Lightweight Masonry Blocks with Expanded Glass Aggregate for Fire Resistance

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***Abstract*—This research study aims to develop masonry blocks using expanded glass aggregate with enhanced fire resistance characteristics. In recent years many research studies focused on developing lightweight construction materials in concrete and masonry for various specialised applications. However, very few studies have investigated their fire resistance characteristics. In this study, we investigate the possibility of using expanded glass aggregate in cement masonry blocks to enhance their fire resistance. Expanded glass is a recycled waste glass product, a lightweight and good thermal insulation material. Both commonly used cement-sand (i.e. control mix) and expanded glass aggregate-based blocks were developed and exposed to simulated fire conditions. Fire conditions included both building fire and bushfire time-temperature curves. The paper presents the results of physical properties of the expanded glass aggregate, mix design and compressive strength and fire test results of both cement-sand and cement-expanded glass aggregate blocks.**

Keywords—masonry, cement blocks, fire resistance, expanded glass, lightweight masonry

I. Introduction

Many previous research studies have aimed at developing lightweight concrete and masonry units (blocks/panels) because of their low cost, energy efficiency and higher strength/weight ratio than conventional units presently used in the building industry. Past studies have developed lightweight cement mixtures with natural and waste materials by replacing cement or normal aggregates [1-8]. They are developed by adding natural and artificial lightweight aggregates such as pumice, perlite, diatomite, polystyrene, foam, waste aggregates, etc. and their physical and mechanical properties have been obtained. However, these studies were primarily focused on mechanical properties, density and thermal conductivity at ambient temperature, etc. Only a few experimental studies have been conducted on fire resistance characteristics. Even most have only determined the thermal conductivity at ambient temperature and residual strength at elevated temperatures [9-12].

Bushfire is one of the most devastating natural hazards in Australia. This adversely affects living entities, properties, livelihood, and the environment. Currently, the risk has increased by climate change and the dense population at the urban/bushland interface. Buildings should be designed against direct flame, radiant and convective heat, burning embers, falling debris, superheated air and smoke, i.e. they should have the required thermal and mechanical properties for bushfire resistance. Conventional building materials, concrete, masonry, clay, steel and timber, have their limitations for fire resistance. Timber, clay bricks and cement blocks have lower thermal conductivity values and perform well to some extent in providing fire resistance. However, the fire resistance of cement-based materials can be further improved by adding natural and artificial lightweight aggregates. Past studies have shown that the higher the lightweight aggregate content in lightweight mixes, the higher the porosity and water absorption and the lower the density and low thermal conductivities [5-10]. Thus, this research study explores the possibility of using expanded glass aggregates in cement-sand mix-based masonry blocks to enhance fire resistance.

Expanded glass is a recycled waste glass product, a lightweight and good thermal insulation material. Both commonly used cement-sand (i.e. control mix) and expanded glass aggregate-based mixes were developed and exposed to simulated fire conditions. Fire conditions included both building fire and bushfire time-temperature curves. The paper presents the results of physical properties of the expanded glass aggregate, mix design and

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compressive strength and fire test results of both cement-sand and expanded glass aggregate blocks.

II. Experimental Program

A. Materials

The mix components were cement, water, sand and expanded glass aggregate. Expanded glass aggregate was sourced from Expanded Glass Technologies Pty Ltd, Australia. They were in three different sizes; 0.5-1 mm, 1-2 mm and 2-4 mm were mixed on an equal volume basis and the particle size distribution is similar to that of the sand. The specific gravity of cement, sand and expanded glass aggregate are 3.06, 2.57 and 0.54, respectively. Also, the water absorption of saturated surface dry (SSD) sand and expanded glass aggregate are 0.1 and 32.4%, respectively.

B. Mix Design

In this study, two cement mixes, 1) Cement-Sand (C-S) and 2) Cement – Expanded Glass (C-G) were developed on the absolute volume method and their mix proportions are given in Table I. In the C-S mix, the cement to sand ratio was 1:3 and the effective water to cement ratio was 0.6:1. Then the sand volume in the C-S mix was fully replaced by an equal volume of expanded glass aggregate to produce the C-G mix. Also, the entrapped air content in both mixes was assumed as 2% of the total mix volume.

TABLE I. MIX PROPORTIONS IN SSD CONDITION

Mix / Materials	***Cement – Sand (C-S)***	***Cement – Expanded Glass (C-G)***
Cement	478 kg/m^3	477 kg/m^3
Sand	1380 kg/m^3	0
Expanded Glass	0	290 kg/m^3
Effective Water	287 kg/m^3	286 kg/m^3

All the mix components were mixed in a pan mixer for about 7 min as per the standard code of practices [13-15]. After completing mixing, test specimens (Fig. 1) were cast within the next 20 min. Later specimens were kept covered and undisturbed on a horizontal surface for 18–36 h at the temperature of 23 ± 2 ºC. After 24 h of initial curing, the test specimens were demoulded and stored inside lime saturated water at 23 ± 2 ºC until 28 days.

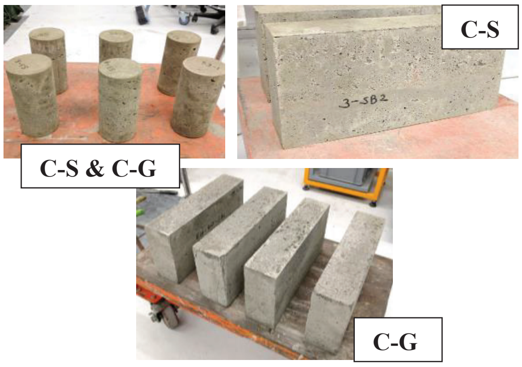

Fig. 1. Test specimens – Cylinders and blocks

C. Detail of Tests

Compressive strength and hardened and oven dry densities were determined based on the standards [16-18]. The 28 days compressive strength of 100 mm diameter cylinders was determined using a universal testing machine by applying the load at a rate of 0.3 (N/mm^2)/s until the failure and unconfined compressive strength was calculated using the aspect ratio of 0.78 in AS/NZS 4456.4-2003 [19].The hardened density of cement mixes was determined using the 100 mm diameter cylinders after 28 days of curing.

Fire testing of solid masonry blocks (390 mm long × 190 mm high × 90 mm wide) was conducted using the 0.3 by 0.3 m gas furnace simulating building fire and bushfire conditions specified in relevant standards [20,21]. A total of six 'K' type wired thermocouples were attached to the blocks' fire and ambient side surfaces. Further, a rod-type thermocouple was placed inside the furnace to measure the furnace temperatures. Fig. 2 shows the masonry block's fire test set-up and thermocouple arrangement.

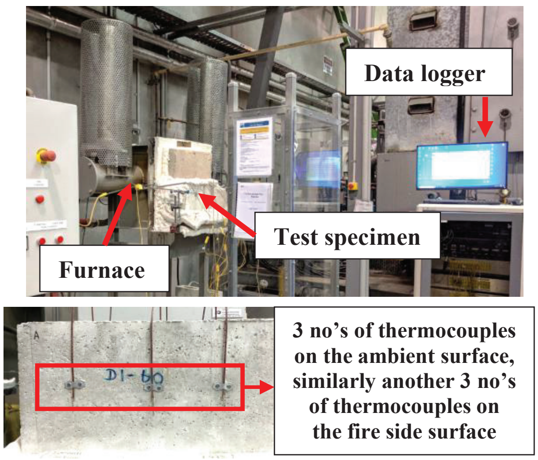

Fig. 2. Test set-up and thermocouple arrangement

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III. Results

The 28-day mean unconfined compressive strength of C-S and C-G mixes are 26.2 and 7.0 MPa, respectively. Fig. 3 shows compression test failure patterns of each mix. Similar to compressive strength, the C-S mix recorded the highest hardened and oven dry densities. The C-S mix's hardened and oven dry densities are 2150 and 1952 kg/m^3, respectively. Table 2 summarizes the properties of both cement mixes.

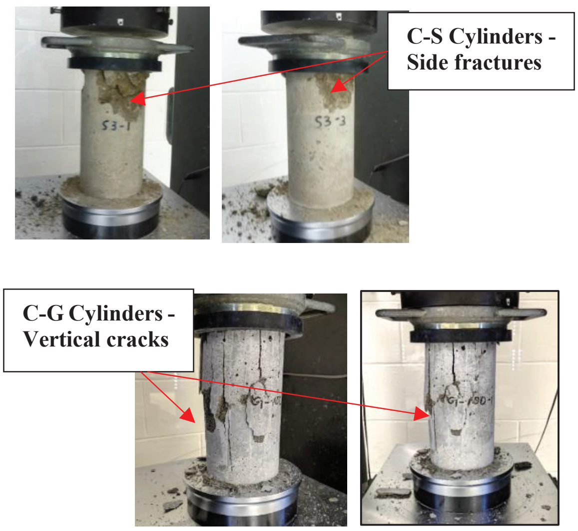

Fig. 3. Test set-up and thermocouple arrangement

TABLE II. PROPERTIES OF C-S AND C-G MIXES

Mix	*Cement – Sand (C-S)*	*Cement – Expanded Glass (C-G)*
Slump	35 mm	240 mm
Avg compressive strength (unconfined)	26.2 MPa	7.0 MPa
Avg hardened density	2150 kg/m^3	1019 kg/m^3
Oven dry density	1952 kg/m^3	791 kg/m^3
Insulation failure time – Building fire exposure	115 min (-/90/90)	>180 min (-/180/180)
Max. ambient surface temp. – Bushfire exposure	89 °C	49 °C

Fig. 4 shows the time-temperature curves of the fire-tested blocks. The initial average temperature on the ambient side surface of the blocks was around 20°C. Hence, the insulation failure occurs when the mean ambient surface temperature reaches 160 °C (i.e. 140 + 20 °C). At the end of three hours of building fire exposure, C-S and C-G blocks recorded average temperatures of 242 and 97 °C and 1094 and 1086 °C on the ambient and fire side surfaces, respectively. Hence as shown in Fig. 4, only the C-S block has failed under the insulation criterion at 115 min. Further, no integrity failure was observed in both blocks throughout the experiment. Also, as shown in Fig. 5, spalling on the fire side was only observed in the C-S block, while the C-G block recorded surface cracks on the fire side. Also, as seen in Fig. 5, crack intensity is higher on the fire side block surface in the C-S block than in the C-G block after three hours of exposure. Fig. 6 shows the time-temperature curves from the bushfire exposure.

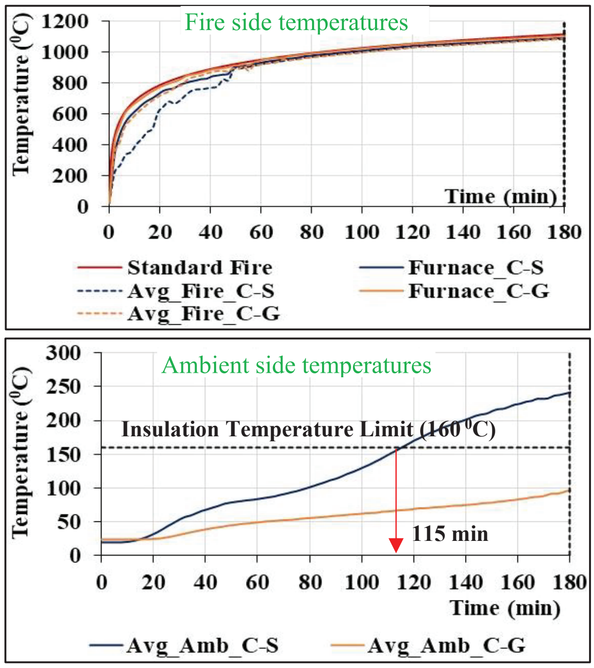

Fig. 4. Time-temperature curves of C-S and C-G blocks after building fire exposure

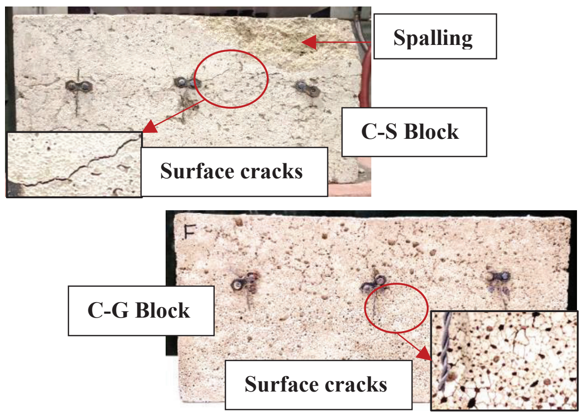

Fig. 5. Fire side surface after three hours of building fire exposure

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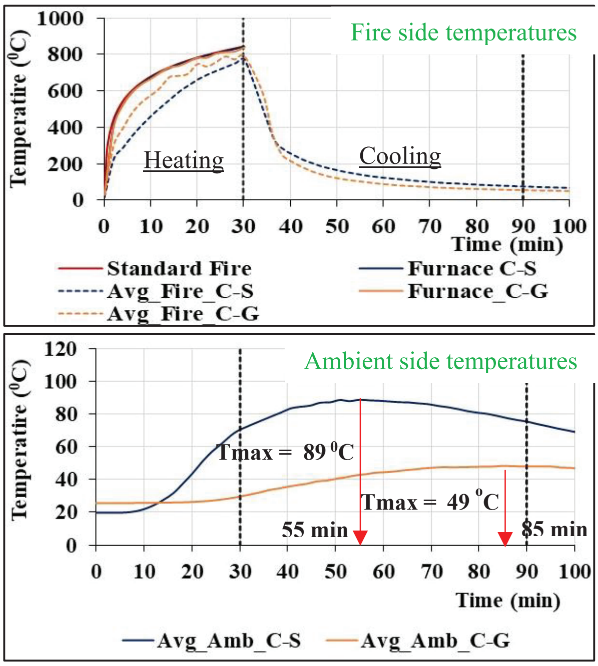

Fig. 6. Time-temperature curves of C-S and C-G blocks after bushfire exposure

IV. Discussions

The C-S mix recorded the lowest slump (35 versus 240 mm). Although it was expected to have a lower slump in the C-G mix due to its lower specific gravity than sand (i.e. 0.54 versus 2.57), the C-G mix recorded the highest slump (240 versus 35 mm) due to the rounded shape of glass aggregate which led to poor particle packing. The average hardened density recorded by the C-S and C-G mixes is 2150 and 1019 kg/m^3, respectively. A 53% reduction in the hardened density of the block when sand is replaced with expanded glass aggregate and thus expanded glass is more effective in reducing the density of the mix. The calculated oven dry density of the C-G mix is 791 kg/m^3. The oven dry density is less than 1400 kg/m^3, thus, it is an ultra-lightweight masonry unit as per [22].

The average unconfined compressive strengths of C-S and C-G mixes are 26.2 and 7.0 MPa, respectively. The compressive strength of the C-S mix is reduced by 73% with the replacement of expanded glass aggregate. However, both C-S and C-G mixes satisfy the loadbearing strength requirement for solid masonry units [23].

Fire resistance levels of C-S and C-G blocks are -/90/90 and -/180/180, respectively (see Table II). A significant increase in the fire resistance level with the use of expanded glass aggregate in the C-S mix. At the end of three hours of building fire exposure, the average ambient surface temperatures in C-S and C-G blocks are 242 and 97 ºC, respectively. A temperature reduction of 60% by the C-G mix. Further, spalling is also not observed in the C-G block. Similar to the building fire exposure, the C-G block recorded lower ambient surface temperatures during the bushfire exposure than the C-S block. The maximum ambient surface temperature was only 49 ºC in the C-G block, whereas in the C-S block, it was 89 ºC. Further, it is to be noted that the C-S block reached this maximum temperature in 55 min of bushfire exposure, and it was after 85 min in the C-G block. The total bushfire exposure test duration is only 90 min, with 30 min of heating and 60 min of cooling period. Thus, it can be concluded that the C-G block is the best suitable for bushfire resistance applications. However, studies are in progress to obtain the optimum mix for C-G mix with the combination of sand and expanded glass aggregate.

V. Conclusions

This paper presented an experimental study investigating the possibility of using expanded glass aggregate in masonry blocks to enhance their fire resistance. Physical and mechanical properties and fire resistance of cement-sand (C-S) and cement-expanded glass (C-G) mixes and blocks were determined based on relevant standards. The developed blocks were exposed to building and bushfire time-temperature curves. The key findings based on this experimental study are;

- The control cement-sand (C-S) mix had the highest hardened density and compressive strength and the lowest fire resistance than the cement-expanded glass (C-G) mix.
- The expanded glass aggregate in the C-G mix reduced the hardened and oven dry densities, compressive strength and most importantly, the ambient side surface temperatures when exposed to building fire and bushfire curves.
- The C-G block recorded the lowest ambient surface temperatures and its fire resistance level was the highest at -/180/180.
- The blocks developed using the C-G mix in this study satisfied the loadbearing strength requirement for solid masonry units and classified as an ultra-lightweight masonry unit.

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