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Methods for assessing the degree of destruction of concrete structures after a fire – review

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ABSTRACT:
The article presents an overview of methods for assessing concrete structures after a fire. The method of concrete behavior during a fire is described and an algorithm for assessing the load-bearing capacity of the structure after its occurrence is given. The types of tests presented were divided into three groups: non-destructive, partially destructive and destructive. The most frequently used methods from each group are discussed. In addition, the most modern, but not yet widely used, methods were mentioned.

KEYWORDS:
concrete structures; fire; non-destructive methods; destructive methods

1. Introduction

A fire is an exceptional situation that does not occur very often, but when it does occur it is very violent and dangerous. The topic of fires in relation to building structures is important, especially since, according to [1], the number of fires has increased significantly in recent years.

According to legal regulations, building structures should be designed taking into account the possibility of fire, so that the structure is able to bear loads for a specified period of time. It is particularly important that the evacuation of people and the work of rescue teams are possible. The damage to buildings affected by fire varies to a varying degree, so it is important to be able to assess the advancement of structural damage after a fire. Assessment of the condition of the structure is important for the further use of the facility.

Due to their low thermal conductivity and high specific heat, concrete structures are one of the most fire-resistant types of structures. Situations of a constructional disaster in concrete structures following a fire are exceptionally rare. Therefore, it is important to assess the damage to the material caused by the fire. By appropriately assessing the damage and the remaining load-bearing capacity of the elements, it is possible to determine whether the facility can still be used, or whether it is possible to design appropriate restorative work.

Due to the increase in temperature during a fire, concrete gradually loses its original properties. As the fire continues and the temperature increases, chemical, physical and mechanical changes occur. Due to the different temperatures that may occur during a fire, material changes may range from insignificant to those that may prevent further use of the facility.

The article discusses various ways of assessing damage to concrete structures after a fire. The methods are divided into two main groups: non-destructive and destructive.

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2. Properties of concrete after fire and classification of test methods

During a fire in concrete structures, a number of processes occur that affect the condition of the structure after it is extinguished. Therefore, many factors must be considered in parallel. All types of concrete are subject to destruction when exposed to fire. Compared to ordinary concretes, lightweight concretes have better resistance to high temperatures, and high-strength concretes have worse properties. The most important part of the process of assessing concrete after a fire is determining the compressive strength, which has decreased due to the high temperature, as well as the layer that has degraded. Concrete that has reached a temperature of 500-600°C can be considered damaged. Processes related to element temperature compensation continue even after the fire has ended. This is especially important in a situation where the fire was extinguished with a cold coolant, because the strength of concrete is lower after cooling than during the fire. As a result of the large temperature difference, tensile stresses appear in the element, which cause cracks to form.

The reduction in compressive strength of concrete after a fire depends on several factors:
– type of aggregate,
– concrete porosity,
– element size,
– fire temperature.

There is no universally accepted course of action in the normative regulations when assessing concrete structures after a fire. Based on the analysis of various documents and studies, the publication [2] presents the most frequently used evaluation algorithm, which is presented below:
1. Visual inspection of the structure.
2. Non-destructive, destructive and partially destructive testing (Table 1).
3. Structural analysis of building elements (in conjunction with the second point to determine the load-bearing capacity of elements after a fire).
4. Determining the repair strategy.

The visual inspection is mainly aimed at assessing changes in the geometry and dimensions of the structure, as well as identifying places of major damage, such as buckling of reinforcing bars or concrete spalling. Both non-destructive and destructive tests together with structural analysis are aimed at determining the degree of degradation of strength and mechanical properties, with particular analysis of the fire temperature.

Table 1
Division of selected methods of testing concrete structures after a fire [1-8]

Non-destructive	Partially destructive	Destructive
– visual assessment – sclerometric method – UPV test – impact-echo test – colorimetry – infrared analysis – radar – modal analysis	– pull-out method – pull-off method – break-off method – Windsor probe – drilling resistance – drilling dust analysis	– compressive strength test of the core not cut from the structure – disk analysis of the core cut from the structure – microscopic examinations – thermogravimetric analysis – petrographic analysis

Reference [9] graphically presents an algorithm consisting of three phases of structure assessment in order to determine the remaining load-bearing capacity of structural elements after a fire. The first phase is to determine the operating conditions of the structure before the fire occurs. The second phase is the search for places of damage that could result in the need to decommission the structure based on determining the conditions, in particular the temperature during the fire. The last, third stage is the estimation of the remaining load capacity of structural elements after the fire.

3. Non-destructive testing

The simplest non-destructive testing of a structure is its visual assessment. This is an imprecise study and is mainly based on the subjective feelings of the people conducting the expert opinion. However, it is helpful in estimating the temperature of the fire and even where it occurred. A particularly important aspect during visual inspection is the search for visible places of damage and defects (concrete spalling may be particularly common), which could indicate the need to demolish a given structure. Estimation of the approximate fire temperature is made by comparing the destruction of various materials present in the facility to the tabulated destruction along with the given temperatures. Examples of materials with given melting points are presented in Table 2. During visual assessment, simplified tools are sometimes used, such as portable microscopes or hammers to check the sound of concrete (which could suggest delamination).

Table 2
Determining the fire temperature based on the destruction temperature of various materials [2]

Substance	Examples	State of destruction	Temperature [°C]
Paint	–	Degradation Destruction	100 150
Polyethylene	Bags, bottles, pipes	Shrinking Softening and dissolving	120 120-140
PVC	Cables, pipes, linings, handles, toys, bottles	Degradation Browning Charring	100 200 400-500
Glass	Bottles	Softening Fallout	500-600 800
Copper	Wire, cables	Dissolution	1000-1100

One of the most popular non-destructive methods is the use of the Schmidt hammer (sclerometric testing) [6, 7]. It is not possible to determine the real strength of concrete after a fire. After a fire, a weakened layer appears in concrete elements and its properties are significantly lower. The thickness of the weakened layer varies depending on the fire temperature.

A large group of non-destructive tests are tests using advanced research equipment. The UPV method is often used, which involves measuring wave speed [8]. After a fire, the wave slows down in concrete elements. Using the UPV method, it is possible to estimate the degree of destruction, but it is very difficult to determine the compressive strength [9]. Unfortunately, the UPV method is sensitive to concrete delamination. Which may cause problems in the interpretation of the results. However, in the case of thick elements, it is possible to determine the depth of material destruction caused by fire. Another type of method based on wave assessment is the "impact echo" method [10]. In this method, the wave (frequency and speed) created by the impact of a steel ball is tested. The analyzed values decrease as the degree of concrete destruction increases. Using this method, the thickness of the damaged layer cannot be determined.

Using simpler measuring instruments such as a digital camera, other methods can also be used. Based on digital photos, it is possible to analyze the degree of concrete destruction. The assessment is based on color analysis. Concrete after a fire may have different shades. It may also be pink, which is caused by a change in the temperature of the iron contained in the aggregate. The colorimetric method allows for relatively accurate analyzes of concrete [11].

4. Partially non-destructive testing

Semi-destructive testing mostly involves very little damage to the structure during measurement. Methods: pull-out, pull-off, break-off and Windsor probe have similar assumptions but differ in the details of implementation. All of the previously mentioned methods involve mounting a small element to the concrete surface and then tearing it out. Tabulated data is used to assess the quality of concrete using the above methods.

An interesting method is to test concrete's resistance to drilling. Weakened concrete is easier to process. Taking this assumption, the mentioned method is based on the measurement of a specific quantity, e.g. the depth of the drilled hole, power consumption or the number of revolutions of the drill during drilling. Apart from the measured parameter, the rest are assumed to be unitary. This method is very easy and quick to use. A variation of the above-mentioned method is the analysis of the alkalinity of dust resulting from drilling a hole in damaged concrete. Thanks to this method, it is possible to determine an isotherm of 450°C.

5. Destructive testing

The most popular destructive test is the compressive strength test of a concrete core cut from a structure. However, during the classical test of the compressive strength of a sample, the heterogeneity in the structure and mechanical properties of concrete is not taken into account. During a compression test, the sample usually fails in the same place (an area 1/3 of the sample height from its center) [3].

A study that takes into account the heterogeneous structure of concrete after a fire is a study of the properties of discs created by dividing a cut concrete core from the structure. Tests are carried out for individual cores: water absorption (the relationship between the temperature of concrete during a fire has been proven). In addition, compression tests and tensile values are calculated for the discs. Based on the above data, the damaged layer can be determined.

A relatively accurate but time-consuming method is petrographic analysis of samples taken from the structure [1]. This method involves assessing microcracks and examining mineral changes. Samples from the structure are cut with a diamond saw and then carefully analyzed in the laboratory. Samples can be subjected to many tests. The basic tests are: visual assessment (occurrence of chips, cracks, color changes), hammer test for checking the sound of concrete, Schmidt hammer and UPV test. Then, detailed analyzes of the samples are carried out. The basic examination in the laboratory is the evaluation of samples under a microscope with a hundredfold magnification. Samples are cut into thin pieces for more detailed analysis. If the core elements taken from the structure are of poor quality, they can be reinforced with resin. Samples are examined in polarized light. Thermoluminescence can be used for testing, thanks to which it is possible to check whether the aggregate has been heated to a temperature higher than 300-500°C.

6. Non-standard testing

The literature also contains information about less frequently used methods or methods which, due to their innovative approach, are still in the development phase. One such method is autonomous detection of concrete damage [12]. This method involves developing a damage detection method based on deep learning. In the method described in [12], convolutional neural networks (CNN) and long short-term memories (LSTM) were used to detect defects, and a hybrid network was created. Research shows promising possibilities of using such an automated method.

Due to the lack of normative guidelines regarding the final assessment of the degree of damage to the structure, the final assessment may often be subjective. In order to avoid the influence of subjective feelings of people examining the elements, it was proposed to use fuzzy theory to analyze concrete parameters [13].

7. Conclusion

The article presents an overview of selected methods for assessing concrete after a fire. Since concrete structures are usually not completely destroyed, it is important to be able to determine the degree of degradation of the facility's load-bearing capacity, and thus provide a declaration whether the facility can continue to be safely used. There are many assessment methods and they differ significantly in terms of accuracy, labor intensity, cost and the degree of interference with the existing structure. However, there is no normatively adopted algorithm for analyzing concrete objects after a fire, so the assessment may be subjective. Methods that could be more autonomous are being investigated, and both procedures and normative tests should be defined in order to standardize the assessment of objects and reduce the share of subjective assessment by researchers.

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Sposoby oceny stopnia zniszczenia konstrukcji betonowych po pożarze – przegląd

STRESZCZENIE:
Przedstawiono przegląd sposobów oceny konstrukcji betonowych po pożarze. Opisano sposób zachowania betonów podczas pożaru oraz podano algorytm oceny nośności konstrukcji po jego wystąpieniu. Rodzaje przedstawionych badań podzielono na trzy grupy: badania nieniszczące, częściowo niszczące oraz niszczące. Z każdej grupy omówiono najczęściej wykorzystywane metody. Ponadto zasygnalizowano najbardziej nowoczesne, lecz jeszcze mało rozpowszechnione metody badania.

SŁOWA KLUCZOWE:
konstrukcje betonowe; pożar; metody nieniszczące; metody niszczące