Performance of autoclaved aerated concrete (AAC) exposed to standard fire

Adrian Andrei Stanescu¹, Octavian Lalu², Oana Luca¹, Florian Gaman¹

¹Technical University of Civil Engineering of Bucharest, Romania
²BRE Global Ltd, Bucknalls Lane, Garston, Watford, Herts, WD25 9XX, UK

E-mail: andrei.stanescu@utcb.ro

Abstract. This paper presents the results of an experimental study carried out within the National Institute for Research, Development in Constructions, Urbanism and Sustainable Territorial Development URBAN INCERC, on a system of walls made of ACC blocks, according to the standard SR EN 771-4 [8], having a density of 480 kg/m³ and standardized compressive strength of 3.5 N/mm², using mortar type binder class M2.5 with compressive strength of 2.5 N/mm². It was exposed to the action of standardized fire for a period of 220 minutes, after 10 days from the execution of the masonry. The results showed that, following the tests on the burned samples, extracted from the wall subject to the test, the standardized unit compressive strength decreased by 54%.

1. Introduction

Autoclaved aerated concrete (ACC) is a material made of sand, water, limestone and a small amount of aluminum powder [7]. Due to its mineral composition, it is classified as a non-combustible building material, included in the fire reaction euro class A1 [1]. Apart the ability to ensure tightness and thermal insulation, in fire situation, ACC does not emit smoke or toxic gases.

The main incombustible materials used for the structure, partitioning and covering of the buildings are: reinforced concrete, stone, bricks, concrete blocks, ceramic blocks or ACC masonry. Compared to the other materials listed, ACC has a considerably lower density (2-4 times lower) but also lower mechanical strength. Studies show that ACC blocks, due to their thermal insulation properties, can also be used to protect metal structures from fire [3-4].

The design practice in Romania used ACC walls as facade walls for structures in frames or with structural walls. The use of ACC walls as structural walls had a limited applicability so far, being used for two or three floors structures, in areas with low seismicity (<0.20g) [16]. Lately, the use of fire-resistant walls has become widespread in fire safety scenarios designed for buildings in classes I and II of importance [2].

In this broad context, the behavior of masonry walls, subjected to gravitational loads, during and after a major fire, is a major area of interest [5-6], [13].

2. Description of the experiment

The test was conducted in the Fire Safety of Buildings Research and Test Laboratory of URBAN-INCERC, Bucharest, on an AAC wall system with a thickness of 100 mm and an area exposed to fire of 9.00 m², 3.00 m long and 3.00 m high.

The wall system was made of ACC blocks with the dimensions: length x width x height: 600 x 100 x 250 mm, according to SR EN 771-4 [8], a density of 480 kg/m³ and standardized compressive strength...
of 3.5 N/mm², solidified with mortar type binder class M 2.5, having a compressive strength of 2.5 N/mm².

The wall made of simple masonry, with thin joints and no plaster, was exposed to standard fire (ISO834 curve) for 220 minutes, according to standard SREN 1363-1 [9]. The test was performed after 10 days from execution of masonry wall, after reducing the humidity in the tested element below the value of 15%.

The standard fire evolved according to equation (1), and the evolution in time is graphically shown in Figure 1. Standard fire is the empirical model used in the evaluation of fire behavior of structural elements of buildings and the values are shown in table 1.

\[ \theta_g = 345 \cdot \log_{10}(8t + 1) + \theta_0 \]  

By comparison, an outside fire reaches a burning temperature of approximately 680°C, and an inside fire, without oxygen supply from the outside and without the help of other fuels, reaches a maximum temperature of 800°C - 900°C. On the other hand, a fire with liquid, solid or gas fuel as combustion materials, does not exceed a temperature of 1350°C [14].

For the experimental study, the wall was fitted with eight temperature sensors inside the furnace, nine temperature sensors on the horizontal, placed at mid-height of the wall, at depths of 40, 60 and 80 mm as against side exposed to fire, and thirteen temperature sensors distributed over the wall side unexposed to fire.

In terms of strain, the values of expansions/contractions of the wall during exposure to fire were measured by three sensors placed at mid-height of the wall, by two sensors at 20 cm away from the left and right edges, and one at the centre.
3. **Description of wall behaviour in time**

The unexposed side of the wall system was permanently monitored with a thermovision camera, and the results are shown in the figure below.

![Figure 2. Location of temperature and measuring sensors inside the wall side unexposed to fire](image)
Figure 3 shows the distribution of temperatures on the side unexposed to fire, after 3, 39 and 219 minutes of exposure to standard fire. After 3 minutes of exposure to fire, figure 3 (a) shows uneven heating, mostly in the upper half of the wall, a phenomenon that disappears at temperatures exceeding 50°C.

Figure 3 (b) shows the thermal bridges in the joint areas due to heat transfer through the binding mortar and the mounting imperfections. In this phase of fire exposure, the thermal bridges are not a danger of fire spreading through transfer of hot gas. In these areas of thermal influence, the temperature does not exceed 110°C.

Figure 3 (c) shows that the temperatures at the thermal bridges in the joints and on the opaque surface of the masonry blocks become even, partially due to the fact that the joints are "filled" as a result of the expansion of the AAC blocks. However, the temperature of hot gas transferred through the cracks exceeds 400°C, which is a danger of fire spreading. At this point the wall system no longer ensures fireproofness and, implicitly, thermal insulation.

4. Experimental results
The average temperature values on both sides of the wall, as well as inside the wall were measured in order to draw temperature curves at certain time intervals within the wall, as indicated in table 2.

| Time [min] | Depth [mm]       |
|------------|------------------|
|            | 0    | 40   | 60   | 80   | 100  |
| 15         | 692  | 57   | 24   | 17   | 17   |
| 30         | 806  | 73   | 81   | 43   | 18   |
| 45         | 882  | 107  | 95   | 81   | 40   |
| 60         | 958  | 179  | 98   | 94   | 71   |
| 90         | 990  | 288  | 119  | 96   | 80   |
| 120        | 1023 | 410  | 204  | 96   | 81   |
| 180        | 1114 | 540  | 405  | 106  | 83   |
| 220        | 1133 | 610  | 517  | 249  | 85   |
The average temperature values measured on the side of the wall exposed to fire (depth 0 mm), on the unexposed to fire side of the wall (depth 100 mm) and at intermediate depths of 40, 60 and 80 mm, recorded at intervals of 15, 30, 45, 60, 90, 120, 180 and 220 minutes are shown in Table 2, and the distribution of temperatures within the wall is shown in Figure 4.

![Figure 4. Distribution of temperatures in depth of the tested element in different moments of time](image)

The strain values were measured at 10-minute intervals in the first 60 minutes, increasing the interval to 20 minutes over the last 160 minutes of the experiment.

5. Considerations on wall resistance and stability after the fire test

The tested wall kept its shape and stability both throughout exposure to fire and during cooling. Once the first AAC block was extracted from the upper part of the wall, it collapsed completely. This behavior confirms that the threshold of stability loss was reached.

There is a good connection between the experimental data obtained and the temperature-time curves, in the wall thickness presented in Figure 5, described in the simplified calculation model (annex C), from Eurocode EN 1996-1-2 [10].

![Figure 5. Temperatures distribution for autoclaved aerated concrete masonry exposed to a standard fire (gross density of 500 Kg/m2), adapted from [10]](image)
Samples have been taken for experimental evaluation of the residual compressive strength of the AAC blocks from the wall exposed to fire as follows.

6. Samples of ACC blocks

In order to determine the compressive strength of AAC blocks, according to standards SR EN 771-4 [8] and SR EN 772-1 [16], twelve samples of burnt AAC, with the size 200 mm (length) x 100 mm (width) x 250 mm (height), have been tested.

Figure 6. Samples of burnt 100 mm-thick AAC blocks

Studies showed that autoclaved aerated concrete has variations in color, depending on the temperature to which it has been exposed. [10-11]

The analysis of the section of burnt samples showed a variation of the material color as a result of the changes caused by the high temperature. Starting from the side exposed to fire on an average depth of 23.5 mm, the color turns to intense white, there are multiple cracks and the material decomposes when the samples are cut; next is a pink layer with an average thickness of 34 mm and at the end there is a 42.5 mm-thick layer where the material kept its white-grey color, as outlined in Figure 7.

Figure 7. Color variation in the section of the burnt AAC block from: cracks and missing pieces in the intense white part (left side), light pink and grey color layer (right side).
In correlation with the temperature diagram in Figure 4, it is concluded that the intense white color occurred as a consequence of reaching a temperature of min. 800°C, the pink color corresponds to an inner temperature ranging from 550 to 800°C, while the material does not change color at temperatures lower than 550°C.

![Figure 8. Color variation scheme](image)

Regarding the behavior in terms of resistance of the material exposed to fire, the simplified calculation method EN 1996-1-2 Annex C [10], considers the wall section in which the critical temperature exceeds the value $\theta_2 = 700 \, ^\circ\text{C}$, as being degraded, without contribution to the general stability of the wall. For the wall section in which temperatures between $200 \, ^\circ\text{C} - 700 \, ^\circ\text{C}$ are recorded, a low design compressive strength is used. The wall section with temperatures lower than $\theta_1 = 200 \, ^\circ\text{C}$ fully preserves its resistance to compression, considering that the material has not been damaged due to thermal action.

The variation in thickness of the three AAC layers correlated to the time of exposure to fire, for a 10 cm-thick AAC wall, is shown in Figure 9.

![Figure 9. Variation in time of the thickness of the three temperature ranges](image)

7. Evaluation of the degradation of the standard unit compressive strength $f_{b}$ under the action of fire

The standard unit compressive strength for AAC blocks with the following length x width x height: 600x100x250 mm, as stated by the producer, is $f_{b} = 3.50 \, \text{N/mm}^2$.

The standard unit compressive strength after exposure to fire $f_{b,\text{calculation burnt}}$ is calculated according to the unit strengths proposed by SREN 1996-1-2, annex C [10] as follows.

According to Figure 9, after an exposure to fire for 220 minutes, the result is: 32 mm of totally damaged AAC, 53 mm of progressively damaged AAC and 15 mm of undamaged AAC.
It is assumed that the linear degradation of the unit strength on the 53 mm, from zero around the temperature of 700˚C to $f_b$ at a temperature of 200˚C. It results that:

$$f_b^{\text{calculation burnt}} = 0*f_b + 0.5*f_b * (\frac{85-32}{100}) + f_b * \frac{15}{100} = 0.415f_b = 1.45 \text{ N/mm}^2$$ (2)

The standard unit compressive strength after exposure to fire $f_b^{\text{experimental burnt}}$ was experimentally determined.

**Table 3.** Break points of the six burnt samples of 10 cm-thick AAC subjected to compression tests

| Number of sample | Break point (KN) |
|------------------|------------------|
| 16               | 19               |
| 17               | 18               |
| 18               | 23               |
| 19               | 24               |
| 20               | 19               |
| 21               | 32               |

An average unit compressive strength $f_{av}=1.125\text{N/mm}^2$ and, with the shape coefficient $\delta =1.45$ according to SREN 772-1, annex A, table A1 [15], a standard unit compressive strength after exposure to fire $f_b^{\text{experimental burnt}}=1.63 \text{ N/mm}^2$, respectively, were obtained.

It was found that the damaging of the wall surface exposed to fire does not allow for it to be used as support for new plaster finishes. On sites, the simplest method to remove the damaged area is by manual roughening with a 3 kg hammer. Thus, the volume of AAC the temperature of which exceeded 700˚C, with zero strength, is removed and the resulting rough surface is a good support for applying new plaster.

The last six samples were prepared by this technology, their thickness being reduced from 100 mm to approximately 80 mm. The standard unit compressive strength is experimentally determined after exposure to fire and removal of the burnt side $f_b^{\text{experimental burnt and cleaned}}$.

**Table 4** Break points of the six burnt samples of 8 cm-thick AAC cleaned by roughening, subjected to compression

| Number of sample | Break point (KN) |
|------------------|------------------|
| 7                | 18               |
| 8                | 15               |
| 10               | 30               |
| 11               | 25               |
| 12               | 15               |
| 14               | 27               |

An average unit compressive strength $f_{av}^{\text{cleaned}}=1.354\text{N/mm}^2$ and, with the shape coefficient $\delta$ according to SREN 772-1, annex A, table A1 [15], a standard unit compressive strength after exposure to fire $f_b^{\text{experimental burnt and cleaned}}=1.96 \text{ N/mm}^2$, respectively, were obtained.

8. **Conclusions**

In the case of a 10 cm-thick AAC wall exposed to fire for three hours, the standard unit compressive strength decreased by:

- 59% according to the calculation;
- 54% according to the tests on burnt and uncleaned samples;
- 44% according to the tests on burnt samples cleaned of the physically and mechanically damaged layer;
It is to be noted that the experiment exceeded the normal stress conditions as any actual wall is covered with 1.5 cm-thick lime-cement plaster or drywall finish, both helping to reduce the damage of the wall during fire, and any actual fire rarely exceeds 60 minutes.

Under these circumstances, the decision to keep/demolish an AAC partition wall is taken depending on the strains occurred as a result exposure to fire, which may determine the collapse of the wall due to loss of local stability. Unfortunately, in case of fire, the actual values of the strains occurring during exposure to fire and of the contractions occurring during quenching with cold water are difficult to be estimated.

For this purpose, the hammering technology ensures not only removal of the "dead" layer of AAC, but also an in situ check of the behavior in terms of loss of the local stability of the wall. Thus, it is eliminated the possibility of accidental collapse due to cracks or strains that are unpredictable or increased by the fire, produced as a result of incorrect initial execution, hidden stress concentrators, atypical loading conditions etc.

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