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Article

Effect of temperature rise caused by fire on the physical and mechanical properties of concrete

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Abstract: In the past few years, several concrete constructions have suffered major fires, causing very significant damage to the structure. The fire resistance of concrete depends on some of its characteristics such as the nature of the components used for its formulation, permeability, water content and mechanical resistance. In the places most exposed to fire, all the coating can be expelled, which seriously threatens the bearing capacity of the construction. In addition, the financial loss due to repair over a long period can reach several million Euros. This paper presents the physical and chemical transformations caused by the increase in the temperature of concrete in the event of a fire. These transformations mainly have an effect on the microstructure, the mechanical properties and the thermal deformation of concrete. The two phenomena of flaking and spalling of concrete were also studied in order to know their origins and found the methods of preventive. Indeed, flaking can manifest itself explosively, and have significant consequences on the resistance of concrete. It thus reduces the cross-section of the structure and also decreases its bearing capacity, which leads to an increase in the risk of structural failure. The factors influencing the flaking phenomenon were also presented.

Keywords: concrete constructions; fire; temperature; flaking phenomenon; spalling phenomenon

1. Introduction

When concrete is exposed to high temperatures, several complex physical phenomena are observed, which cause changes in the properties of concrete as well as that of structure. Due to the relatively large size of members and low thermal diffusivity, reinforced concrete structures have good natural fire resistance [1–3].

The main physical phenomenon responsible for the expulsion of the concrete during the fire is that of flaking. This phenomenon has been observed since the beginning of the XXth century, but experimental and digital studies have really intensified when concrete sensitive to risk of flaking (high performance concrete, ultra high performance concrete) has appeared. The works in literature are mainly based on experimental approaches which allow us to identify the characteristics of the phenomenon. On the other hand, regulatory and advanced models are still limited. The studies presented do not yet allow this phenomenon to be described. In addition, the preventive methods are not perfectly adapted under certain conditions because of the difficulties of installation (in the case of passive protection).

In the past few years, there have been at least ten major fires as well as countless minor fires in road and rail tunnels that have resulted in heavy loss of life. This requires further study not only of fire safety but also of damage to concrete to avoid the risk of structural instability.

The fires also caused significant structural damage in areas directly exposed to fire. In a very severe condition (the temperature can reach 1200 °C after a few minutes), it has been found that the concrete is badly damaged and that detachments on several scales have been observed [4,5].

Faced with these extremely severe conditions and contrary to the behavior of the thermohydric type in other material used in construction such as bricks [6,7], several thermo-phenomena hydro-chemo-mechanics are observed in concrete. These phenomena cause changes in the structure of the concrete as well as in its properties which leads to significant degradations. There are two types of degradation: losses in the mechanical strength of concrete such as the reduction in Young’s modulus, or detachments of concrete called flaking. This phenomenon denotes the mechanism by which concrete facing loses part of its surface concrete when exposed to high temperatures. It often occurs at the start of the fire, for the first few minutes and is characterized by small pieces of concrete expelled from the structure gradually over a period of time, accompanied by continuous noise [8]. This phenomenon can manifest itself explosively and remove all the coating exposing the reinforcements.

There are several types of concrete detachment: aggregate detachment, angle detachment, surface detachment and explosive detachment. Khoury [9] proposed a definition and classification of the types of detachments of material, which are widely accepted by the scientific community, from the least violent (not significant) to the most violent (a significant part of the structure is expelled).

This work studies the physical and chemical transformations caused by the increase in the temperature of concrete in the event of a fire. These transformations mainly have an effect on the microstructure, the mechanical properties and the thermal deformation of concrete. The two phenomena of flaking and spalling of concrete were also studied in order to know their origins and found the methods of preventive.

2. Fire safety objective

Fire safety objectives are effective protection against the risk of fire of people and property (**Figure 1)**. More specifically, they relate to:

- Saving the lives of the occupants of the building;
- the protection of the lives of intervention services;
- Protection of the integrity of the building;
- Safeguarding of adjacent buildings.

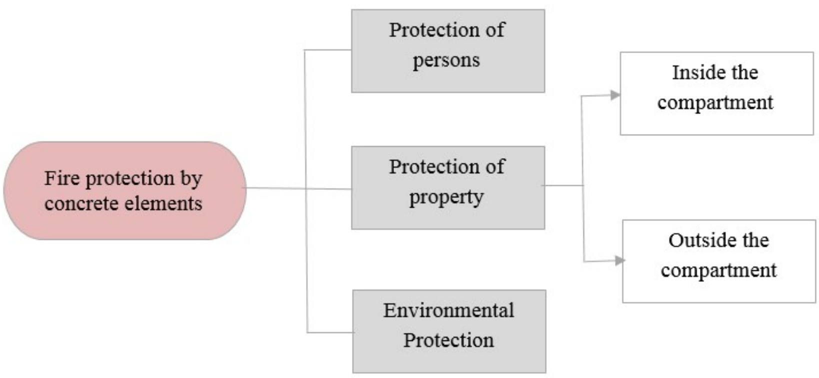


Figure 1. Overall effects of fire protection with the use of concrete elements.

Two types of measures are conventionally implemented to protect people and buildings.

2.1. Active protection measures

These are measures aimed at providing means of struggle direct against fire and its consequences (automatic extinction, alarms, …). They aim to limit the risk of a severe fire. To reap the benefits of active measures, their use is conditioned by appropriate maintenance measures, training, certification, certification of people.

2.2. Passive protection measures

These are means allowing, because of their design and location, control of the consequences of the fire (compartmentalization, partitions or fire floors, etc.). They constitute operational protection at all times.

Fire protection is achieved by a series of measures extending the design of evacuation routes, compartments, protection against heat, smoke and toxic gases up to the fire design of the supporting structures.

Concrete material occupies a very large place in the field of passive protection measures. By its recognized fire resistance, it provides highly secure compartmentalization to prevent the spread of fire. This compartmentalization allows the evacuation or the safety of the occupants towards another compartment. It facilitates access to emergency services and thus contributes greatly to their security in the fight against fire. The subdivision must be studied as soon as the building plans are drawn up.

3. Evaluation of the properties of concrete with temperature

The elevation of the concrete temperature causes a number of physical and chemical transformations and microstructure that will then lead to a change in mechanical properties and transfer. The main changes in the properties of concrete under the effect of temperature are as follows:

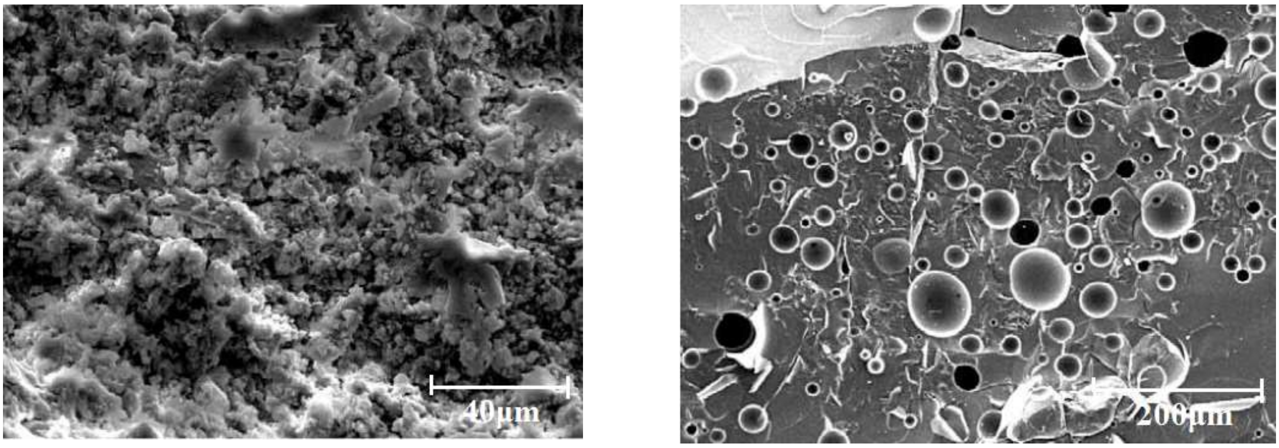
3.1. Effect on microstructure

During a rise in temperature, the different categories of concrete water are successively eliminated according to their binding energy. Likewise, aggregates can undergo transformations depending on the nature of the constituent minerals. **Table 1** gives the main physico-chemical reactions in concrete during its heating.

These physico-chemical transformations, in particular the departure of chemically bound water, result in a considerable increase in the porosity of the concrete (**Figure 2**) which then causes a change in the mechanical properties of the material as well as its transfer properties.

Table 1. Pyhsico-chmical reactions in concrete as a function of temperature.

Temperature θ (°C)	**Phenomenon**
≤80 °C	Open water outlet
θ > 80 °C	Part of the adsorbed water escapes from the concrete. Beginning of the loss of the water of constitution of certain hydrates. Chemically bound water therefore begins to evaporate from the concrete
θ ≤ 300 °C	First stage of dehydration of hydrated calcium silicates (C-S-H)
450 °C ≤ θ ≤ 550 °C	Decomposition of portlandite into free lime according to the following reaction: $Ca(OH)_2 \rightarrow CaO + H_2O$
θ = 573 °C	Allotropic transformation of quartz α into quartz β accompanied by a phenomenon of expansion (cracking of the silicate aggregates).
600 °C ≤ θ ≤ 700 °C	Decomposition of C-S-H phases and formation of β-C_2S. This is the second stage of dehydration of C-S-H which produces a new form of bicalcium silicates (C_2S).
700 °C ≤ θ ≤ 900 °C	Calcium carbonate breaks down, releasing lime: $CaCO_3 \rightarrow CaO + CO_2$
1100 °C ≤ θ ≤ 1200 °C	Wollastonite formation β ($CaO.SiO_2$). Beginning of the fusion of certain aggregates and cement paste. Replacement during heating of the hydraulic connections by ceramic connections.



(a) **(b)**

Figure 2. Scanning Electron Microscope (SEM) of the cement paste. **(a)** Normal appearance of a cement paste that has not undergone heating; **(b)** Vitreous cement matrix with very high macroporosity. This phenomenon occurs beyond 1000 °C and comes from the melting and then cooling of the cement paste [10].

After cooling of the concrete, certain mineral phases of the cement paste, such as lime (CaO) or anhydrite ($CaSO_4$) can rehydrate during a supply of water and possibly produce swelling.

3.2. Evolution of mechanical properties

The compressive strength after heating depends on the composition of the concrete (type of cement, water content, porosity), its age, the shapes and dimensions of the structural elements and the stress state of the concrete during the fire. The rate of temperature rise and the heating time also have an influence on the compressive strength [11,12].

Figure 3 gives the values of the compressive strength as a function of the temperature for a concrete taken from two different zones under the effect of a fire. There is a significant drop in compressive strength for a temperature value around 200

°C. A change in the structure of the concrete is thus observed due to the different coefficients of thermal expansion, the increase in porosity and the appearance of microcracks.

According to **Figure 3,** we notice the existence of two zones. The first zone, which varies from room temperature to 200 °C, there is an increase in compressive strength of small magnitude. This increase can have as its origin the departure of water from the material which re-increases the forces of attraction by bringing together the sheets of CSH [13].

In the second zone, which varies from 200 °C to 800 °C, there is a significant decrease in compressive strengths of the concrete. They remain below 5 MPa when the concrete is heated to 800 °C. Many studies have also shown a gradual decrease in elastic modulus and tensile strength with temperature.

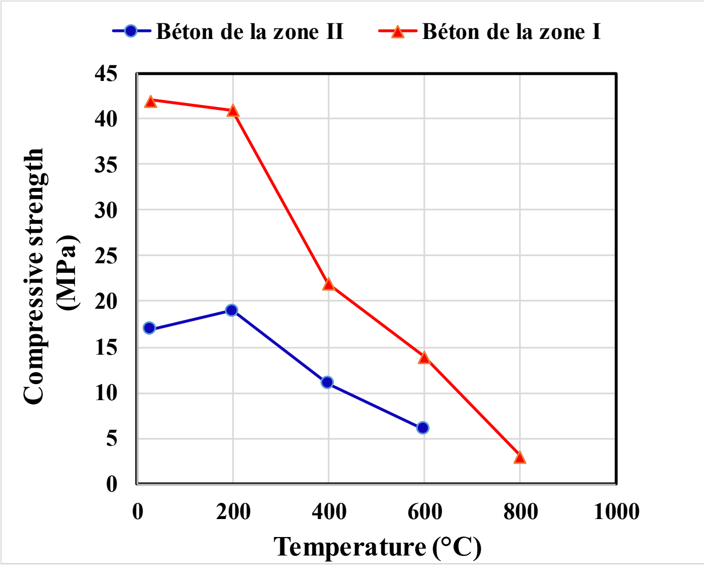


Figure 3. Evaluation of the compressive strength of concrete depending on the temperature.

3.3. Thermal deformation

The total deformation of an unloaded concrete specimen during a rise in temperature is due to:

- The thermal expansion of the various constituents of concrete;
- The removal of concrete due to the evaporation of free water;
- The chemical transformations;
- The cracking;
- The physical deterioration of the various constituents.

In the event of a fire, a very large increase in temperature can cause physicochemical changes in concrete such as dehydration by drying the concrete and decarbonation. These phenomena can produce shrinkage and loss of strength and stiffness of the materials.

Dehydration and decarbonation are endothermic reactions: they absorb energy and therefore slow down heating. They therefore go hand in hand with the absorption of heat which delays the heating of the material exposed to fire.

From the heated surface forms a dehydration and vaporization front where the temperature hardly exceeds 100 °C (**Figure 4**). If the capillary pores are too fine, the increasing vapor pressure in the concrete can generate tensile stresses such that the concrete resistance limit is exceeded. This phenomenon is all the more accentuated as the humidity of the concrete is high and the heating is rapid. Fragments of concrete can then be thrown from the surface of the element with more or less violence.

The changes that take place in concrete at low temperatures (<300 °C) mainly reflect changes in the cement paste, since almost all common aggregates are relatively stable up to 350 °C [14]. River gravel, has been shown to already burst at this temperature, unlike the excellent behavior of other aggregates.

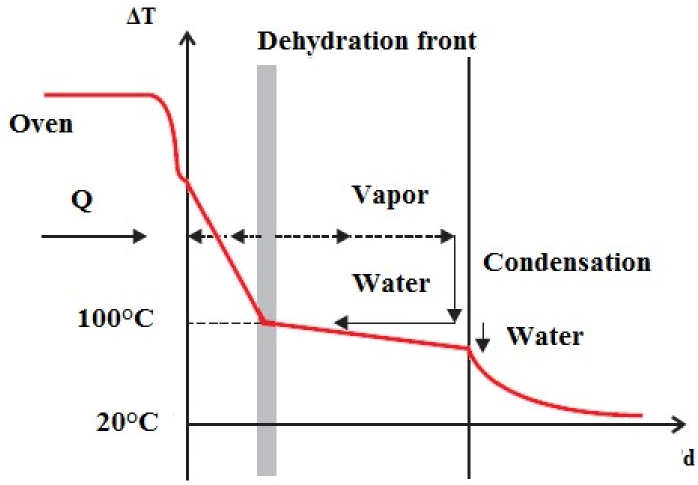


Figure 4. Temperature in a concrete wall exposed to fire [15].

For a column exposed to fire on all four sides, for example, the concrete heats up quickly on the surface and wants to expand. Its expansion is prevented by the heart of the column which remains cold. The core is stressed in tension and the outside of the column in compression.

As the thermal stresses are superimposed on the stresses resulting from the applied loads, the exterior concrete, whose resistance decreases with the rise in temperature, is subjected to very high stresses close to the ultimate resistance. These constraints, combined with the effects resulting from the dehydration front and the expansion of the bars, explain the concrete chips that were observed during the tests [16].

These fragments primarily concern the concrete covering the reinforcement of the corners, then the concretes on the faces of the columns. They reduce the cross-section of the column and increase the bending because, locally, the eccentricity of the load increases. In addition, exposed reinforcement heats up faster than where it remains protected by concrete.

4. Concrete flaking and spalling phenomenon

Concrete deterioration is characterized by the detachment of scales ranging in thickness from a few millimeters to a few centimeters or by the spalling of structural elements (**Figure 5**). This behavior is due to the thermal stress (heating rate and temperature reached), the shape of the element, the density of reinforcements and the porosity of the concrete [17].

(a) (b) (c)

Figure 5. Concrete degradation due to temperature rise. **(a)** Superficial flaking; **(b)** moderate peeling; **(c)** spalling of the concrete revealing the reinforcements.

The two main processes contributing to the degradation of concrete during thermal stress are associated on the one hand with thermal expansion gradients in the element (called thermomechanical process), on the other hand with the establishment of pressure gradients of vapor in the porous network (called thermohydric process). These processes are controlled by the microstructural properties and characteristics of the material. Thus, spalling is the result of chemical, thermal, water and mechanical processes coupled through microstructural characteristics which evolve during thermal stress.

The thermomechanical process is directly associated with the establishment of a temperature field in the element. The temperature gradient induces in the element a thermal expansion gradient: the heated face undergoes greater expansion than the cold face, which generates shear and traction components. The gradient is very large in the vicinity of the heated surface.

The thermohydric process is associated with the movements of water in liquid form and vapor in the porous network. This water is that initially present in the porous network, but also that resulting from the dehydration of the cement matrix.

When the temperature increases, the water in the material (in free or bound form) evaporates. Part of this vaporized water evacuates to the heated surface, another migrates inward (or the temperature is still low) and condenses. It thus forms a quasi-saturated zone which plays the role of a membrane impermeable to water vapor. It is near this area that the pressure reaches its maximum, inducing significant stresses, which leads to flaking of the concrete.

4.1. Flaking temperature

Experimental studies have shown that concrete begins to flaking very early, from 10 to 15 first minutes [18–20] when the temperature in the concrete reaches values between 150 °C and 450 °C. Akhtarnrzaman and Sullivan [21] have observed that the temperatures in the flaking area are between 375 °C and 425 °C. For very dense concretes whose compression resistance is greater than 150 MPa and the density is 2680 kg/m^3, Hertz [22] observed a temperature of 375 °C on the heated surface when flaking occurs. Flaking therefore occurs very often around the critical water temperature (374 °C), above which the liquid and the vapor cannot be distinguished.

4.2. Flaking of ordinary concrete and high performance concrete structures

Ali [23] carried out several experimental tests to compare the risk of chipping of ordinary concrete posts with compression strength fc_{28} = 24 MPa with that of high performance concrete posts of compressive strength fc_{28} = 106 MPa subjected to a rise in temperature corresponding to the fire curve BS476. The author concluded that ordinary and high-performance concrete show the same risk of chipping in the event that there is no axial confinement. Ordinary concrete may be more susceptible to chipping than high performance concrete under the effect of axial confinement (**Figure 6**).

On the other hand, other authors have shown that high performance concretes are more likely to flake than ordinary concretes. For example, in the tests carried out by Bostom and Larsen [24], with the same test conditions, the high-performance concrete of 107 MPa resistance has chipped up to 271 mm, three times more than a 73 MPa resistance concrete.

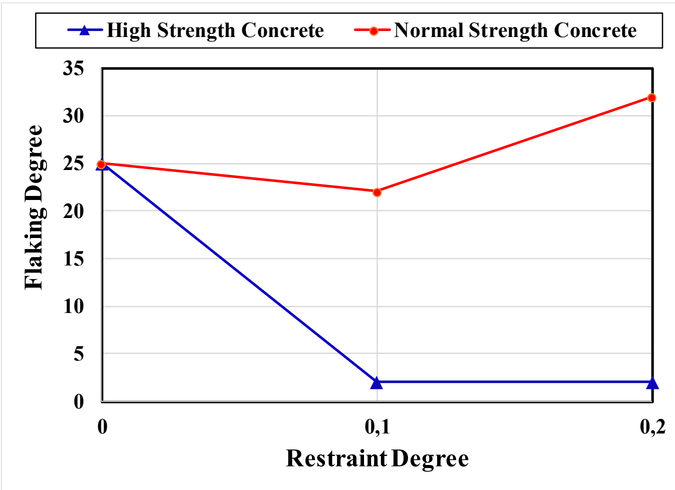


Figure 6. Results of experimental tests of ordinary concrete and high performance concrete [23].

4.3. Dimension of scales

The size of the scales is particularly difficult to determine because the scales are expelled at a very high speed from 3 m/s to 15 m/s [25] from the heated surface where the temperature of the fire is between 550 °C and 1200 °C. In addition, when the tests are completed, the scales are completely degraded under the heat of the fire. With different types of concrete and different thermal stresses, the thickness of the scales can vary between 15 mm to 20 mm.

In a test companion on B40 and B60 concretes subjected to the ISO 834 fire curve and other less violent thermal stresses, Mindeguia et al. [19] noted that the thickness of the scales depends not only the type of concrete but also the thermal stress. With slow heating on a B40, it observed scales of 15 to 30 mm thick against scales of 6 to 15 mm thick with the ISO 834 fire on the same concrete. Slow heating on a B60 gives about 40 mm thickness scales and the ISO 834 fire tests for the same concrete give smaller dimensions scales, of the order of 2 to 3 mm.

5. Preventive methods against concrete flaking

There are mainly two methods of preventing the problem of flaking of concrete exposed to high temperatures: the use of polypropylene fibers and the use of passive protective plates.

5.1. Use of polypropylene fibers

The addition of polypropylene fibers to concrete gives it good chipping behavior. In **Figure 7**, the efficiency of polypropylene fibers is demonstrated by Bilodeau et al. [26]. Polypropylene fibers melt at 170 °C, a temperature which is generally lower than that encountered at the time of flaking. The molten fibers are absorbed by the cement paste [27]. Then a free empty space for steam is instead creates fused fibers reducing the pressure in the pores [26–29]. Polypropylene fibers, on the other hand, are expensive and they reduce the workability of concrete in the fresh state, making it difficult to place in formwork.

(a) **(b)**

Figure 7. Efficiency of polypropylene fibers. **(a)** Concrete without fibers; **(b)** concrete with polypropylene fibers [27].

5.2. Use of passive protection plates

Passive protective plates are attached to the structure to isolate the structure in the event of a fire. The protective plates reduce the temperature rise of the concrete and therefore reduce the risk of flaking as well as the loss of strength. In addition, by using the protective plates, the internal section of the structure is reduced, making it difficult to install the underground tunnel in certain cases. It should be noted that the thickness of the protective plates is often chosen so that the temperature on the surface of the concrete is between 250 °C and 400 °C during 2 h of fire.

6. Factors influencing the flaking phenomenon

6.1. Heating rate

One of the major factors influencing the flaking phenomenon is the rate of heating. The likelihood and severity of chipping increases with the rate of heating. This is related to the temperature gradient which generates a significant gas pressure in the layer exposed to fire. By increasing the rate of heating, flaking occurs with greater speed and it stops earlier [18].

Some authors have not noticed the influence of the severity of fire on the flaking phenomenon. Ali et al. [20] carried out experimental tests on six concrete slabs exposed to ISO 834 fire and Hydrocarbon fire. Flaking starts very early with the Hydrocarbon fire, between 2–3 min and later for the ISO 834 fire, between 15–17 min. However, the chipping depth of all slabs is not affected by the severity of heating. They are included between 15 and 25 mm.

6.2. Water content

Water content is one of the important factors in the flaking phenomenon. In the absence of water in concrete, the probability of chipping is significantly reduced [22,29].

Several studies have shown that the probability of flaking increases with the water content of the concrete. According to Khoury [29], flaking can occur in ordinary concrete if the water content exceeds 2% by mass corresponding to 5% by volume. Hertz [22] considers that the most important factor in increasing the risk of chipping is the water content of the specimen. In addition, he believes that traditional constructions in concrete, the water content of which is less than 3% will not give rise to flaking and that the latter is very limited for concrete with a water content of between 3% and 4%. The water content can also be expressed in relative humidity. The higher the humidity of the concrete, the greater the flaking.

6.3. Permeability

The influence of permeability on the flaking of concrete is widely confirmed by several authors in the literature [8,9,18,19,22] due to its influence on pressure peaks. A high performance concrete with a very small permeability of the order of 10^{-20} m^2 is more vulnerable to chipping than an ordinary concrete. Indeed, the compactness of high performance concrete prevents the liquid and the vapor from moving. The pressure of the vapor trapped in the pores is therefore much higher than in the case of ordinary concrete.

Other researchers have expressed the possibility of spalling as a function of permeability through the ratio of saturation and porosity. It is unlikely that flaking will occur for permeability values by exceeding a threshold of the order of 5×10^{-15} m^2.

6.4. Aggregates

The behavior of concrete at high temperature is strongly linked to the nature of aggregate [24]. It has been observed that siliceous aggregates do not give very good fire resistance [29]. This is explained by a large difference in the coefficient of thermal expansion between the aggregates and the cement paste and by the increase in volume in the transformation phase (at around 570 °C) of α quartz to β quartz. The expansion of the aggregates leads to cracks and bursts of the aggregates. In general, the risk of flaking is less likely for concrete whose aggregates have a low coefficient of thermal expansion.

Increasing the size of the aggregates increases the risk of flaking. In an experimental test campaign on different concretes [30] exposed to the RWS fire (equivalent to a fire in a tank truck containing fuel or petrol for a period of up to 120 min), concrete with aggregates with a maximum size of 25 mm flakes twice as much as that with a maximum aggregate size of 16 mm.

7. Conclusion

The present paper presented the physical and chemical transformations caused by the increase in the temperature of concrete in the event of a fire and describes their effect on the microstructure, the mechanical properties and the thermal deformation of concrete. The two phenomena of flaking and spalling of concrete were also studied in order to know their origins and found the methods of preventive. Significant risks of chipping in high performance concrete structures as well as in ordinary concrete through experimental work are also presented. It is widely accepted that high performance concretes are more susceptible to chipping than ordinary concretes. The factual observations made it possible to note the main characteristics of the flaking phenomenon; the temperature at which the phenomenon occurs and the size of the scales. Due to the random nature of the flaking phenomenon, it is therefore difficult to propose solutions through experimental tests. On the other hand, these experimental observations are the first elements making it possible to construct hypotheses of mechanisms on the origin of flaking.

Conflict of interest: The author declares no conflict of interest.

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