Fire damage of concrete building structures

M V Akulova¹, D V Flegontov², Yu A Sokolova³ and A G Sokolova³

¹Department of building materials and technology, Ivanovo State Polytechnic University, ISPU, 153000, Sheremetevsky prospect, Ivanovo, Russia
²Department of supervising and offensive activity, Ministry of Emergency Situations of Russia, Lazareva 8/2, Nyagan, Russia
³Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. The authors proposed innovative approach to defining the extent of damage for concrete building structures. The present paper factors in the problems of detection of damaged structures arising due to thermal stress. The detection methods have been analyzed. There has been found and justified the need for elaboration of complex methodic applicable to detection of fire pocket and the evaluation of possibility of further structural use. The authors have shown the possibility of applying methods of synchronous thermal analysis for investigation of concrete composites with the purpose of further detection of hidden fire pocket and finding severely damaged members of building structures. The obtained results of synchronous thermal analysis are recommended for evaluation of further possible service of building structures.

1. Introduction
One of the main tasks of fire safety of buildings and structures is estimation of residual strength of building structures after fire exposure. Many non-combustible building materials lose their strength when experience high-temperature thermal exposure. It can be observed through cracks formation due to high internal stresses and chemical decomposition of a material [1]. Presently, concrete is considered the principal most widely used building material. It is used for foundation pouring, cements straining and for bearing reinforced concrete structures [3]. Its composition comprises water that starts evaporating at high temperatures destroying crystal cells and leading to decomposition of a material and structure’s failure.

Impossibility of assessment of damage extent of a building after fire exposure can lead to irreversible consequences, i.e. building failure at the time of people’s presence resulting in their death. Timely and adequate detection of thermal damage places enables to identify possibility of future site operation, to develop and carry out activities for prevention of possible damage caused by fire.

The literature data analysis has shown that for the review study of concrete structures survived the fire, various methods are presently used [5]. In practical activity, for evaluating extent of the damage of building structures the experts use various non-systemic methods leading to multiplicity of expert conclusions.

The present paper describes the complex methodic for evaluation of the damage extent for concrete building structures caused by fire. For solution of the problem of building structures failure after high-temperature thermal exposure, the special equipment and special instrumental methods of investigation have been used. They include hydraulic press, muffle furnace MIMP-UE, sclerometer Condrot Beton Pro, instrumentation group ‘Ultraterm’, thermal analyzer SETSYS EVOLUTION [4,5].
2. Results and discussion
The results of ultrasonic analysis of concrete block preheated at the temperatures 500°C and 900°C and further cooled are given in the table 1.

Table 1. The results of ultrasonic analysis of concrete block

| Concrete grade | Heating time, minutes | Ultrasound transit time, microseconds |
|----------------|-----------------------|--------------------------------------|
|                | 500°C  | 900°C  | 500°C  | 900°C            |
|                | Original specimen | After heating | Original specimen | After heating |
| B 15           | 20     | 50     | 200    | 270              | 205            | 370            |
| B 22.5         | 20     | 50     | 207    | 250              | 213            | 387            |
| B 25           | 20     | 50     | 220    | 250              | 228            | 500            |

Relationship between the change of ultrasound transit time at lengthwise and through sonic test for concrete and the temperature is given in the work of Klyuchnikova V.Yu. and Dashko L.V. [1] (figure 1).

![Figure 1](image.png)

Figure 1. Relationship between the alteration of rate of ultrasonic waves transmission through concrete at heating

The results of through and lengthwise sonic test are similar for concrete and prove that when increasing the extent of thermal damage, the rate of ultrasonic wave’s transmission through the specimen is reduced. Ultrasonic waves’ transmission time is also affected by the time of specimen heating [2].

The table 2 gives the results of dependency of change in concrete compressive strength on heating temperature obtained by means of the sclerometer Condrol Beton Pro.

Table 2. Dependency of change in concrete compressive strength on heating temperature obtained by means of the sclerometer Condrol Beton Pro

| Specimen temperature, °C | Sclerometer readings, MPa |
|--------------------------|---------------------------|
|                          | Concrete B15 | Concrete B22.5 | Concrete B25 |
| 20°C                     | 22.30        | 26.80          | 33.44        |
| 500°C                    | 18.46        | 19.34          | 23.50        |
| 900°C                    | 3.54         | 3.70           | 4.90         |
The given data analysis (table 2) has shown that at the temperature exceeding 500°C significant loss of strength is observed. Thus, in the thermal damage zones with the temperatures exceeding 500°C, a sclerometer could be applied only for detection of the maximum thermal damage zone of a concrete structure [3].

Change of concrete stone strength as a function of concrete grade and preheating temperature at various research methods is presented in the table 3.

Table 3. Change of concrete stone strength as a function of concrete grade and preheating temperature

| Concrete grade | Parameters of concrete stone strength loss, % |  
|----------------|---------------------------------------------|
|                | With the use of sclerometer | Ultrasonic analysis | Hydraulic press method |
| B15 500°C      | 20.8 | 12.0 | 29.5 |
| B15 900°C      | 84.1 | 80.5 | 94.8 |
| B22.5 500°C    | 27.8 | 17.2 | 37.5 |
| B22.5 900°C    | 86.2 | 81.7 | 91.6 |
| B25 500°C      | 29.7 | 12.0 | 50.6 |
| B25 900°C      | 85.3 | 119.2 | 90.6 |

As seen from the given data, under the conditions of hidden fire the extent of building structure’s damage is difficult to estimate by means of ultrasonic and impact-acoustic method. That’s why in the present paper, for more accurate estimate it’s proposed to use the method of synchronized thermal analysis additionally. For execution of experiments the following grades of concrete have been used:
- B15 – not exposed to heat;
- B15 – exposed to heat in the muffle furnace for 20 minutes with the temperature reaching 500°C;
- B22.5 – exposed to heat in the muffle furnace for 20 minutes with the temperature reaching 900°C;
- B25 – not exposed to heat;
- B25 – exposed to heat in the muffle furnace for 20 minutes with the temperature reaching 500°C;
- B25 – exposed to heat in the muffle furnace for 20 minutes with the temperature reaching 900°C;
- B25 – exposed to heat in the muffle furnace for 50 minutes with the temperature reaching 900°C.

On the figures 2-4 one can find the thermographs of grade B15 concrete before and after preliminary heating up to 500 and 900°C obtained by the methods of synchronized thermal analysis.
Figure 2. Thermograph (DTA) of grade B15 concrete not exposed to preliminary heating

Figure 3. Thermograph (DTA) of grade B15 concrete heated up to 500 °C with indication of weight loss per unit time at the temperature range, mg/min
Figure 4. Thermograph (DTA) of B15 grade concrete heated up to 900 °C with indication of weight loss per unit time at the temperature range, mg/min

The tables 4-6 present the results of estimation of concrete weight loss and the change of energy flows in the function of intensity of their preliminary heating, grade and temperature of thermograph [6-9].

Table 4. Concretes weight loss in the function of the intensity of preliminary heating, grade and temperature of thermograph, percent of specimen gross weight

| Concrete Grade | Specimens’ weight loss at the temperature range, % (TGA) |
|----------------|--------------------------------------------------------|
|                | 70-150°C | 400-450°C | 450-600°C | 600-800°C |
| B15            | 0.405    | 0.43      | 1.242     | 6.5       |
| B15 500°C      | 0.546    | 0.919     | 0.706     | 3.816     |
| B15 900°C      | 0.012    | 0.00828   | 0.116     | 3.311     |
| B22.5          | insignificant | 0.831       | insignificant | 12.332   |
| B22.5 500°C    | insignificant | 1.057       | insignificant | 4.486     |
| B22.5 900°C    | insignificant | 0.457       | insignificant | 4.361     |
| B25            | 0.631    | 0.694     | 0.979     | 5.073     |
| B25 500°C      | 0.307    | 0.542     | 1.111     | 4.287     |
| B25 900°C      | 0.157    | 0.066     | 0.991     | 4.286     |

Table 5. Concretes weight loss in the function of the intensity of preliminary heating, grade and temperature of thermograph, mg/min

| Concrete grade | Weight loss per unit time at the temperature range, mg/min (DTA) |
|----------------|--------------------------------------------------------|
|                | 70-150°C | 400-450°C | 450-600°C | 600-800°C |
| B15            | 0.013    | 0.043     | 0.00943   | 0.163     |
| B15 500°C      | 0.011    | 0.099     | 0.00948   | 0.093     |
Table 6. Variation of thermal flows in concretes in the function of the intensity of their preliminary heating, grade and temperature range, mW

| Concrete grade | Variation of thermal flows at the temperature range, mW (DSC) | 400-450°C | 450-600°C | 600-800°C |
|---------------|-------------------------------------------------------------|-----------|-----------|-----------|
| B15 900°C     | 0.00324 0.00204 0.00504 0.116 | 3.293     | 4.855     | 11.737    |
| B22.5         | insignificant 0.092 insignificant | 7.859     | 4.474     | 6.677     |
| B22.5 500°C   | insignificant 0.102 insignificant | 0.38      | 6.57      | 8.552     |
| B22.5 900°C   | insignificant insignificant 0.013 | 6.831     | 2.99      | 22.387    |
| B25           | 0.018 0.079 0.00666 0.127 | 7.723     | 3.677     | 7.225     |
| B25 500°C     | 0.00923 0.059 0.00967 0.12 | 0.348     | 5.15      | 11.077    |
| B25 900°C     | 0.00748 0.0023 0.00836 0.124 | 5.608     | 3.692     | 8.053     |

Analysis of the obtained data has shown that at the temperature range from 100 up to 150°C physically bound water evaporates. At the next stage, at the temperature range 400-450°C the weight loss and consequent gradual decrease in concrete stone’s strength occurs due to the processes of hydro aluminates dehydration as well as decomposition and repeated crystallization of calcium hydrosulfoaluminates.

At the third stage, starting from 450-600°C dehydration of calcium hydroxide Ca(OH)₂ takes place. At the fourth stage, at 600-800°C decomposition of tricalcium silicate and carbonates predominantly occurs that facilitates further loss of strength properties of cement stone. The presence of endothermic peak at the thermograph (T=568.73°C) proves structural transition of silicon oxide from α- to β-modification.

The comparison of thermographs of the concrete of various grades shows that the lower grade concretes are characterized by the greater content of physically bound water while the higher grade concretes have the increased content of crystal water. Thus, thermographs enable determining specific structural features of concretes of various grades.

The thermographs of concretes preliminarily exposed to high-temperature heating exhibit significant correlations if compared to the control thermographs. As seen from the given data, the greater temperature and time of preliminary heating, the less weight change on the thermographs. Thus, by means of the method of synchronized thermal analysis it’s possible to evaluate not only intensity of fire occurred but also its duration.

Analyzing the thermographs obtained, it’s possible to establish specific structural features of concrete that allow identifying thermally affected zones, duration of heat impact and the extent of damage of a structure as a whole.

At the scheme below one can find the proposed algorithm of identifying the extent of thermal damage for concrete structures occurred due to hidden fire (figure 5).
1st stage
Inspection of structures by means of the sclerometer, identifying the zones with various extent of thermal damage

- Zones with consistent or insignificantly reduced strength
- Identifying the zone with the maximum strength loss

2nd stage
Ultrasonic inspection (longitudinal sonic test) of a section of structure with the most affected strength properties. Identifying zones with various extent of thermal damage

- Zone of moderate thermal damage (500°C)
- Zone of high temperature damage (over 700°C)

3rd stage
Sample acquisition from the zones of high temperature damage of concrete for the laboratory testing by means of STA. Ascertainment of the presence of thermal damage in laboratory settings and estimation of the extent of heat impact. Comparison of the obtained results with control specimens

4th stage
Aggregation of all the test data. Fire mapping based on the all obtained data

Figure 5. Scheme of complex method for identifying the extent of thermal damage for concrete structures occurred due to hidden fire

3. Conclusions
Thus, complex method for identifying the extent of thermal damage for concrete structures occurred due to hidden fire comprises both physical and physical and chemical methods of analysis.

References
[1] Plotnikova G, Dashko L, Klyuchnikov V and Sinyuk V 2013 Bulletin of Eastern Siberian Inst. MIA 2 (65) 24
[2] Kosarev B Development of the method of detection fire outbreaks on concrete and reinforced concrete structures by ultrasonic waves 1991 185
[3] Larionova Z, Solomonov V and Ledneva N 1989 Ind. Construction 2 20-1
[4] Leshchinsky M Concrete testing 1980 Stroyizdat 360
[5] Smirnov K, Cheshko K, Egorov B and others Complex method of identifying the points of outbreaks of fire 1987 114
[6] Dashko L and Klyuchnikov L Expert inspection of widespread sites of fire technical expertise by thermal analysis method 2016 128
[7] EN 1992-1-2 Eurocode 2 Design of concrete structures Part 1-2 2004 Commission of the European Communities 12-15
[8] Davie C, Zhang H and Gibson A 2012 Comput Struct, 94–95 (3) 54–69
[9] Pham D T, Buhan P, Florence C, Heck J V and Nguyen H 2015 Eng. Structures 90 38-47