MECHANICAL PROPERTIES OF CONCRETE SUBJECTED TO HIGH TEMPERATURE

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Abstract
The paper discusses key processes and phenomena occurring in concrete subjected to elevated temperatures. It refers to main pre-requisites of the Eurocode model (EN 1992-1-2) discussing mechanical properties of heated concrete and it discusses the behaviour of concrete in reinforced concrete structures exposed to fire, which does not necessarily have to be fully compliant with expectations based on standard guidelines. The compression stress, although not excessively high, inhibits the reduction of the strength of concrete when heated. The strength of concrete heated to high temperature and subsequently cooled down is lower than its strength in high temperature. In the result of concrete transient creep, the internal forces of a concrete structure or the stresses in the cross-section of an element may be redistributed. Ignoring transient creep in concrete while performing advanced computational analyses may generate inadequate results. Thermal spalling of heated concrete may result in sudden disclosure of reinforcing bars of elements or sudden reduction of their cross-section.

Streszczenie
W artykule omówiono najważniejsze procesy i zjawiska występujące w betonie podczas działania na niego wysokiej temperatury. Przytoczono najważniejsze założenia Eurokodowskiego (EN 1992-1-2) modelu opisującego cechy mechaniczne ogrzewanego betonu, a następnie zwrócono uwagę, że zachowanie się betonu w konstrukcjach żelbetowych narażonych na działanie pożaru nie zawsze musi być w pełni zgodne z tym, co można przewidywać na podstawie wytycznych normowych. Występowanie w betonie niezbyt dużych naprężeń ściskających powoduje powstrzymanie pogarszania się wytrzymałości betonu podczas ogrzewania. Wytrzymałość betonu rozgrzanego do wysokiej temperatury, jest po jego ochłodzeniu niższa od występującej w wysokiej temperaturze. Na skutek pełzania termicznego betonu może wystąpić redystrybucja sił wewnętrznych w konstrukcji lub redystrybucja naprężeń w przekroju elementu. Nieuwzględnienie zjawiska pełzania termicznego betonu w zaawansowanych analizach obliczeniowych może być przyczyną uzyskania nieadekwatnych wyników obliczeń. Odpryskiwanie betonu podczas ogrzewania może prowadzić do gwałtownego odsłonięcia zbrojenia elementów żelbetowych lub do gwałtownego zmniejszenia ich przekroju.

Keywords: **High temperature; Concrete; Mechanical properties.**

1. INTRODUCTION

From the structural engineer's point of view, ensuring the fire safety of a structure is reduced to applying suitable solutions that would ensure required fire resistance of all structural elements. While designing simple ordinary reinforced concrete structures, it is generally enough to use tabulated data [1] which determine the minimum dimensions of the cross-section of the given element and the minimum axis distance of the reinforcement cross-section from the edge of the element's cross section for various types of elements and required fire resistance. For advanced, sophisticated structures, structures of special economic importance or for those which may pose high risk to human safety, tabulated data [1] may prove not precise enough for predicting fire resistance of reinforced concrete elements. In such cases, a more precise prediction may be obtained when fire is considered as an accidental design situation in which ultimate limit states of a structure are tested [1-3].

One of the key stages for an analysis of RC structures consists in determining the reduction of the value of strength properties of concrete caused by elevated temperature [4-6]. Basic information on the issue is available in Eurocode [1]. A more extensive summary of the state-of-the-art knowledge and experimental research is provided in [7-10]. Works of fundamental importance for the development of the knowledge of high temperature influence on the mechanical properties of concrete include, among others [11-15].

Heated concrete undergoes simultaneously a number of chemical and physical (thermodynamic) transformations and suffers mechanical damage. Due to the complexity of these processes, the reaction of concrete to high temperature does not always have to be fully compliant with estimations based on standard guidelines [1]. This paper uses the Eurocode model [1] as a background for presenting basic data concerning phenomena which occur in heated concrete and the key issues which are decisive for reducing the value of the resistance features of concrete in reinforced structures exposed to fire. However, one should emphasise that due to the presence of a considerable variety of types of available concrete, precise predictions of their reaction to high temperature require a more precise description of the type of concrete, than it is usually provided while designing ordinary reinforced concrete structures. [8].

2. MECHANICAL PROPERTIES OF CONCRETE HEATED TO HIGH TEMPERATURE – STANDARD MODEL [1]

Figure 1 presents the mathematical model of stress-strain relationship for compressed concrete exposed to high temperature [1]. In this model, in the strain range from zero to $\varepsilon_{c1,\theta}$, the stress should be determined by applying the following formula:

$$\sigma(\theta) = \frac{3\varepsilon \cdot f_{c,\theta}}{\varepsilon_{c1,\theta}\left(2+\left(\frac{\varepsilon}{\varepsilon_{c1,\theta}}\right)^3\right)} \tag{1}$$

Within the strain range from $\varepsilon_{c1,\theta}$ to $\varepsilon_{c1u,\theta}$ (Fig. 1), one recommends linear correlation, or alternatively, an undefined curve. Table 1 presents the values of strain and strength properties for ordinary concrete, used for preparing the stress-strain relationships in terms of temperature, for two types of aggregates.

Figure 2 presents curves drafted by the author basing on the general model [1] (Fig 1, formula (1), tab. 1). They present stress-strain relationships for compressed concrete with siliceous aggregate in temperatures between 20 and 700°C, for the strain range from zero to $\varepsilon_{c1,\theta}$. For higher temperatures, the decrease of mechanical properties is so significant that the concrete should be practically considered as damaged. Further consideration of the stress-strain relationship is therefore of no significance.

Applying simplified methods of structural analysis one usually finds that the stress-strain relationships are less useful than the diagrams describing relative decrease of concrete compressive strength against temperature. Figure 3 presents such diagrams prepared by the author [6] basing on data from [1], for ordinary and high strength concrete.

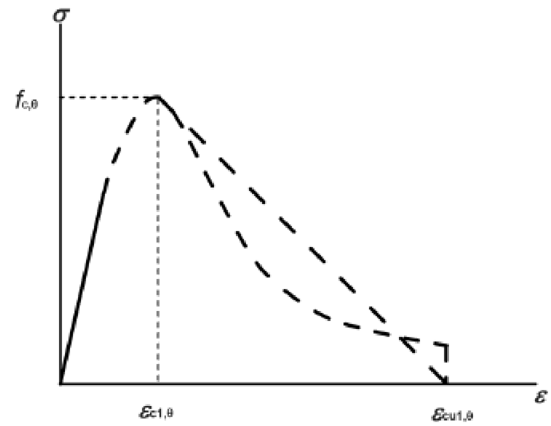

Figure 1.
Mathematical model for stress-strain relationship of concrete under compression at elevated temperatures [1]

Table 1.
Values for the main parameters of the stress-strain relationship of normal weight concrete at elevated temperatures

Temp. °C	Siliceous aggregates			Calcareous aggregates		
	$f_{c,\theta}/f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$	$f_{c,\theta}/f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$
20	1.00	0.0025	0.0200	1.00	0.0025	0.0200
100	1.00	0.0040	0.0225	1.00	0.0040	0.0225
200	0.95	0.0055	0.0250	0.97	0.0055	0.0250
300	0.85	0.0070	0.0275	0.91	0.0070	0.0275
400	0.75	0.0100	0.0300	0.85	0.0100	0.0300
500	0.60	0.0150	0.0325	0.74	0.0150	0.0325
600	0.45	0.0250	0.0350	0.60	0.0250	0.0350
700	0.30	0.0250	0.0375	0.43	0.0250	0.0375
800	0.15	0.0250	0.0400	0.27	0.0250	0.0400
900	0.08	0.0250	0.0425	0.15	0.0250	0.0425
1000	0.04	0.0250	0.0450	0.06	0.0250	0.0450
1100	0.01	0.0250	0.0475	0.02	0.0250	0.0475
1200	0.00	0.0250	-	0.00	0.0250	-

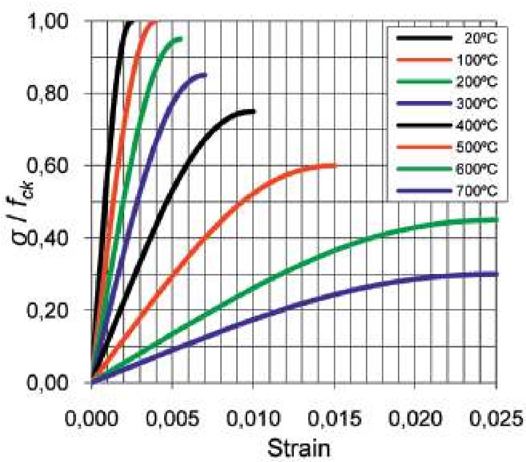

Figure 2.
Stress-strain relationships for compressed concrete with siliceous aggregate (subsequent lines, as seen from the top downwards, reflect temperatures of 20, 100, 200, 300, 400, 500, 600 and 700 °C respectively)

It is worth noting that heated high strength concrete loses its strength properties faster than ordinary strength concrete. The relative reduction of strength of ordinary strength concrete is not, however, related to its strength at room temperature or to the type of cement used. Concrete types made with siliceous aggregates lose their strength faster than concrete made with calcareous aggregates.

Eurocode [1] provides also data on free thermal strain of concrete and its tensile strength. The relative reduction of ordinary concrete's tensile strength is linear from 1.0 to zero for temperatures from 100 to 600°C, irrespective of the used aggregate.

3. PHYSICAL AND CHEMICAL TRANSFORMATIONS IN HEATED CONCRETE

The effect of high temperature on concrete becomes significant starting from 100°C. At this point, the free capillary water evaporates. The key processes occurring in heated concrete are listed below [9, 15]:

100°C	water evaporation,
100-300°C	thermal spalling,
100-800°C	dehydration of the ingredients of cement paste C-S-H,
350-900°C	transformations in the aggregate begin, depending on aggregate type: 350°C – some river gravels, 570°C – siliceous aggregates, 650°C – calcareous aggregates, 700°C – basalt aggregates,
400-600°C	dissociation of calcium hydroxide $Ca(OH)_2$, into CaO and water,
374°C	critical point of water when no free water is possible,
573°C	$\alpha - \beta$ transformation of quartz in aggregates and sands; this is an endothermic process accompanied by violent increase of the material volume. It is one of the main causes for which the siliceous aggregate based concrete show the lowest resistance to high temperature,
700-800°C	decarbonation of calcium carbonate $CaCO_3$ into CaO and CO_2 in cement paste and aggregates,
1350°C	melting of concrete.

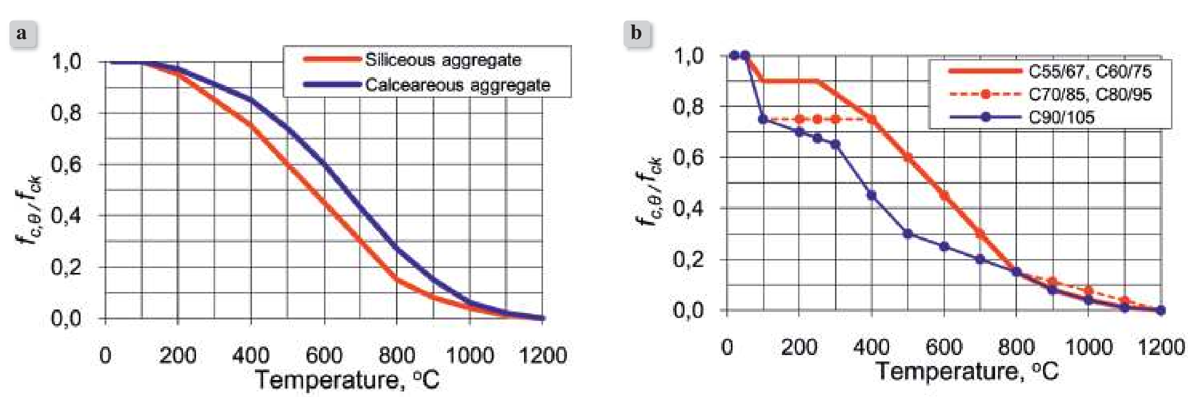

Figure 3.
Relative concrete compressive strength decrease in high temperature [1]: a) ordinary strength concrete, b) high strength concrete

It is worth noting that concrete heated to temperatures between approximately 500 and 600°C shows such significant decrease in strength that generally it should be considered as damaged from the point of view of analyses of RC structures load bearing capacity during fire or afterwards. Therefore, processes occurring in concrete in temperatures exceeding 600°C, are practically of no significance.

Chemical and physical transformations occur in concrete in the result of high temperature affecting it for sufficiently long time.

4. MECHANICAL DAMAGE TO THE STRUCTURE OF HEATED CONCRETE

Mechanical damage of concrete is primarily caused by its sharp heating or cooling. In case of unsteady heat flow in concrete, the temperature is distributed in non-linear manner resulting in uneven distribution of thermal strain, causing thermal stress. Figure 4 presents non-linear distribution of thermal strain (or temperature changes) occurring in a cross-section of a simple element (e.g. a beam, a slab or a wall) with unsteady heat flow in the course of heating or cooling.

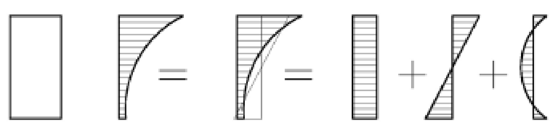

Figure 4.
Temperature or thermal strain in cross-section of an element, for unsteady heat flow

The curvilinear graph can be presented as a total of three components selected so as the third one should be equilibrated [16].

In the result of the first component, the element is contracted or elongated, while the second component curves it further. This may cause stress, but only in cases when the element is restrained. In statically determined structural systems, these components do not generate internal forces.

The third component of the diagram generates so-called self-equilibrating stress, both in statically determined and indetermined members. Such stress does not cause deformations of the element as a whole, but it results only in internal material effort. It should be therefore noted, that in the situation of unsteady heat flow, each part of the structure is "internally statically indetermined".

When a structural element is heated, the self-equilibrating stress is compressing in the external parts of the cross-section and tensile in its internal parts. A reverse situation occurs when the element is cooled: the self-equilibrating stress is tensile in the external parts of the cross-section and compressing in the internal parts.

The self-equilibrating stress increases with the increase of the curvature of the graph describing distribution of temperature; in other words, to the intensity of heating or cooling. When the tensile stress reaches the concrete tensile strength, cracks begin to appear. In some cases, instead of easily discernible cracks, there may occur micro-cracks or weak zones, occurring in areas where potential cracks appear, prior to the appearance of proper cracks. Cracks, micro-cracks and weak zones significantly reduce the strength of concrete.

5. THERMAL SPALLING

As mentioned above, concrete exposed to high temperature evaporates free (capillary) water. In the process, steam appears in concrete pores; the higher the moisture content of concrete and the faster the heating, the higher is the amount of steam. In porous concrete steam may move relatively freely and in the result its pressure does not reach higher levels. In dense concrete, (high strength and self-compacting concrete) the migration of steam is more difficult, hence its pressure can reach much higher values.

Once high temperature begins to affect concrete, the location of the maximum concentration of steam in concrete pores gradually moves away from the surface of the element towards its inside. In temperatures from approximately 200 to 300°C, a so-called "water plug" develops in concrete pores, making it difficult for steam to get through [7, 9]. Concrete which is outside the maximum pore pressure zone is pushed away from the centre of the element. Therefore, the concrete suffers tensile stress caused by pore pressure. Most frequently, such stress is directed approximately perpendicularly to the external, heated surface of the element. In addition to stress caused by steam pressure, the concrete may also suffer tensile stress caused by uneven distribution of temperature in the cross-section, or stress directed perpendicularly to the external surfaces of the element, related to the presence of high compressive stress which is most commonly parallel to the surface and generated by external load.

When resultant tensile stresses reach the concrete tensile strength, an external fragment of concrete can chip away. This phenomenon is called thermal spalling. In some cases, the release of energy of the pressurised steam and energy of deformation of stressed concrete can shoot a fragment of structure away. This phenomenon is called explosive thermal spalling. In some cases, thermal spalling is replaced with gradual scaling of the surface.

Thermal spalling is expected when the moisture content of concrete is high, according to [1] exceeding 2.5-3%. Structures in dry environment generally do not suffer thermal spalling [1]. Thermal spalling should be expected in case of fast heating of the element. In porous concretes, thermal spalling seems to be sporadic, while in high strength and self-compacting concrete, which has compact structure, the probability of thermal spalling seems to be very high.

The following parts of RC structures are most prone to thermal spalling:

– corners of elements, as steam pressure is affecting smaller cross-sections of concrete there,
– places where concrete suffers high compressing stress directed parallel to the surface (compressed zones of beams or columns); the steam pressure there combines with stress from imposed loads,
– concrete cover in places where bars are positioned at close distance; in such places, the connection of the concrete cover with the inside concrete in the cross-section is weakened anyway; moreover, the reinforcing bars constitute an additional partition hampering the flow of steam, increasing its pressure in pores of concrete located in between.

The concrete cover and corners of elements can also spall when the concrete is cooled down sharply, for instance when water is poured on it during fire-fighting. However, in such case, the spalling is caused primarily by stress caused by sudden shrinking of concrete which is initially weakened by high temperature.

From the practical point of view, concrete spalling is very dangerous. Moreover, it is difficult to incorporate in calculations performed for structures in accidental design situation of fire. Concrete thermal spalling may cause the reduction of the cross-section of RC columns which quickly reduces their load bearing capacity. The problem becomes particularly acute for columns in high-rise buildings, where high strength concrete is used on an increasingly common scale. In practice, one encounters also instances of very fast damage of thin webs of prefabricated I-beams of pre-stressed concrete (Fig. 5).

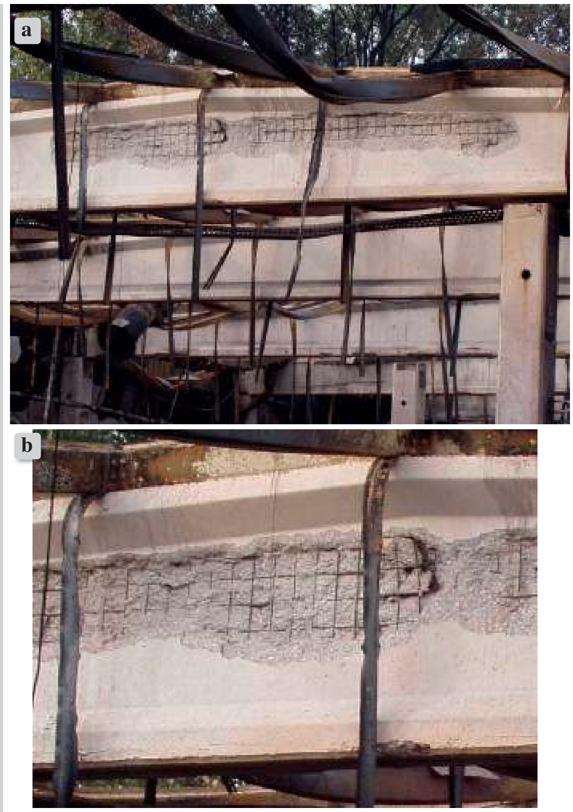

Figure 5.
Thermal spalling of a pre-stressed I-beam web concrete: a) general view, b) close-up (photos by the author)

A very dangerous phenomenon in bent elements is the thermal spalling of concrete cover which causes the disclosure of the reinforcement. In such causes, the reinforcing bars quickly get very hot, elongate violently and lose their strength parameters. Figure 6 presents examples of RC ceilings after fire and close-ups of places where thermal spalling of the concrete cover of the reinforcement occurred. Thermal spalling of the reinforcement concrete cover is particularly dangerous in simply supported beams which are exposed to fire acting from under them. The stripping of the whole main reinforcing bars may result in very fast collapse of the element. While designing simply supported important beams it is recommended to design two layers of bars as a precaution [1]. In RC slabs, local spalling of the concrete cover is not of such paramount importance, as it only weakens the reinforcement locally.

In order to reduce to minimum the probability for concrete spalling or to reduce its effects, polypropylene fibres are added to the concrete mixture. At the beginning of fire these fibres melt creating outlet spaces for free evaporation of steam. Steel dispersed

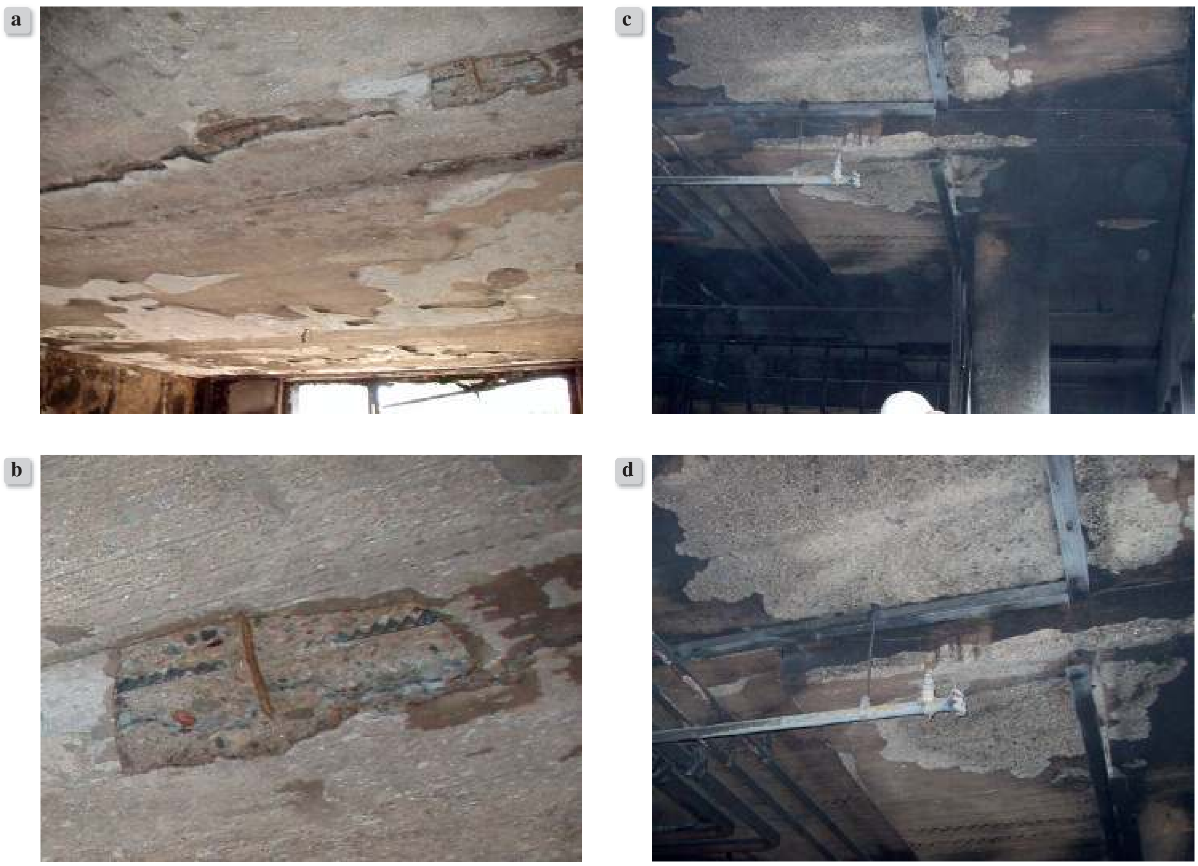

Figure 6.
Concrete spalling: a) and b) fragments of ceilings after fire, c) and d) close-ups of places where the concrete cover spalling occurred (photos by the author)

reinforcement which increases the concrete tensile strength also reduces the risk of spalling. The surface reinforcement mesh may prevent explosive thermal spalling. Specialised companies provide concrete mixtures which reduce the risk of concrete spalling when placed on the surface of the structure.

6. TRANSIENT CREEP

Considering the behaviour of concrete ingredients during heating, one should note that the hardened cement paste shrinks and the aggregate generally increases its volume [7, 17, 18]. Therefore, one should expect that the differences between the thermal expansion of the aggregate and hardened cement paste should lead to the destruction of the structure of the concrete at the initial stage of heating. However, this does not occur, due to the reciprocal movement of concrete ingredients.

In the course of the first stage of heating, the shrinking cement matrix is adjusting itself to "fit" aggregate grains which increase their volume. This phenomenon is called transient creep of concrete and occurs only during the first stage of heating concrete to high temperature.

Figure 7 presents examples of thermal deformations of non-loaded concrete made with different types of aggregate, and also deformations of hardened cement paste; the graphs have been drawn by the author basing on data from [18]. The non-loaded concrete expands during heating, in spite of the internal creep of its ingredients.

However, if compression stress occurs in concrete while heating, then the concrete, in the result of transient creep, yields to the load and contracts, instead of extending. The difference between the deformation of non-loaded concrete and loaded concrete is called load induced thermal strain. According to [18], the contraction (transient creep) of concrete compressed while heated does not depend on the type of used aggregates. This allowed to create graphs which describe the deformation of concrete as a function of

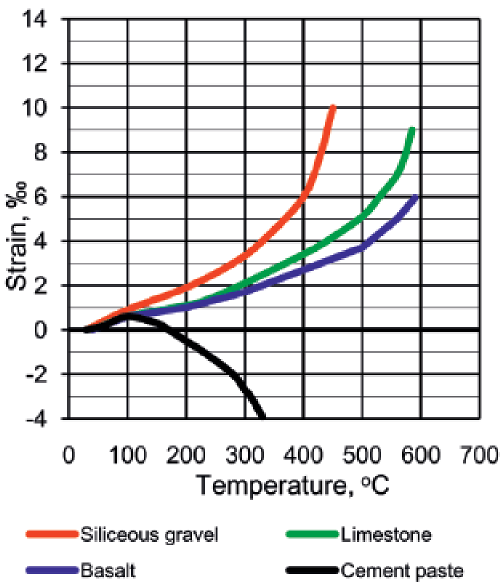

Figure 7.
Deformations of non-loaded concrete and hardened cement paste in relation to temperature [18]

temperature, for three values of the ratio of compressing stress to the concrete strength. Figure 8 presents the graph drawn by the author basing on the data from [18]. Additionally, it shows graphs which describe free strain of non-loaded concrete with siliceous and calcareous aggregates, drawn on the basis of Eurocode [1] recommendations and a graph which corresponds to the commonly adopted value of the concrete thermal expansion coefficient which is 10^{-5}.

From the practical point of view concerning the safety of RC structures subjected to high temperature during fire, the transient creep of concrete usually brings favourable effects. Naturally, the highest deformations of heated concrete occur in the most stressed members of the structure or in the most stressed zones of the element cross-sections. One may expect that transient creep will cause re-distribution of internal forces in the structures or of the stress in cross-section. In the result, the parts of the structure or cross-sections of the elements which are subjected to the highest stress can be relieved, and the parts which had some spare load bearing capacity before fire may in fire take over the stress which cannot be borne any more by weakened concrete in the most stressed places.

Transient creep of concrete may pose an obstacle to advanced calculations using the finite element method. The author shares the view expressed by G.A. Khoury in [7], that the advanced stress analysis of heated concrete which ignores the effect of transient creep, particularly when assuming linear thermal expansion of load-bearing concrete subject to heating, may provide erroneous results.

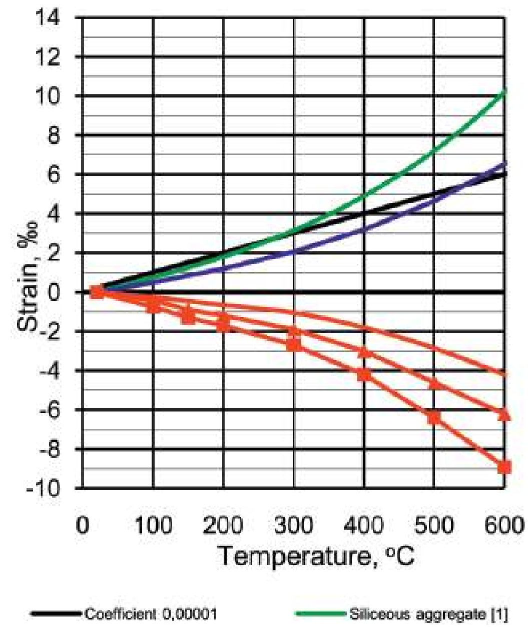

Figure 8.
Thermal strain of non-loaded concrete (with stress amounting respectively to 10, 20 and 30% of the compressive strength) [18]

7. THE EFFECT OF LOAD ON THE STRENGTH OF CONCRETE SUBJECTED TO HEATING

It is a well known fact that compressive stress between 20 and 40% of the concrete compressive strength delays the speed of the decrease of this strength during heating [13].

According to the author's opinion, the favourable effect of compressive stress on delaying the reduction of concrete strength during heating can be explained in the following way: firstly, compressing the concrete hampers chemical and physical transformations which result in increasing the volume of the material, and secondly, due to the transient creep, the load bearing specimens undergo the re-distribution of stress in the course of heating which increases the value of strength obtained in the tests.

It should be noted that the load bearing concrete in compressed zones of bent elements or columns exposed to fire should show a lower strength decrease than non-load bearing specimens tested in the laboratory.

Until now, no research has been conducted on the decay of concrete strength due to heating, while under tensile stress. However, one may predict that the effect of such stress should be unfavourable.

8. THE RESIDUAL STRENGTH OF HEATED CONCRETE

The residual strength of concrete heated to high temperature and subsequently cooled down is usually lower than its strength in high temperature [11, 14, 15]. It is due to the fact that additional strength reduction occurs in concrete which reaches high temperature and is subsequently cooled down. If the process of cooling down is slow, the concrete retains high temperature for a longer time which prolongs the duration of unfavourable chemical and physical transformations. On the other hand, when the cooling down process is sharp, the concrete may suffer mechanical damage in the result of high temperature gradients.

It is worth considering that due to thermal inertia of concrete, the maximum temperature zone may still progress into the structural element after high temperature ceases to affect its surface; while doing so, it may further destroy the structure of concrete in the middle part of the element, even for some hours after the end of fire.

Examples of the test results performed by the author [19] provide material for further discussion of the effect of sudden cooling on the strength of heated concrete. Cylindrical specimens of diameter 103 mm and height 200 mm made of concrete C25/30 with siliceous gravel aggregate were heated up to 330, 430 and 550°C, with slow temperature increase approximating 2°C/min. Afterwards, the specimens were cooled freely in the air or sharply, by immersing them in water for 5, 10, 15 or 20 minutes. Afterwards, the immersed specimens were taken out and also air cooled.

Figure 9 shows results of tests on the residual compressive strength of concrete in relation to the cooling time in water (zero time marks specimens which were not immersed at all). Water cooling of heated specimens affected the additional decrease of concrete strength at most when the temperature of specimens amounted to 330°C. For specimens heated to 550°C, the effect of immersing in water was much lower.

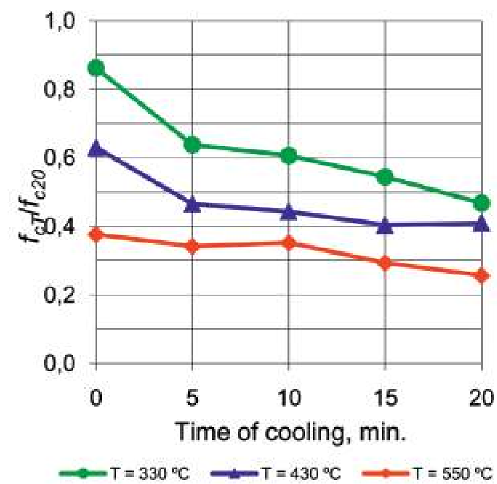

Figure 9.
Relative decrease of the residual compressive strength of tested specimens

The observed phenomenon can be explained as follows [19]: sharp cooling of concrete may only cause new mechanical damage to its structure. However, if the structure of concrete has already been damaged due to high temperature, then its internal stiffness is relatively low. Such concrete adjusts quite well to deformations enforced by sudden cooling. Its internal stress does not achieve high levels and therefore, the number of new cracks is relatively low. Therefore, the additional decrease of residual strength is also low. However, if the structure of concrete has been only slightly damaged due to heating, then the sharp cooling induces restraint forces which cause cracks with resulting considerable strength decrease.

From the practical point of view, sudden cooling can be particularly dangerous when concrete is heated to a relatively low temperature, such as 200-300°C. The decrease of concrete strength is not high then, and the effect of heating would be hardly significant for slow cooling; however, sudden cooling may cause considerable structural damage to concrete. Such situation may occur during fire-fighting when structural elements can be heated several times and then violently cooled with water.

9. CONCLUSIONS

- While considering RC structures in the accidental design situation of fire, and while reassessing them after fire, one should be aware of the fact that due to the complexity of processes occurring in heated concrete, its reaction to high temperature does not always have to be fully compliant with estimations based on Eurocode [1] guidelines.
- The reduction of residual strength of heated concrete depends on the type of used aggregates. Concretes made of siliceous aggregates are the least resistant to high temperature, while calcareous aggregates show the highest strength.
- High strength concrete with dense structure is less resistant to high temperature than ordinary strength concrete. The relative decrease of compressive strength of ordinary concrete is not related to its strength at room temperature.
- The presence of compressive stress in concrete approximating 20-40% of its compressive strength results in lower decrease of this strength during heating.
- The residual strength of concrete heated to high temperature is lower after cooling than it is during heating.
- Due to thermal inertia of concrete, temperature may continue to rise inside structural elements for some time after the end of fire, which may further decay the residual strength of concrete.
- The additional decrease of the strength of concrete heated to high temperature caused by its sudden cooling will be the most significant for temperatures which are not very high and range, for instance, between 200-300°C.
- The concrete transient creep is extremely important, as it may cause the re-distribution of internal forces in the structure or the re-distribution of stress in the cross-section of the element, which is often favourable. However, ignoring concrete transient creep while performing advanced computational stress analyses may provide erroneous results, particularly when one assumes the linear thermal expansion of concrete.
- Thermal spalling of concrete is very dangerous, as it may lead to sudden disclosure of reinforcing bars in RC elements, or to sudden decrease of the cross-section of elements. The probability of thermal spalling increases for dense structure concrete (high strength or self-compacting concrete), high moisture content concrete and in case of sharp temperature increase.

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