



SCIENTIFIC INFORMATION

Damage behavior of concrete at high temperature: a general review

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ABSTRACT

Concrete is a poor conductor of heat, but can suffer considerable damage when exposed to fire. However, the damage mechanisms of this material are complicated because the concrete is a heterogeneous material with the transformation of phase and microstructure under the effect of high temperatures. This report has focused on microstructures of cement pastes/aggregates, system of pores, and separation of the cement paste from aggregates in heated concrete samples. An overview of damage behavior of concrete at high temperatures with various chemical and physical processes is also summarized and discussed.

1. Introduction

Nowadays, the problem of damage behavior of concrete at elevated temperature attracted special attention of scientists, especially in forecasting and assessing the safety of the structure under high temperature. In fact, the concrete structures present as buildings, tunnels or underground constructions containing nuclear waste can be fully threatened by fire. The high temperatures not only caused great material damage, but also entailed irreparable loss of human, especially in narrow spaces, enclosed like in the tunnels as the following cases: the English channel tunnel (1996 and 2008), the Mont Blanc tunnel (1999), Fréjus (2005) in France, tunnels Storebealt (1994) in Denmark, Tauern (1999) in Austria or the Gotthard Tunnel (2001) in Switzerland (Mindeguia, 2009). These investigations showed that the concrete structures were

severely damaged with the thickness of the bursting that ranges from be 10cm to 20cm on average. In particular, this occurs on the areas that contacts directly with fire sources.

The thermal behavior of concrete under high temperatures is associated with the hypothesis of chemical and physical processes such as: the expansion of aggregate, shrinkage and transformation chemistry of the cement paste, the gradient of temperature increases, the incompatibility of the deformation between the aggregate and cement paste under high temperatures, increasing pressure and compressive stress in areas close by the surface heated, the formation of micro-cracks,... The mechanism of these processes is complicated because the concrete is a heterogeneous material with the transformation of phase and microstructure under the effect of high temperatures. In this report, an overview of damage behavior of concrete material at high temperatures are summarized and discussed.

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2. Microstructure of concrete

The concrete is considered heterogeneous materials include multiple phase (cement paste, aggregate, interfacial transition zone ITZ, bubble) distributed randomly with varied sizes from nm (the composition of cement paste) to cm (biggest coarse aggregate) and a system of pore can be filled in whole (saturated) or in part (unsaturated) by the water.

2.1. Cement paste

Cement paste in concrete is formed by the hydration (soluble) of its mineral components C_3S , C_2S , C_3A and C_4AF to create cohesive CSH (calcium silicate hydrates), portlandite $Ca(OH)_2$ (Calcium hydroxide - CH) and a compound of hydrated sulfo aluminates of calcium (Lacarière, 2007).

CSH represents approximately 50 to 70% of the volume and give considerable adhesion and strength to the completely hydrated cement paste. This is a compound in the form of rigid gel and has the properties of a solid body. It is composed of extremely small particles with a

layer structure (Figure 2) that tend to aggregate in formations a few μm in dimension, characterized by interlayer spaces of small dimensions ($<2nm$) and by a large surface area (Bertolini et al., 2004). The layers were connected together by surface forces or ionic bonding which were born when the paste became hardened. This connection will be destroyed when the humidity increases (Baroguel-Bouny, 1994) and this explains that why the strength of the concrete is smaller when it is wet.

Calcium hydroxide (CH) is produced during hydration of C_3S and C_2S . These have dimensions of the order of a few micrometers and occupy 10 to 20% of the volume of solids. Calcium hydroxide has a form of hexagonal crystal and does not contribute to the strength of cement paste. However, CH is present in a small amount, which is very important with regard to protecting the reinforcement, because it causes an alkaline pH up to 13,5 in the pore liquid (Bertolini et al., 2004).



Figure 1. Fire damage in the English channel tunnel, 1996 (Mindeguia, 2009)

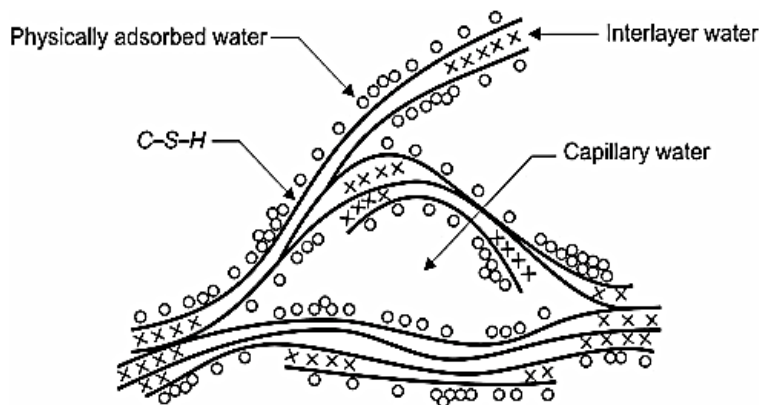


Figure 2. Feldman-Sereda model for C-S-H (Feldman and Sereda, 1968)

2.2. Aggregate

The coarse aggregate particles called "inert" phase do not participate in chemical reactions of cement, exceptionally an alkali aggregate reaction. Aggregate plays a major role in the formation of concrete strength and occupy 50 to 80 % of the volume of concrete. Aggregate is characterized by his grading curve (Pham Duc Tho, 2013).

2.3. Interfacial Transition Zone (ITZ)

During the hydration, a bond is formed between the cement and the aggregate which it coats. Its formation depends on the nature of these two phases, the water content in mortar and storage conditions. Around the aggregate forms a particular zone of hydrated paste called Interfacial Transition Zone (ITZ, zone 2 in Figure 3).

This ITZ has a W/C (water/cement) ratio higher than the rest of the mortar, and

consequently has more porosity than the paste. From the mechanical point of view, ITZ has a lower resistance than the rest of cement paste due to large size pore in this area. The thickness of ITZ increases proportionally to the diameter of the aggregate and the W/C ratio (Pham Duc Tho, 2013). The damage of the concrete strongly depends on this area.

2.4. System of pores

Concrete materials are porous, the voids appear in the rigid mortar as well as on the surface or inside the aggregate, and have important influence to the mechanical properties of this material. The cement paste formed by the hydration reactions always contains interconnected pores of different sizes, as shown in Figure 4 (Bertolini et al., 2004). The pores can be divided into macropores, capillary pores and gel pores.

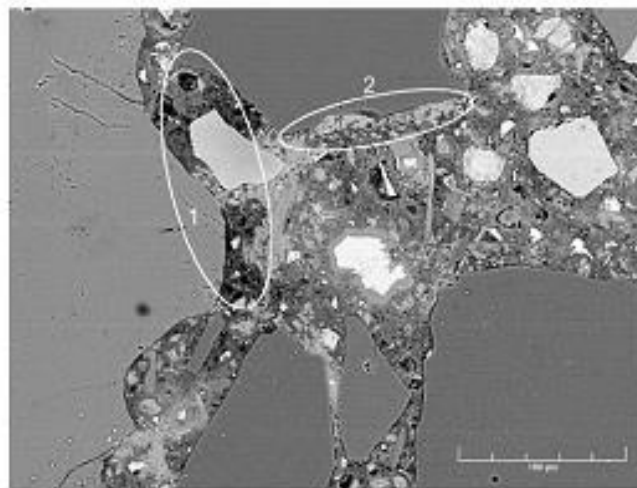


Figure 3. Microstructure of concrete (Pham Duc Tho, 2013)

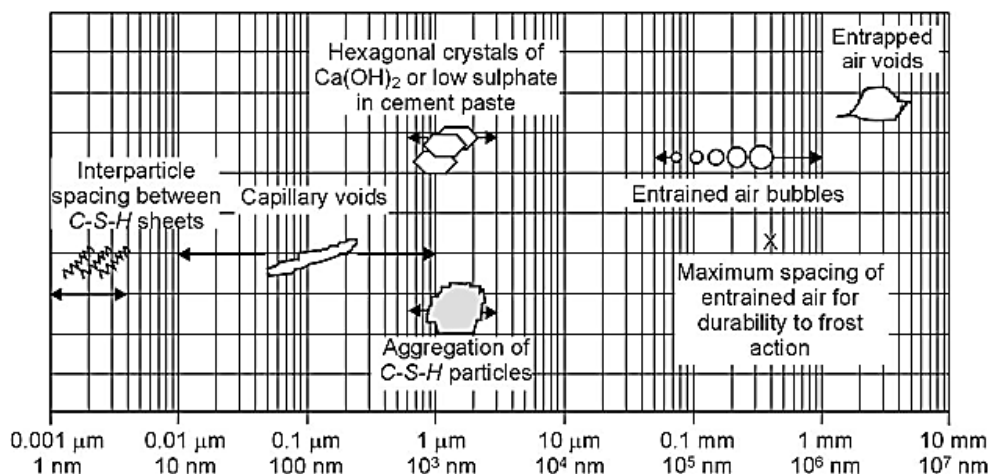


Figure 4. Dimensional range of solids and pores in hydrated cement paste (Bertolini et al., 2004)

Larger pores of dimensions of up to a few mm are the result of the air entrapped during mixing and not removed by compaction of fresh concrete. Air bubbles with diameters of about 0.05-0.2mm may also be introduced in the cement paste intentionally by means of air entraining admixtures, so as to produce resistance to freeze-thaw cycles (Bertolini et al., 2004). This category of pores occupies around 2% to 3% of the total volume of an ordinary concrete. According to the plasticity of the fresh concrete, some air bubbles may however reach the dimension of the largest aggregates. The isolated pores which inside the aggregates have same category but usually negligible.

The capillary pores are the voids not filled by the solids products of hydration of hardened cement paste. They have dimension of 10 to 50 nm if the cement paste is well hydrated and produced using low W/C ratios or it is not well hydrated. They form a layer contain water which have thickness of several micrometers and

determine the permeability of concrete. They also hold a key role in the rupture of concrete.

The interlayer spacing within CSH (gel pores) have a volume equal to about 28% of the gel and dimensions ranging from a few fractions of nm to several nm. These do not affect the durability of concrete and its protection of the reinforcement because they are too small to allow significant transport of aggressive species (Bertolini et al., 2004).

It should be noted that only the pore and fissure join to transport material in concrete.

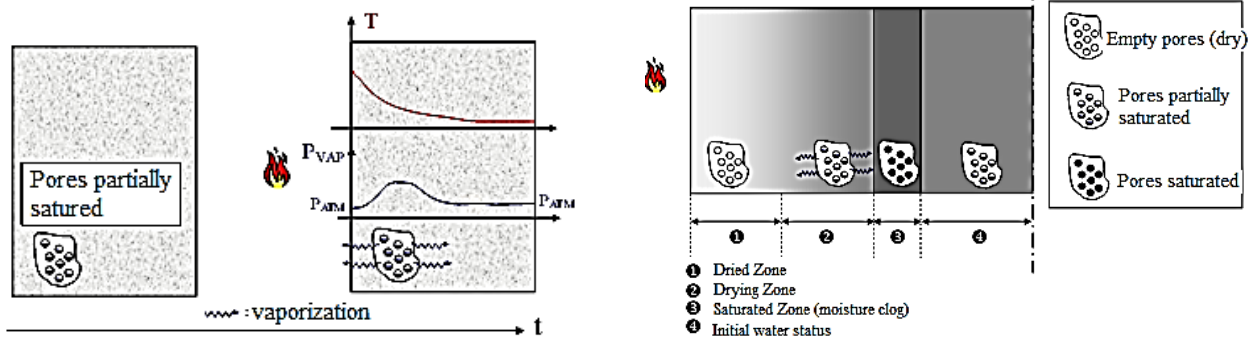
3. Mechanism of concrete damage at high temperature

3.1. Chemical transformation

During heating process, there are several physical, chemical phenomena which cause degradation of the concrete, for example: the decomposition of CSH; the decomposition of portlandite CH; the decomposition of Calcium carbonate. The main physico-chemical reactions in the heating process are shown in Table 1.

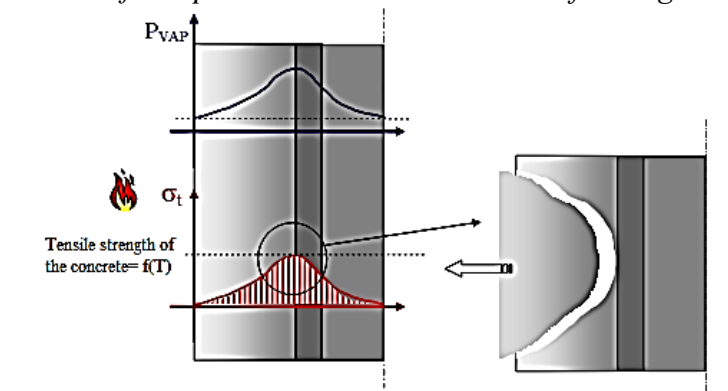
Table 1. Effects of fire on characteristics of concrete (Lin Wei-Ming and Lin T.D., 1996; Ye et al., 2007)

20°C -105°C	Free water and a part of absorbed water evaporate
105°C–450°C	The unbound water is removed completely at a temperature of 120°C. Among 100°C-200°C: The material property of the cement paste begins to lose its stability due to a weak physical/chemical reaction, particularly for the first heating cycle. In this temperature range, the evaporable moisture plays a dominant role in reducing cohesive forces between C-S-H layers and their gel surface energy. Chemical bonds before hydration are generally in the form of hydroxyl silanol groups (Si-OH, HO-Si). This chemical decomposition and the release of water depends on the microstructure of cement paste as: chemical bonding, cohesive strength (strength Val der Waal), porosity, and the size distribution of the pores.
450°C – 550°C	The decomposition of portlandite: $\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$
About 570°C	Low quartz in aggregate containing α quartz undergoes a phase transformation to β quartz (high quartz) accompanied by a nearly 1 percent volume increase. The effect is very pronounced with aggregate containing large amounts of a quartz, such as sandstone, granite, and some schist.
600°C-700°C	Decomposition of CSH or CSH (type II) generally occurs to form β -C ₂ S.
About 800°C	Decomposition of Calcium carbonate : $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ The calcination causes limestone aggregates to expand, crack, and spall, and the carbon dioxide gas that is produced escapes by a strongly endothermic reaction.
About 1300°C	Destruction completely of material concrete.



a. The evaporation of water in the heated concrete and remove to the zone of low pressure

b. The condensation of vapor and forming saturated "clog"



c. Thermal instability induce the destruction of concrete when pressure "clog" exceeds the tensile strength

Figure 5. Formation of pressure "clog" and mechanism of damage induce (Mindeguia, 2013)

3.2. Pressure clog (pressure of pores)

Harmathy in (Harmathy, 1965) shown this phenomenon occurs because of the drained condition on the heated surface, which can be interpreted as follows: when the temperature increases, the free or bound water contained in the material evaporates. A part of them is removed to the heated surface and another part migrates to the interior of concrete (the equilibrium of pressure according to the law of Darcy), where the temperature is still low and condenses. Thus it forms a quasi-saturated zone which plays a role of "clog" to prevent the further movement of vapor to interior of concrete and induce an augmentation of pressure close by a heated surface which reaches its maximum 1MPa, for ordinary concrete, 2-3MPa for the high-performance concrete (HPC) (Bazant and Thongutai, 1978; Noumowé et al., 1995; Consolazio et al., 1997). This significant pressure of pore is one of the important mechanisms leading to flaking of superficial layers of concrete (Bazant and Thongutai, 1978;

Noumowé et al., 1995; Consolazio et al., 1997; Pham Duc Tho, 2013).

3.3. Pressure of water (liquid)

Some authors (especially (Khoylou and England, 1996) noted that thermal instability is not only due to pressure of moisture but also by the pressure of liquid water. According to these authors, in a pore which is considered closed, the augmentation of temperature induce an augmentation of the degree of saturation in the pore due to the difference of thermal expansion between the water and the rigid skeleton. The total saturation of the pore increase strongly at high temperature (the author (Khoylou and England, 1996) showed that the initial saturation may increase from 32% to 100% under the effect of elevated temperature). The weak compressibility of liquid water may induce a strong tensile stress on the rigid body of concrete and when the value of this stress overcome the tensile strength of concrete, it will lead to the destruction.

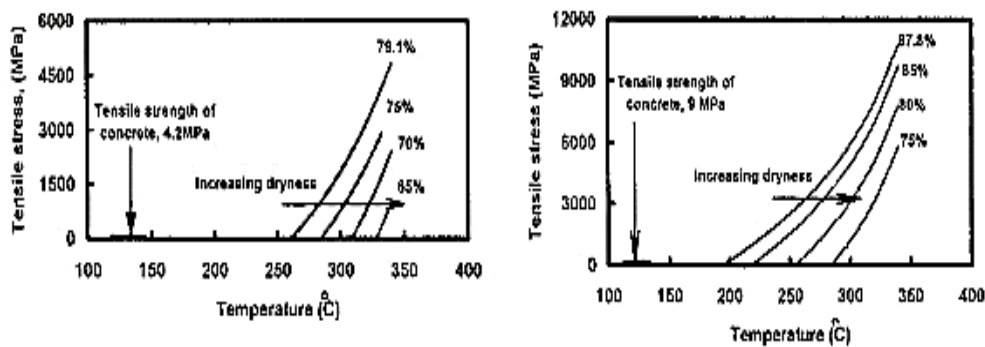


Figure 6. Numerical estimation of pressures in a pore due to the effect of the expansion of the liquid water with different degrees of initial saturation (Khoylou et England., 1996)

3.4. Macroscopic thermal gradient

The heating of the concrete induce a high thermal gradient, which results in important deformations and therefore a high constrained stresses. These compressive stresses are parallel to the heated surface and the maximum valeurs are observed in the proximity of the heated surface (Bazant, 1997).

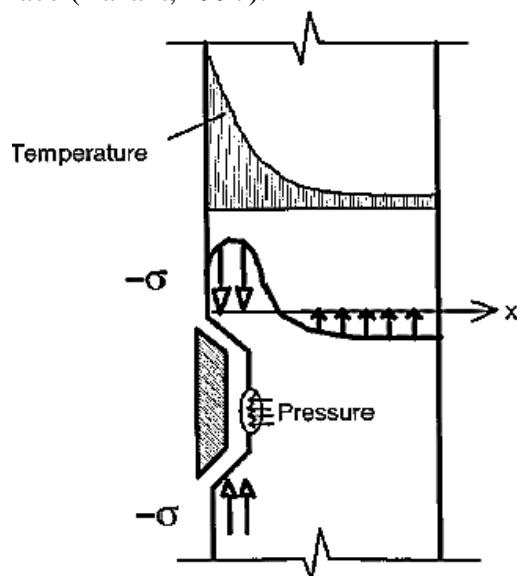


Figure 7. Thermal instability due to gradient thermique (Bazant and Thongutai, 1978)

These stresses are released by the brittle fracture of concrete as spalling. According to (Ulm et al., 1999), these compressive stresses induce the crack while the pressure of pore in the structure keep only a secondary role in the list of factor which influence on the destruction after localization of deformation. This hypothesis is consistent with the case of HPC (high performance concrete) which present a higher risk of spalling than ordinary concrete due to their high compressive fragility.

3.5. Incompatibility of deformation between cement paste and aggregate

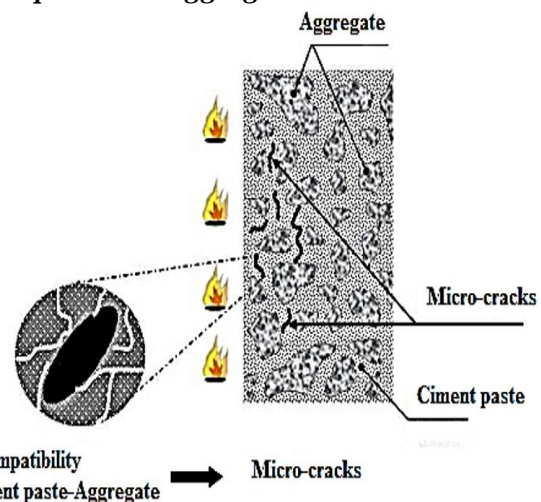


Figure 8. Formation of micro-crack due to the incompatibility of deformation between cement paste and aggregate (Le Thu Huong, 2011; Pham Duc Tho, 2013)

During heating process, the cement paste expands until about 150°C. From this temperature, it undergoes a shrinkage which primarily due to the dehydration of CSH gel (Diederichs et al., 1989) while most of aggregates continuously expand at this temperature. In most cases, until 150°C, the expansion of the cement paste is larger than that of the aggregate and induce the tangential stresses which appear on the interface paste/aggregate and can form the micro-cracks (Figure 8) (Le Thu Huong, 2011).

4. The factors of influence on the damage behavior at high temperature

All above-mentioned phenomena occur at the same time. We can note here some parameters that have influence to the

degradation of concrete at high temperature, such as (Pham Duc Tho, 2013):

- Heating rate: The greater heating rate induces the strongly formation of micro-cracks due to the temperature gradient;
- Location of heat sources;
- The initial water content in concrete: The experiments have shown that the concrete at the dry state have less crack than the wet state because the pressure of vapor is less important;
- The geometry of the structure (size, shape...);
- The position of the reinforcement in concrete structures;
- The risk of degradation is higher in the case of high performance concrete (than ordinary concrete) because of the low permeability which induce the strong pressure gradient at the proximity of the heating surface (Harmathy, 1965).
- The external loadings can induce the resonance that increase the probability of destruction.

5. Conclusion

In this report, we discussed on the heterogeneous microstructure of concrete (ciment paste, aggregate, ITZ...) and the damage mechanism of concrete at high temperature. These main processes of this damage behaviour are summarized such as: chemical transformation, pressure clog, pressure of water, macroscopic thermal gradient and the incompatibility of deformation between cement paste and aggregate. All of these phenomena occur at the same time and induce the degradation of concrete with many parameters influential (heating rate, geometry of the structure,...).

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