28]. The formulation for specific strength is expressed in Eq. (2), where $f_c$ is the compressive strength of the AAC sample and $\rho_w$ is the work density of the AAC sample.

$$S = \frac{f_c(MPa)}{\rho_w(kg)} \tag{2}$$

### *3.3 Fire Resistance Testing*

All specimens underwent exposure to a direct fire temperature of 920°C for a duration of 300 seconds, with the maximum temperature reaching 926.4°C. Following the 300-second exposure, the fire source was deactivated, and the samples naturally cooled down over a span of 900 seconds. The ambient conditions during this cooling period were a workshop temperature of 27.5°C and humidity at 68%. Visual observations of the physical surfaces of the samples were conducted both during and after exposure to direct fire, with any changes duly recorded. Two thermocouples, T1 (surface) and T2 (opposite surface), were utilized to detect the thermal load temperatures in the specimens. The temperature range of the Type-K thermocouple employed was 50°C to 1300°C, with an accuracy of ±3°C. Figure 2 illustrates the direct fire testing set-up in Kim Hoe Thye Industries Sdn Bhd laboratory. The direct fire test was conducted in adherence to the United Kingdom fire standards, specifically BS-7974, 2019 [29].

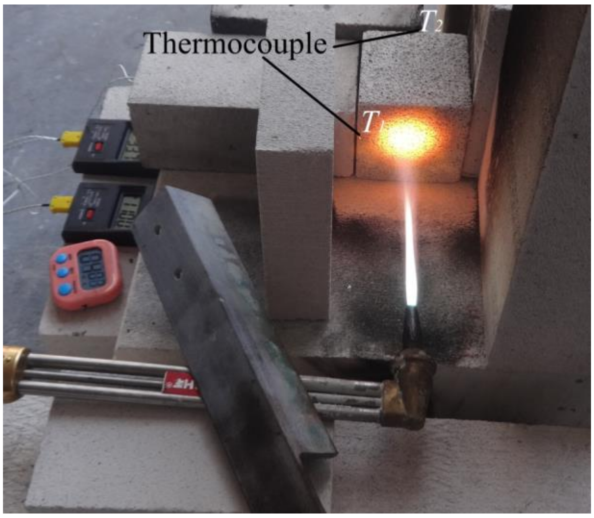



**Fig. 2.** The direct fire testing set-up in Kim Hoe Thye Industries Sdn Bhd Laboratory

## 4. Results and Discussion

### *4.1 Physical and Mechanical Properties of AAC-CGW before Direct Fire Testing*

Table 2 and Figure 3 present the work density, compressive strength, and specific strength of various compositions of ceramic-glass waste for AAC-CGW addition. The work density demonstrated a linear increase with the increasing ratio of CGW addition, indicating an increase in the range of 2.62% to 13.30% for CGW additions ranging from 5% to 30% by weight. The impact of CGW addition significantly influenced the work density of AAC, primarily attributed to the increased volume of the slurry sample. Remarkably, all work densities surpassed those of the reference sample (RS), aligning with findings from a previous study [30].

**Table 2**
The work density, compressive strength, and specific strength of different compositions of ceramic-glass waste for AAC-CGW addition

| Samples | Work Density(kg/m$^3$) | Compressive Strength (MPa) | Specific Strength (N.m/kg) | Enhance strength (%) | Enhance Density (%) |
|---|---|---|---|---|---|
| RS-0 | 593.71 | 1.64 | 2762.29 | - | - |
| A-05% | 609.32 | 2.39 | 3922.41 | 45.73 | 2.63 |
| B-10% | 627.05 | 2.38 | 3795.55 | 45.12 | 5.62 |
| C-15% | 632.70 | 2.35 | 3714.24 | 43.29 | 6.57 |
| D-20% | 639.51 | 2.18 | 3408.86 | 32.93 | 7.71 |
| E-25% | 649.57 | 2.14 | 3294.49 | 30.49 | 9.41 |
| F-30% | 672.70 | 2.12 | 3151.48 | 29.27 | 13.30 |

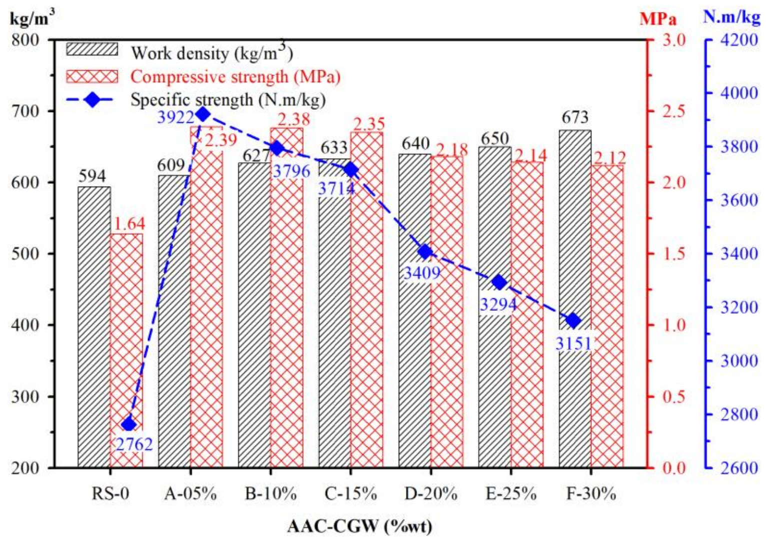



**Fig. 3.** The work density, compressive strength and specific strength of different composition of ceramic-glass waste for AAC-CGW addition

Compressive strength exhibited an increase with incremental CGW addition, particularly up to 5% by weight. The addition of CGW to AAC led to a significant enhancement in compressive strength, ranging from 31.01% to 45.73%. The highest compressive strength recorded was 2.39 MPa for a 5% weight addition of CGW, surpassing the compressive strength of RS. The effectiveness of CGW in enhancing AAC compressive strength was found to be more evident compared to prior studies [9,31]. This enhancement was attributed to the pozzolanic effect of ceramic waste, owing to its higher silica and alumina content. Previous studies by Rashid *et al.,* [32] and Li *et al.,* [33] have highlighted that higher percentages of silica, alumina, and calcium oxide contribute to pozzolanic reactivity and cementitious properties, supporting the formation of C-S-H and tobermorite as major phases in AAC, thereby enhancing compressive strength. Additionally, pozzolanic materials have been shown to improve the long-term strength of Portland cement binder through pozzolanic reactions [34]. The positive impact of pozzolanic material on the compressive strength of AAC and aerated concrete has been explored in previous literatures [35,36]. The non-linear correlation between the increment of compressive strength and increasing density is attributed to the additional volume of the slurry sample.

The results also suggest that gypsum waste may contribute to increasing compressive strength. Previous research has explored the positive effects of gypsum waste on concrete compressive strength [37]. In some instances, gypsum has been known to transform into anhydrite during the autoclaving process, enhancing physical properties and water resistance [38]. The positive influence of calcium sulfate dehydration on AAC compressive strength has also been recognized [39]. While increasing CGW addition from 10% to 30% of sand weight led to a gradual reduction in compressive strength from 2.39MPa to 2.14MPa, the values remained higher than RS at 31.01%. The fluctuation in compressive strength could be elucidated by the insufficient reaction of calcium hydroxide formed after cement hydration with a high volume of silica from ceramic waste powder (CWP), leaving some silica unreacted [40]. Furthermore, AAC compressive strength is contingent on the presence of tobermorite and C-S-H (B) formation in AAC samples [41].

Meanwhile, the specific strength increased from 2762.29N.m/kg to 3922.41N.m/kg with CGW addition from 0% to 5% by weight, and it exhibited a linear decrease with increasing CGW addition from 10% to 30% by weight. The observed correlation between specific strength and compressive strength indicated a nonlinear relationship with work density. This observation aligns with findings from other studies that explored the inverse correlation between specific strength and work densities [42]. The highest specific strength recorded was 3918.58N.m/kg for a 5% weight addition of CGW, underscoring the significant influence of CGW addition on specific strength.

### *4.2 Direct Fire Resistance Properties of AAC-CGW*
#### *4.2.1 Direct fire resistance - thermal analysis*

Figure 4(a) shows the temperature progression during direct fire exposure for AAC-CGW addition. The initial average temperature before direct fire was 32.5℃, with the temperature escalating by more than 100℃ per minute after 60 seconds of direct fire exposure. The maximum temperature at the surface ($T_1$) reached 926.4℃ at the 300-second mark. Throughout the process, the average temperature for each sample was 760℃. Despite the substantial heat, no visible flame or smoke was emanating from the sample after direct fire testing. This can be attributed to the non-combustible nature of AAC samples containing materials like ceramic waste. Lugaresi *et al.,* [43] emphasize that ceramics exhibit high incombustibility, with a failure temperature ranging from 700℃ to 1200℃. Post direct fire exposure for 300 seconds, the cooling process of the sample was rapid, with an average temperature of 175.3°C recorded after 900 seconds. The outcomes indicate that CGW addition successfully enhances the thermal insulation ($T_1$) of AAC by 20.1%.

In Figure 4(b), the temperature profile of the opposite surface of the AAC-CGW addition sample located 100 mm distance from the exposed surface is depicted. Despite exposure to direct fire at a high temperature of 926.4℃ for 300 seconds, the average temperature at $T_2$ remained at 34.1℃, nearly identical to the room temperature recorded during testing at the same duration. This temperature stabilization could be attributed to the beneficial influence of gypsum and ceramic waste within the AAC. The average thermal diffusion of the sample increased proportionally with the CGW ratio, rising from 1.5℃ to 2.2℃ as the CGW ratio increased from 5% to 30% by weight. This emphasizes the substantial impact of CGW on the thermal diffusion of the sample, indicative of CGW's positive role in enhancing thermal diffusion. The ability of CGW to improve thermal diffusion may stem from its capacity to avoid reducing the connected pores of AAC. Moreover, the results demonstrate that CGW addition successfully improves the thermal insulation ($T_2$) of AAC by 16.7%.

The analysis of the temperature profiles during and after direct fire exposure reveals critical insights into the performance of AAC-CGW samples under extreme conditions. The rapid temperature increase during direct fire testing, reaching a maximum surface temperature of 926.4℃, underscores the robustness of the AAC-CGW composition in withstanding high-temperature environments. The absence of flame and smoke during and after the test reinforces the non-combustible nature of the AAC-CGW samples, primarily attributed to the presence of ceramic waste.

The substantial improvement in thermal insulation at both surface points ($T_1$ and $T_2$) further accentuates the efficacy of CGW addition in enhancing the overall thermal performance of AAC.

The temperature stabilization observed at the opposite surface ($T_2$) near room temperature despite exposure to intense direct fire substantiates the advantageous influence of gypsum and ceramic waste. The recorded increase in thermal diffusion with rising CGW ratios emphasizes the positive impact of CGW on enhancing the thermal properties of the AAC-CGW samples. This enhancement in thermal properties is particularly crucial in applications where fire resistance and thermal insulation are paramount considerations, such as in constructing fire-resistant walls or structures requiring heightened thermal performance. The findings from the temperature analysis indicate the benefits of incorporating ceramic and gypsum waste into AAC compositions. The observed improvements in thermal insulation, temperature stabilization, and thermal diffusion highlight the potential of AAC-CGW samples for wall applications in extreme environments.

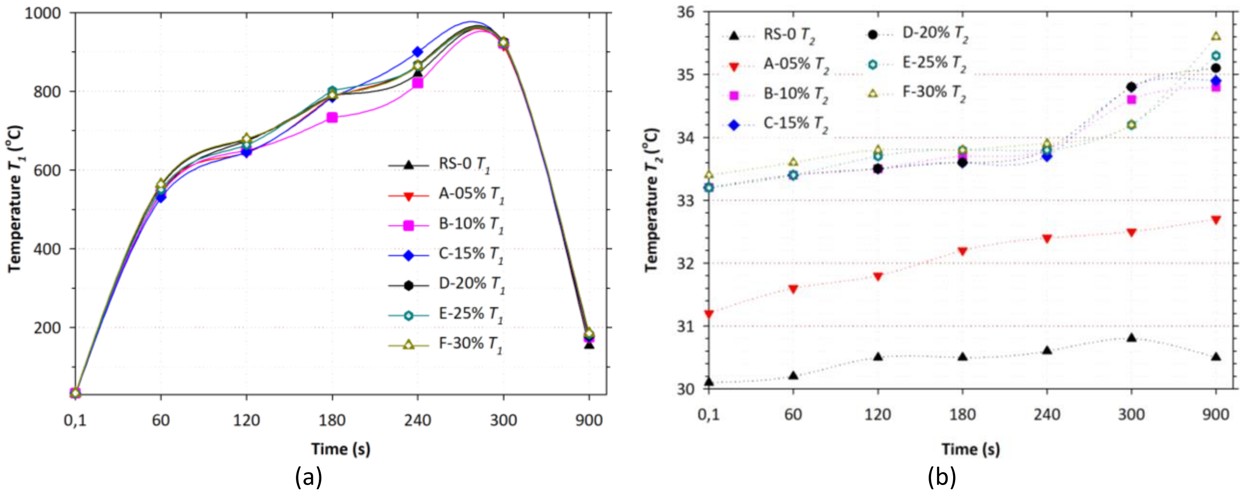



**Fig. 4.** (a) Temperature process ($T_1$) of AAC-CGW addition during direct fire testing, (b) Thermal diffusion analysis ($T_2$) of AAC-CGW addition during direct fire testing

### *4.2.2 Direct fire resistance - surface analysis*

Figure 5 depicts the effect of the direct fire test on the surface of AAC-CGW addition samples, which were subjected to temperatures exceeding 920°C for 300 seconds. Visual observations were conducted during exposure to fire, and the conditions of the samples were recorded before and after the fire exposure. Notably, all samples exhibited an unconventional coloration, appearing black, which can be attributed to the fire temperature being below 1000°C. A similar coloration phenomenon has been reported by Ahmed *et al.,* [44] study on the fire resistance of high-performance self-consolidating concrete and normal strength-vibrated concrete exposed to a maximum direct fire temperature of 520°C for 0.75 hours. Despite exposure to direct fire at 926.4°C for 300 seconds, the physical surfaces of the samples remained crack-free and unburnt, visibly discernible to the naked eye. This resilience could be attributed to the positive influence of CGW on AAC, given its categorization as containing non-combustible materials.

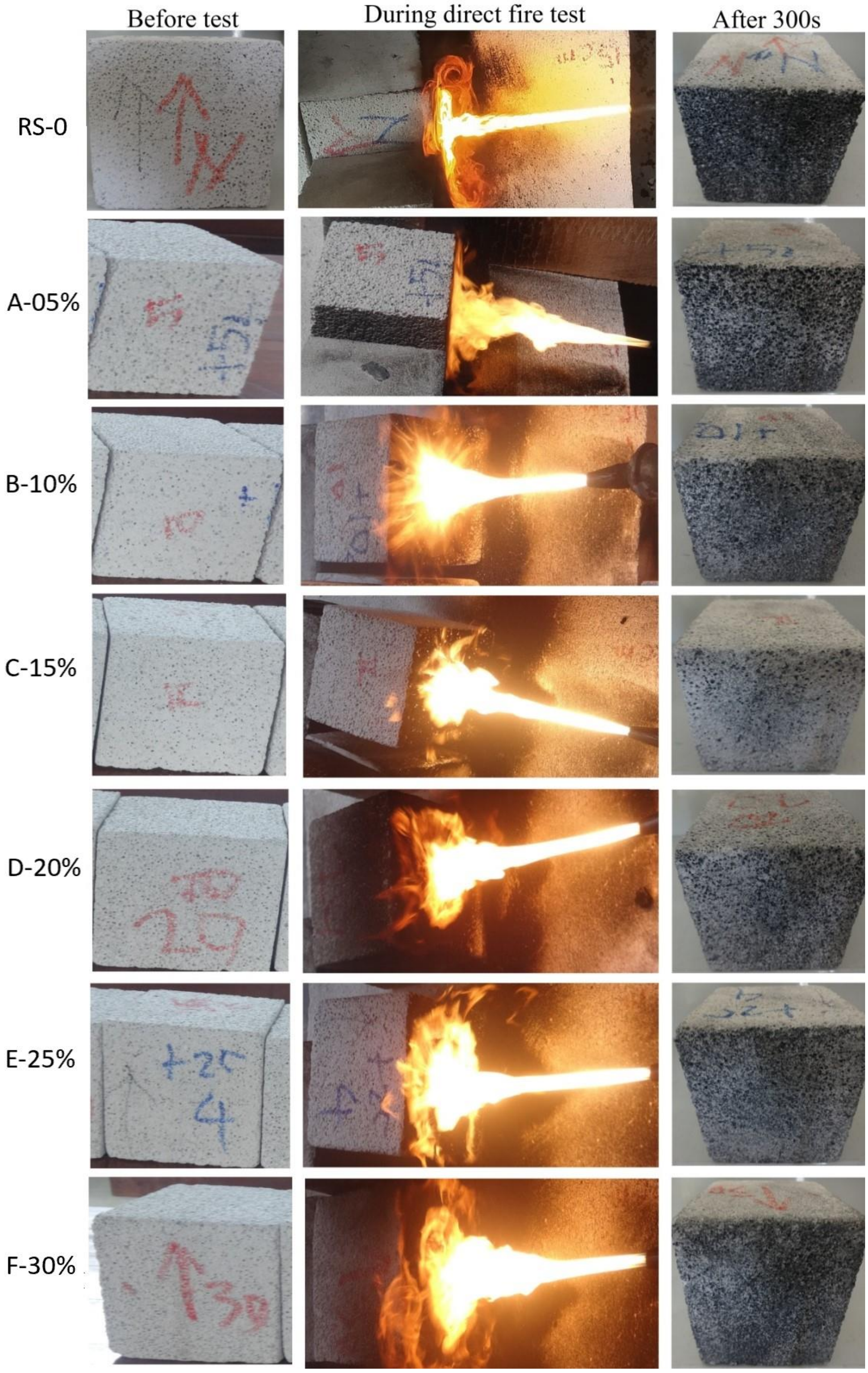



**Fig. 5.** Effect of direct fire test on the surface at different composition of ceramic-gypsum waste of AAC-CGW addition

In contrast to the observed coloration and surface condition of AAC-CGW samples, the reference sample (RS) demonstrated abnormal color behavior. The black coloration exhibited by all samples, including RS, could be explained by the fire temperature remaining below 1000°C. It is crucial to highlight that the AAC-CGW samples did not undergo melting during exposure to the direct fire at 926.4°C for 300 seconds. This resilience is particularly remarkable and can be attributed to the high melting point of ceramic waste, which stands at 2000°C. The results stand in contrast to a study by Almeshal *et al.,* [45], where eco-friendly concrete containing recycled plastic as a partial replacement for sand exhibited abnormal black coloration, cracks, and burning during direct fire exposure at temperatures below 1000°C for 300 seconds.

These findings highlight the significant fire resistance and strength properties of AAC-CGW samples, even under high-temperature conditions. The absence of melting, cracking, and burning in the AAC-CGW samples, coupled with the unconventional black coloration, aligns with the expected behavior of non-combustible materials present in the composition. The positive outcomes observed in this study contribute to the growing body of evidence supporting the use of CGW in AAC for applications where fire resistance and structural stability are crucial considerations. Moreover, the contrast with previous studies highlights the unique advantages and characteristics of AAC-CGW, positioning it as a promising material for diverse construction and fire-resistant applications. The analysis of the surface conditions and color behavior of AAC-CGW samples following exposure to direct fire demonstrates the material's resilience and non-combustible nature. The unconventional black coloration, absence of cracks or burning, and the non-melting behavior, even at high temperatures, validate the potential of CGW addition to AAC for enhancing fire resistance and strength properties.

*4.2.3 Effects of work density and compressive strength analysis before and after direct fire testing*

*4.2.3.1 Effect of work density before and after direct fire testing*

Figure 6 shows the result of the work density of AAC-CGW addition both before and after the direct fire test at 926.4°Cfor 300 seconds. The analysis reveals a decrease in the work density of the samples, ranging from 5.59% to 14.19%. The most substantial reduction, amounting to 84.22 grams, is observed in the reference sample (RS). This reduction in work density can be attributed to the evaporation of water content within the samples during exposure to the intense flames at 926.4°C for 300 seconds. As the CGW ratio increases, the work density exhibits a corresponding decrease, spanning from 5% to 30% by weight in comparison to the reference sample. For the sample with a CGW ratio of 30% by weight, the reduction in work density is limited to 5.59%. This observation suggests that samples with higher CGW ratios experienced water scarcity during the preparation phase, resulting in reduced work density. The study emphasizes that the direct fire test has a positive impact on mitigating the work density of AAC-CGW addition. This reduction in work density following exposure to direct fire is a significant finding with implications for the material's performance in real-world fire scenarios. The decrease in work density, particularly in the RS and higher CGW ratio samples, indicates the unstable water content within the samples during exposure to extreme temperatures. The positive effect on reducing work density may be attributed to the release of water in the form of steam during the direct fire test, contributing to a decrease in overall sample density.

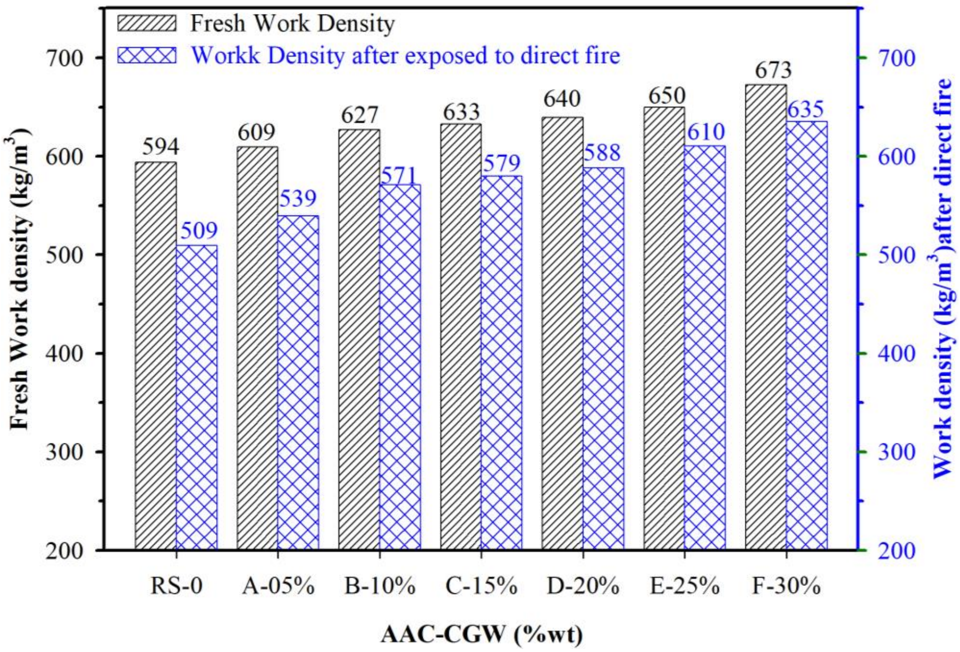



**Fig. 6.** The work density of AAC-CGW addition before and after direct fire test at 926.4°C for 300s

In practical terms, the reduction in work density observed in AAC-CGW addition samples post-direct fire exposure aligns with the material's behavior under extreme conditions. The decreased work density could potentially be advantageous in improvements where lightweight materials are desirable, such as in certain construction applications or in the development of structures where weight considerations are critical. The analysis of work density variations in AAC-CGW addition samples before and after direct fire testing provides significant interpretations of the material's response to high-temperature conditions. The observed reduction in work density, particularly in samples with higher CGW ratios, highlights the influence of direct fire exposure on the volatile components within the AAC-CGW composition. This research contributes understanding of the dynamic behavior of AAC-CGW under extreme conditions and underscores its potential for applications where reduced work density is a desirable attribute. The analysis reveals a decrease in the work density of the samples, ranging from 5.59% to 14.19%. The most substantial reduction, amounting to 84.22 grams, is observed in the reference sample (RS). This reduction in work density can be attributed to the evaporation of water content within the samples during exposure to the intense flames at 926.4°C for 300 seconds. As the CGW ratio increases, the work density exhibits a corresponding decrease, spanning from 5% to 30% by weight in comparison to the reference sample. For the sample with a CGW ratio of 30% by weight, the reduction in work density is limited to 5.59%. This observation suggests that samples with higher CGW ratios experienced water absence during the preparation phase, resulting in reduced work density. The effects of the study emphasize that the direct fire test has a positive impact on mitigating the work density of AAC-CGW addition. This reduction in work density following exposure to direct fire is a significant finding with implications for the material's performance. The decrease in work density, particularly in the RS and higher CGW ratio samples, indicates the volatile nature of water content within the samples during exposure to extreme temperatures. The positive effect on reducing work density may be attributed to the release of water in the form of steam during the direct fire test, contributing to a decrease in overall sample density.

### *4.2.3.2 Effect of compressive strength before and after direct fire testing*

Figure 7 presents the compressive strength of AAC-CGW addition samples before and after undergoing a direct fire test at 926.4℃ for 300 seconds. The observed trend indicates an increase in compressive strength ranging from 2.35% to 53.30%, comparing RS to F-30%. The maximum enhancement in compressive strength, amounting to 53.30%, was recorded for the sample with a 5% weight ratio of CGW. This significant increase can be attributed to the direct fire effect, which, during the test, caused the melting of some silica within the sample, resulting in a more compact structure for the AAC. On average, the compressive strength showed a significant increase of 19.07%. These results show the positive impact of the direct fire test on increasing the compressive strength of AAC-CGW addition. However, it is significant that for CGW weight ratios of 20% to 30%, the direct fire test exhibited a less significant effect on compressive strength. The average increase in compressive strength for samples within this range was 6.49% after exposure to the direct fire at 926.4℃ for 300 seconds. This less pronounced impact on compressive strength could potentially be attributed to a lack of water in the samples during the preparation phase. The decrease in compressive strength following exposure to direct fire appears to exhibit a linear correlation with the initial compressive strength of the sample.

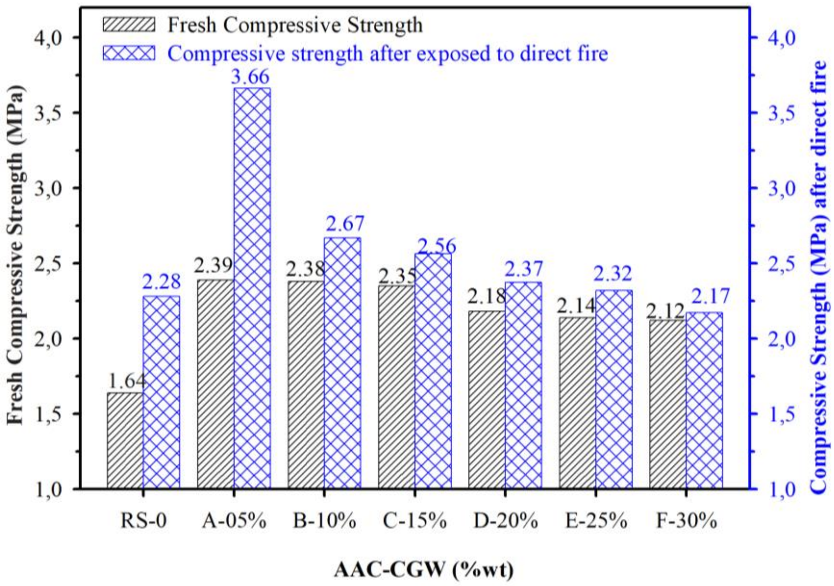



**Fig. 7.** The compressive strength of AAC-CGW addition before and after direct fire test at 926.4°C for 300s

The findings highlight the influence of direct fire on compressive strength is remarkable in evaluating the material's behavior under extreme conditions. The melting of silica during the direct fire test, leading to a more compact AAC structure, aligns with the observed increase in compressive strength. This suggests that the direct fire test serves as a contributing factor in strengthening the AAC-CGW addition samples. Moreover, the results indicate that the effect of direct fire on compressive strength is more effective in samples with lower CGW weight ratios. The optimal enhancement observed in samples with a 5% CGW weight ratio may be attributed to a balance between the positive effects of direct fire and the composition of CGW in the AAC. The observed increase in compressive strength, particularly in samples with lower CGW weight ratios gives the impact of the direct fire test on enhancing the material's structural robustness.

## 5. Conclusions

The AAC, incorporating varying compositions of CGW addition (0%, 5%, 10%, 15%, 20%, 25%, and 30%), was successfully formulated. The results demonstrated an incremental improvement in compressive strength, particularly up to a 5% weight addition of CGW, reaching a maximum compressive strength of 2.39MPa. The CGW infusion resulted in a substantial 45.73% increase in compressive strength compared to the baseline reference sample (RS). In terms of fire resistance, all CGW-added samples, except for RS, exhibited robust performance, showcasing an absence of cracks, burning, or melting even under direct fire exposure exceeding 920°C for 300 seconds. Additionally, the CGW addition demonstrated a commendable 20.1% enhancement in thermal insulation compared to RS. The direct fire resistance test not only substantiated the material's resistance to extreme conditions but also positively impacted various physical and mechanical properties of the AAC samples.

The comprehensive analysis revealed a 9.9% reduction in average working density, coupled with an 18.8% increase in compressive strength following direct fire testing. This demonstrates to the direct fire test's efficiency in enhancing the overall performance of AAC samples. The direct fire contributed to a remarkable 53.30% increase in compressive strength compared to the initial sample. In conclusion, the AAC formulations with CGW addition exhibit promising characteristics, well-suited for applications in wall constructions, particularly in thermal walls and those demanding high fire resistances. The study not only validates the material's capability to withstand direct fire at elevated temperatures but also highlights the significant improvements in thermal insulation and mechanical properties presented by the incorporation of CGW. These findings contribute valuable insights to the field of construction materials, particularly in the development of AAC with enhanced fire resistance and thermal insulation properties.

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