SUSTAINABLE AND RESISTANT MATERIALS, APPLICATION AND SAFETY

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Investigation of Thermal Damage and Structural Weakness in Concrete

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Abstract. This study investigates the impact of high temperatures on the structural and physico-chemical properties of concrete, emphasizing the degradation of material strength under fire exposure. Through a review of reference data, it was confirmed that elevated temperatures significantly reduce concrete strength, potentially leading to structural failure. The rebound hammer method, a mechanical non-destructive testing technique, was selected for on-site evaluation due to its accessibility, speed, and ability to provide immediate preliminary results. Field measurements conducted at fire-affected sites allowed for the identification of temperature zones and heat flow directions based on variations in concrete strength. Comparative analysis between intact and damaged areas enabled the identification of critically affected zones and the estimation of structural degradation. The study demonstrates that using the Schmidt hammer, with proper calibration and error consideration, provides reliable data for determining the origin of the fire and for making informed decisions on structural repair or reinforcement.

1 Introduction

Targeted attacks on infrastructure such as warehouses, industrial plants, energy facilities, and residential buildings are often accompanied by fires caused by direct hits from shells, missiles, or debris [1]. Incendiary munitions, air strikes, terrorist attacks, and explosions of ammunition in warehouses or transport pose a significant risk. Damage to fire extinguishing systems, power supplies, and water pipes leaves the affected facilities unprotected, contributing to the intensive spread of fire. In addition, the presence of a large amount of flammable materials in the fire load (fuels and lubricants, rubber, plastic, wood, chemicals) increases the intensity of the fire.

Shelling, road blockages, damage to transport infrastructure, lack of fuel and specialized equipment, as well as risks to the lives of rescuers in war zones, significantly delay or prevent fire and rescue units from arriving promptly at the scene. As a result, the fire develops uncontrollably, spreads over large areas, covers several floors or adjacent buildings, causing deeper thermal damage to the load-bearing elements of structures [2]. Prolonged exposure to high temperatures without timely extinguishing leads to a decrease in the strength of materials, cracking, detachment of the protective layer of concrete, collapse of structures, and, as a result, a significant deterioration in the technical condition of the facility [3, 4].

A number of factors contribute to the difficulty of technical inspection and restoration of buildings after fires under martial law, including limited access to facilities due to the threat of repeated shelling, mining, or destruction of infrastructure [5]. In difficult emergency conditions and instability, it is often impossible to engage specialized equipment or qualified specialists, making it impossible to promptly inspect the condition of structures. In addition, there is an increasing likelihood that standard equipment for non-destructive testing or laboratory analysis will not be available, reducing the accuracy of diagnostics. In the face of resource shortages and logistical constraints, it is also difficult to supply materials and carry out full-scale rehabilitation works. All of this greatly complicates the decision-making process regarding the further operation or dismantling of damaged buildings.

The scientific literature identifies several typical temperature regimes, each characterized by a certain rate of temperature increase, peak values, and duration of exposure [6]. The most common are the standard temperature regime, the hydrocarbon (hydrocarbon) regime, and external fire regimes.

The standard temperature regime simulates the development of a fire in enclosed spaces and is used in most fire resistance tests of building structures. The temperature in the standard fire curve increases exponentially and reaches approximately 550 °C in 5 minutes, 738 °C in 10 minutes, 945 °C in 30 minutes, and over 1000 °C within one hour. This regime does not account for real conditions (ventilation, fire load, room size) but allows for a unified assessment of the behavior of structures under thermal impact [7].

The hydrocarbon temperature regime models the combustion of flammable liquids and gases, which is typical for industrial facilities, oil refineries, and transport tunnels. A hydrocarbon fire develops much faster than a standard fire: the temperature reaches 1100 °C in just 5 minutes. This intensity creates an extremely aggressive environment for structures, requiring the use of special fire-resistant materials or enhanced protective measures [8].

Analytical methods are used to assess unsteady temperature fields in massive structures during a fire. These methods make it possible to predict the temperature distribution over the thickness of a structure and assess its fire resistance depending on time and conditions of heat exchange with the environment [9, 10].

Studies on mathematical modeling of the thermal conductivity of fireproof coatings show that the heating temperature affects the thermal conductivity of the coating, which is important to consider when designing structures with fire protection [11, 12]. Rapid heating or cooling of concrete leads to temperature gradients, which can cause internal stresses and crack formation, especially with significant temperature changes [13].

An increase in temperature can lead to a decrease in the strength of concrete. At temperatures above 300 °C, there is a significant loss of strength due to dehydration and other chemical changes in the material [14].

Studies show that as the temperature rises, there is a significant decrease in the strength and stiffness of steel reinforcement. For example, certain works analyze the behavior of reinforcement of different classes under thermal influence [15].

High temperatures cause plastic deformation of reinforcement, which can lead to its destruction. The paper defines dependencies describing the behavior of reinforcing steel at elevated temperatures [16, 17].

Microstructural changes, such as crack formation or phase transitions, can significantly affect the physical and mechanical properties of materials [18]. For example, hydrogen can cause microstructural changes leading to the degradation of structural material properties, which is critical for materials used in nuclear power [19, 20].

Similarly, studies show that degradation of surface layers due to environmental exposure can significantly affect the properties of structural and tool materials [21, 22].

Laboratory methods that currently exist have high information content but some drawbacks. These include the need for sampling and the impossibility of testing directly at the fire site, the high cost of equipment, the requirement for special premises for testing, the labor intensity, and the time needed for sample preparation.

The analysis showed that visual inspection, although it is the first stage of assessing the state of structures after a fire, does not fully reveal hidden or deep areas of damage. Therefore, the use of non-destructive testing methods is of particular importance, as they allow for detailed identification of critical zones of thermal damage without violating the integrity of structures. Methods such as infrared thermography, ultrasonic sensing, acoustic emission, and others allow recording changes in the internal structure of materials, identifying localized damage, and predicting the residual life of structures [23]. Consequently, the use of non-destructive testing methods is key in shaping a modern approach to the technical diagnosis of structures affected by fire, especially in wartime conditions, when security issues, rapid assessment, and restoration of infrastructure become critical.

Modern fires are often accompanied by explosions, which creates combined thermal and mechanical loads on building structures. As shown in [24], explosions significantly increase the impact on structural elements, deepening the degree of their damage under fire load conditions. This is especially true for reinforced concrete structures, in which high temperatures and dynamic impulse loads can simultaneously reduce the strength of the material and break the bond between concrete and reinforcement. In turn, [25] substantiate the feasibility of using easily dumpable structures, which allows reducing the pressure of the blast wave and preventing destruction. These studies are consistent with the results of our analysis, emphasizing the need for a comprehensive approach to assessing the technical condition of structures after a fire, and subsequently with explosions.

2 Main Part

The purpose of the work is to analyse experimental studies of determining areas of critical damage to structures after a fire.

An important condition is the comparison of indicators in intact areas with indicators in damage areas, which allows us to assess the decrease in strength and identify critical areas. The use of a Schmidt hammer ensures the accuracy of the estimate, given the possible errors and the correct calibration of the device. This allows you to make informed decisions about repairing or strengthening structures after a fire.

In Table 1. the influence of martial law on fire hazard of buildings and structures is given.

Table 1. Influence of martial law on fire hazard of buildings and structures

Factor	The essence of the impact	Consequences
Increased risk of fires	Shelling, explosions, fire due to debris or disruption of power grids	Increase in the number of fires, damage to residential and industrial facilities
Change in the nature of the combustible load	Use of temporary materials, accumulation of flammable substances in storage facilities, warehouses	Rapid fire spread, difficulty in predicting fire behavior
Difficult access to extinguishing	Destruction of entrances, restriction of movement of fire equipment, lack of water supply	Delay in extinguishing, spread of fires over large areas
Significant structural damage	High temperature exposure to fire, additional damage from the blast wave	Falling structures, loss of stability of buildings, the threat of collapse
Difficult technical examination	Danger of repeated attacks, mining of territories, lack of specialists or technical means	Impossibility of operational installation of technical condition of structures
Complexity of recovery	Logistical difficulties, shortage of materials, lack of funding	Delays or failure to restore damaged facilities, increase the number of emergency buildings

Materials. Vertical reinforced concrete slabs, 140 mm thick, 3270 mm high, and 1180 mm wide, were selected as the object of study for the experiment. These slabs were previously used in a public facility as internal partitions between rooms.

The test was carried out using a model compartment with a fire load consisting of rubber products – specifically, two passenger car wheels with a radius of 22.5 inches. The total weight of the fire load was 40 kg.

Before the test, 28 chalk marks were applied to the vertical surface of the reinforced concrete slabs at four height levels relative to the floor: 0.5 m, 1.0 m, 1.5 m, and 2.0 m (Fig. 1).

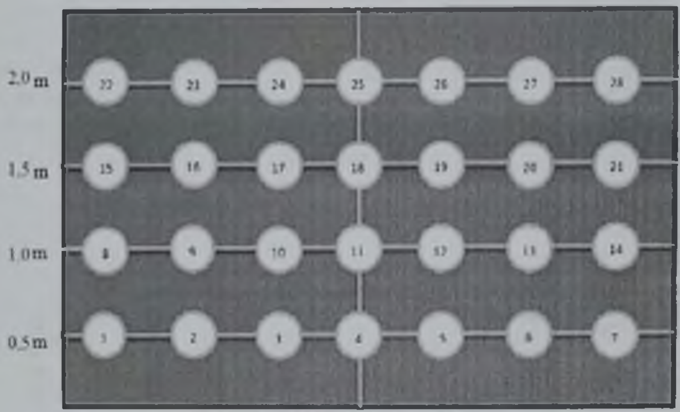

Fig. 1. Layout of points - measurement points

In order to reduce discrepancies in the measurement results, a series of five measurements was performed at each of the 28 designated points of the model compartment, using each method for determining strength, and the results were then averaged.

During the fire test, the temperature of the concrete structure was monitored using measuring equipment, specifically a FLIR infrared camera and a Stanley thermal detector. The duration of fire exposure was recorded with a stopwatch.

The interpretation of the obtained research results was carried out taking into account the volumetric and planning features of the facility where the fire occurred.

Study conditions:

1. Ambient temperature – 25 °C.
2. Atmospheric pressure – 100.5 kPa.
3. Air humidity – 45 %.

The fire exposure lasted for 110 minutes, during which the surface temperature of the reinforced concrete structure exceeded 500 °C.

During the fire test, peeling and spalling of the concrete protective layer, fire-induced erosion of the reinforcement, and the formation of cracks in the reinforced concrete structure were observed (Fig. 2).

Fig. 2. Nature of structural damage

Figures 3–6 show the changes in the concrete strength index at levels of 2.0, 1.5, 1.0, and 0.5 meters, respectively. The graphs illustrate the effect of thermal loading on the rear side of the reinforced concrete structure, depending on the height of the measurement point, demonstrating a gradual decrease in concrete strength toward the fire center. This representation makes it possible to identify areas with the most intense thermal damage that require additional inspection or reinforcement.

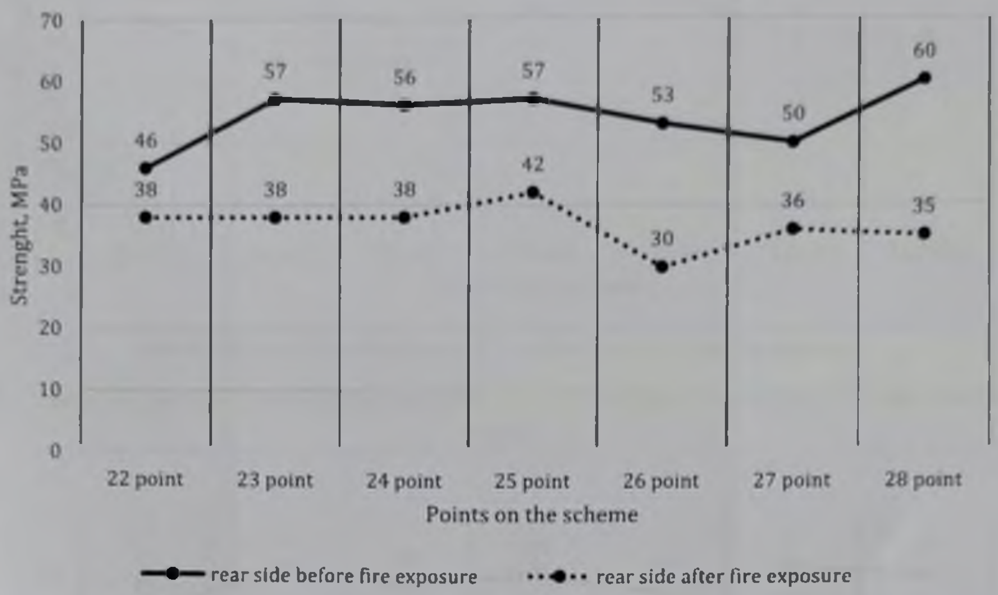

Fig. 3. Change of strength index of the rear side of reinforced concrete structure at the level of 2.0 meters

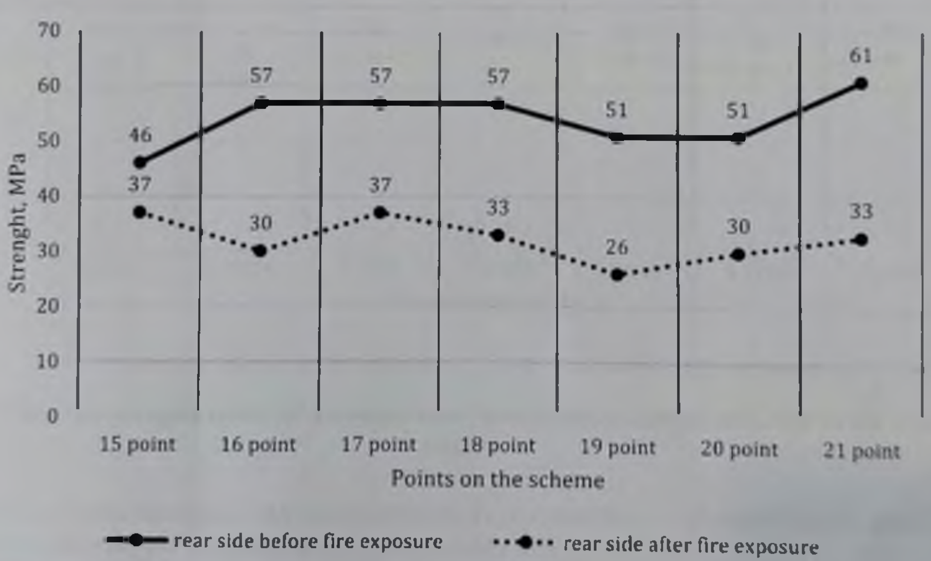

Fig. 4. Change of strength index of the rear side of reinforced concrete structure at the level of 1.5 meters

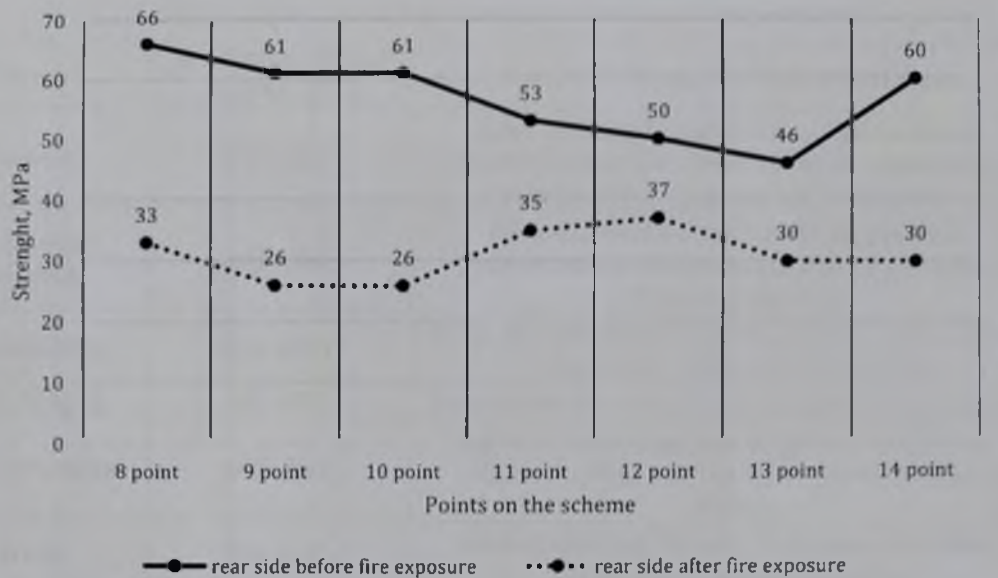

Fig. 5. Change of strength index of the rear side of reinforced concrete structure at the level of 1.0 meters

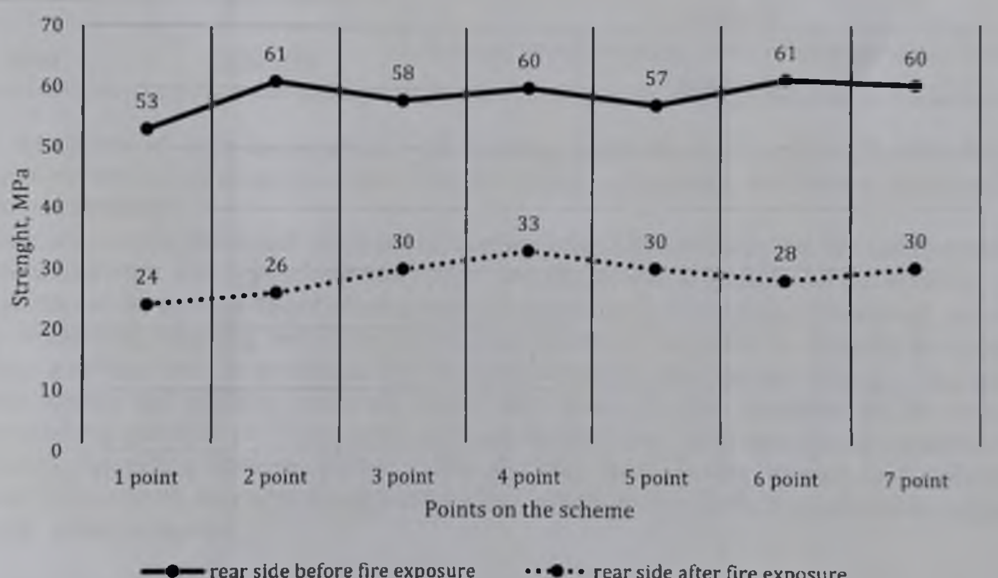

Fig. 6. Change of strength index of the rear side of reinforced concrete structure at the level of 0.5 meters

Due to significant damage to the structure (Fig. 2), measurements of the strength of the front side of the reinforced concrete slab after fire exposure were not performed.

Before and after the tests, measurements of the strength values on the reverse (back) side of the reinforced concrete slab were carried out. The average strength value before the tests was determined to be 55.93 MPa, and after the tests, it was 32.18 MPa. The loss of strength amounted to 42.5 %.

Table 2 presents the interaction of high temperatures with construction materials.

Table 2. Interaction of high temperatures with building materials

Material	Temperature limit of change, [°C]	Nature of exposure to high temperatures
Concrete	300–600	Loss of strength, appearance of microcracks, delamination of the protective layer, dewatering of cement stone, expansion of reinforcement
Reinforced concrete	300–600	Concrete-reinforcement bond degradation, reinforcement corrosion, load-bearing capacity decrease, cracking
Ceramic brick	600–1000	Color change, cracks, loss of geometry, in the case of long-acting - a decrease in strength
Silicate brick	300–400	Loss of strength, structure destruction, lime sintering
Steel structures	400–600	Significant decrease in strength and modulus of elasticity, plastic deformations, threat of loss of stability
Wood	200–300	Surface charring, burning, reduction of section, reduction of bearing capacity
Foams and polymers	100–250	Deformation, melting, toxic smoke emission, complete combustion
Drywall	100–150	Moisture evaporation, deformation, delamination, cracking
Glass	500–700	Thermal stress cracking, reduced transparency, loss of tightness

The interaction of high temperatures with building materials is a complex physico-chemical process, accompanied by changes in their structure, phase composition, mechanical properties, and operational suitability.

Factors influencing the extent of structural damage after a fire include the fire temperature, the duration of exposure, the type of materials used, and the structural features of the building. High temperatures are the primary factor causing material degradation, particularly in concrete and metal, leading to charring, cracking, and deformation. The duration of exposure to elevated temperatures also plays a critical role, as prolonged fire exposure results in more severe damage. The type of structural system and building materials largely determines the fire resistance of the structure. Additionally, the presence of microcracks, moisture content, and other operational conditions can significantly exacerbate damage during a fire. Overall, these factors interact and collectively determine the extent of structural damage after a fire, which, in turn, influences decisions regarding restoration or reconstruction.

3 Conclusion

The following results were obtained:

1. Reference data on changes in the structure and physico-chemical properties of concrete under temperature effects were analyzed. It was established that high temperatures lead to a decrease in strength, up to the complete destruction of the structure.
2. Among the mechanical methods of non-destructive testing, the rebound hammer method was chosen for comparing the strength of concrete structures directly at the fire site, as it is more accessible, reduces research time, and allows obtaining preliminary results.
3. The obtained material strength data reflect the degree of changes in the physical properties of the concrete. Measurements at the fire site enable the identification of fire temperature zones or prevailing directions of heat flow. Analysis of the strength indicators helps to pinpoint the most