Investigation of the Fire Resistance of Panels of Porous Papercrete, Containing Expanded Polystyrene Gravel

Vera Cherkina ¹, Dmitry Korolchenko ¹
¹National Research Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow 129337, Russia
articbs@mail.ru

Abstract. Papercrete panels are used in low-rise and individual construction intensively with each year. This article is devoted to the study of fire resistance of fragments of wall panels, which made of porous papercrete on wood shreds and containing expanded polystyrene gravel. While maintaining the compressive strength, partial replacement of the crushed stone with polystyrene gravel allowed to reduce the humidity, reduce the average density and increase the thermal resistance of the products. In order to determine the time to the onset of the limiting state of fire resistance of papercrete panels with a modified composition, fire tests were conducted. In the process of fire exposure in the heating zone of the sample, polystyrene was smelted from the volume of papercrete with the formation of voids and microcracks. The results of the study under the effect of fire on the “standard fire” mode for 3.75 hours and 2.5 hours on samples of fragments of wall panels made of porous papercrete containing expanded polystyrene gravel showed that none of the two limiting states was reached. There is a possibility of practical application of the obtained scientific results in questions of increasing the operational reliability of low-rise construction.

1. Introduction
The series of the projects of one-storey and two-storey buildings with fire-resistant load-bearing walls of porous papercrete on wood filler has been developed for the house-building construction in rural areas [1]. The papercrete (wood concrete), as a building material, is a type of lightweight concrete based on organic aggregates from forest and wood processing industries. Wood concrete mixture is found to reduce cement consumption, improve workability, cohesion and uniformity of wood concrete mixture, increase crack, water and frost resistance.

Fire tests of panels of internal walls made of this material showed that the limit of their fire resistance with respect to loss of carrier, fire-retarding and heat insulating ability is at least 2.5 hours [2–4]. In a further study of the papercrete, in order to improve the structure and physical-mechanical properties of the mixture, the volume of wood-spring crushers was partially (up to 35%) replaced by a light less water-absorbing material - expanded polystyrene gravel, the size corresponding to the size of concrete pores. Such a partial replacement of crushed stone with polystyrene gravel allowed, while maintaining compressive strength, to reduce moisture, reduce average density and increase thermal resistance of products [5–9].

The purpose of these tests was to determine the fire resistance of fragments of glass panels made of porous papercrete containing expanded polystyrene gravel (PAP) based on signs of loss of fire-retarding and heat insulating abilities in accordance with the standard of the CMEA 1000-2016 [10].
2. Methodology

The samples (sample 1 and sample 2), intended for fire resistance tests are the two halves of one wall panel of 2580x1180x300mm in size, which was separated in the manufacturing process with a wooden batten. The inner layer of samples with a thickness of 225mm is made of porous papercrete, containing expanded polystyrene gravel, compressive strength of 3.4 MPa, with an average density in the dry state of 600 kg/m3. Fencing (textured) layers of samples with a thickness of 35 mm are made of cement-sand mortar brand M 100.

The following materials were used to prepare the PAP: quick-hardening cement of the M500 grade; polystyrene grade PSB-25, average bulk density 28.0 kg/m3, fraction size: from 0 to 10 mm; sodium liquid glass; calcium chloride; resin saponified; water. Porous papercrete mixture was prepared in accordance with the requirements of standards [9-11].

Products were formed in a horizontal position by flow-aggregate technology in the metal forms [12]. The preformed structures were preliminarily kept in the workshop room at a temperature of +20 °C for 4 hours, after which they were subjected to heat treatment in the pit chambers according to the following mode:

- temperature rise up to 55 °C for 3 hours;
- extract at 55 °C for 10 hours;
- decrease in temperature in the chamber from 55 °C to 20 °C for 3 hours.

Then the plates were unloaded from the chamber and kept in the workshop at a temperature of 20 °C for 3 days, then they were dismantled. After that, until the moment of research on fire-resistance, they were stored in normal temperature-wet conditions.

To control the strength and average density of the PAP, simultaneously with the manufacture of experimental samples of structures, concrete cubes 10x10x10 cm in size were formed for enclosing layers and 15x15x15 cm in size for papercrete of the base layer. The strength of concrete for compression was determined by the results of tests of these cubes in accordance with GOST10180-2012.

To prevent the possibility of an explosive destruction of the protective concrete layer, the panel samples were dried in a special chamber for 5 days at the air temperature in the chamber +65 °C [10].

Fire resistance test of PAP panel samples was carried out in special laboratory furnaces with a fuel supply and combustion system. According to the standard of the CMEA 1000-2016 [9] during the tests were determined:

1) the nature and magnitude of the deformation;
2) the temperature on the unheated surface of the sample and in the thickness of the sample;
3) the nature and time of formation of cracks, delaminations, holes;
4) the time of occurrence of the flame on the unheated surface of the sample.

In the process of fire exposure (testing), the prototypes were heated on one side at a special installation (Figure 1) in accordance with the requirements of the standard CMEA 1000-2016 [9].

The side surfaces of the samples were insulated from the effects of high temperature mineral wool plates. The temperature regime in the furnace chamber was maintained according to the “standard” fire curve in accordance with the fire resistance test guidelines for building structures [13–20].

The temperature control in the furnace was carried out using 2 oven chromel-alumel thermocouples. These thermocouples are the most common devices of general purpose with a sensitivity of about 41 mcV/°C. This type of instrument operates in the range from 200 °C to 1350 °C, thereby ensuring reliable measurement of the maximum temperature in the furnace. The installation of thermocouples during testing was carried out in accordance with GOST R 56076-2014. The sensors were located on the unheated surface and inside the sample under study.
3. Results

Since the beginning of the experiment up to 50 minutes, no significant features in the behavior of samples 1 and 2 have been observed. After 60 minutes from the beginning of the fire exposure, sample 1 was marked by a small (5 mm) deflection of the heated surface and the appearance of a crack on it, directed from the periphery to the center, 250 to 300 mm long. By this time, the temperature on the heated surface reached 580 °C, in the thickness of the protective layer at a depth of 20 mm from the surface - 360 °C, and throughout the thickness of the papercrete - 100 °C.

On the 75th minute from the beginning of the experiment, the disclosure of the above-mentioned crack was recorded and on the 85th minute the collapse of a part of the heated protective concrete layer in the center of the slab of 300x400 mm.

Over the next 5 minutes, further detachment of the protective layer of concrete in the center of the slab occurred. By 105 minutes from the beginning of the tests, the protective layer of concrete collapsed over an area of 400x500 mm. The indications of thermocouples, which located on the surface and in the thickness of sample 1 after fire exposure for 3.75 hours are presented in Table 1.

Table 1. Indications of thermocouple sample 1 PAP after fire exposure for 3.75 hours.

| Positions of points in the studied samples | Thermocouple location in the thickness of the sample | Thermocouple indications during the collapse of the protective layer of concrete, °C | Thermocouple indications during the formation of charring zones, °C |
|-------------------------------------------|----------------------------------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------|
| 1                                         | on heated surface                                   | 790                                                                             | 1000                                                             |
| 2                                         | at a depth of 20 mm                                 | 630                                                                             | 790                                                              |
| 3                                         | at a depth of 40 mm                                 | 375                                                                             | 650                                                              |
| 4                                         | at a depth of 60 mm                                 | 150                                                                             | 390                                                              |
| 5                                         | at a depth of 100 mm                                | 100                                                                             | 175                                                              |

According to the test results for sample 1, a possible fracture pattern has been determined, shown in figure 2.
Figure 2. Fracture pattern of a fragment of a PAP wall panel after a fire attack for 3.75 hours: 1 - plate support zone on the unit; 2 - unbroken layer of papercrete; 3 - papercrete charring surface; 4 - the remaining layer of cement-sand solution; 5 - burnt and collapsed layer of wood concrete; 6 - unheated protective layer of concrete.

In the second experiment, the behavior of sample 2 during a fire attack on it in the mode of “standard fire” for 2.5 hours turned out to be similar to the behavior of the first one. A slight deflection (5–7 mm) of the heated surface was also observed at the 75th minute of the experiment. Then the detachment of the part of the protected layer in the 80th minute and its collapse in the 117th minute of the fire impact. The readings of thermocouples located on the surface and in the thickness of the sample 2, after fire exposure for 2.5 hours are presented in table 2.

Table 2. Indications of thermocouple sample 2 PAP after fire exposure for 2.5 hours.

| Positions of points in the studied samples | Thermocouple location in the thickness of the sample | Thermocouple indications during the collapse of the protective layer of concrete, °C | Thermocouple indications during the formation of charring zones, °C |
|------------------------------------------|-----------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------|
| 1 on heated surface                      | 785                                           | 940                                                                              |
| 2 at a depth of 20 mm                    | 620                                           | 790                                                                              |
| 3 at a depth of 40 mm                    | 365                                           | 650                                                                              |
| 4 at a depth of 60 mm                    | 145                                           | 410                                                                              |
| 5 at a depth of 100 mm                   | 95                                            | 175                                                                              |

According to the test results for sample 2, a possible fracture pattern is presented, shown in Figure 3.

The dependence of the temperature in the heated wall on the time and distance from the heated surface of the wall with respect to the conditions of the experiment can be restored using the measurement data according to [13,14] in the following form:

\[
T(\tau, x) = \begin{cases} 
  20 + A_{11} \cdot \left[1 + \Phi\left(\frac{L_{11}(x)}{\sqrt{\tau}} + n_{11}(x)\right)\right] & \forall \in [0; 35] \\
  20 + 40 \cdot \left[1 + \Phi\left(\frac{L_{21}(x)}{\sqrt{\tau}} + n_{21}(x)\right)\right] + A_{22} \cdot \left[1 + \Phi\left(\frac{L_{22}(x)}{\sqrt{\tau}} + n_{22}(x)\right)\right] & \forall \in (35; 260) 
\end{cases},
\]

(1)

where \( \tau \) - is time, sec;
\( x \) - coordinate, mm;
Function of errors: \( \Phi(x) = \frac{1}{\sqrt{\pi}} \int_0^x e^{-u^2} \, du \),

(2)

\( A_{11}, A_{22}, L_{11}, L_{22}, n_{11}, n_{21}, n_{22} \) – coefficients, depending on the X coordinate and experimental results.

**Figure 3.** Fracture pattern of a fragment of a PAP wall panel after a fire attack for 2.5 hours: 1 - plate support zone on the unit; 2 - papercrete charring surface; 3 - the remaining layer of cement-sand mortar area of 200x300mm; 4 - unheated protective layer of concrete; 5 - burnt and collapsed layer of wood concrete; 6 - unbroken layer of papercrete; 7 - layer of charring papercrete.

The graph of temperature dependency in the heated wall versus from time and distance from the heated wall surface as applied to the conditions of the experiment performed is presented in Figure 4.

**Figure 4.** Graph of temperature dependency in the heated wall from time and distance from the heated wall surface

The numbers of the curves shown in the figure correspond to the points (positions), where the temperature measurement sensors were located and for which empirical dependencies were obtained. The average deviation error of the presented dependences on the experimental data does not exceed 10–20 °C.
4. Discussions

The analysis of the obtained data and the results of their processing indicate that the fire resistance of fragments of wall panels made of PAP during their continuous heating according to the “standard mode” was established only according to two signs set forth in the CMEA standard 1000-2016 [5]:

- loss of thermal insulating ability of the sample (Section 6.2 of the standard);
- loss of flame retardant ability of the sample (Section 6.3 of the standard).

It should be noted that the flame burning of the samples did not occur; they were only charred. The second limiting state of the fire resistance design, described as “formation in the structures of through cracks or through holes through which the products of combustion or flame penetrate” [5], has not come. In the process of fire exposure in the heating zone of the sample, polystyrene was smelted from the volume of papercrete with the formation of voids, macro- and micropores. As the measurements showed, the average thickness of the charred layer of wood concrete from the side of the heated surface was:

- for sample 1 after 3.75 hours of exposure to fire - 13.5 cm;
- for sample 2 after 2.5 hours of exposure to fire - 9.5 cm

The charring depth increased every hour by 30 mm.

Thus, when exposed to fire in the “standard fire” mode for 3.75 hours and 2.5 hours on samples of fragments of PAP wall panels, none of the two limiting states (Section 6.2 and Section 6.3 of the ST of SEV 1000-2016) not achieved.

5. Conclusions

It should be noted that comparative analysis of the results of tests of papercrete wall panels conducted at VNIIPO [2], as well as a result of this work, allows us to conclude that, based on the signs of heat insulating and fire-blocking abilities, the fire resistance of wall panels of porous papercrete containing polystyrene gravel is not less than 2.5 hours. The scope of the panels is determined in accordance with the Building Code 112.13330-2012 "Fire safety of buildings and structures" (in Russian) and current regulatory documents in coordination with the State Fire Safety Authority.

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