Exposure of high performance concretes at elevated temperature : residual mechanical properties and thermal spalling

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Résumé :

Les structures en béton peuvent être soumises à des températures élevées en conditions accidentelles. L'incendie est la situation la plus connue mais le domaine nucléaire peut aussi être confronté à d'autres situations induisant des températures élevées (accident par perte de réfrigérant primaire, fusion du cœur). Le formulateur de béton peut être amené à limiter les risques d'éclatement thermique des bétons dans de telles situations. Cette donnée d'entrée est généralement accompagnée d'autres requis n'allant pas dans la même direction : des requis de haute durabilité peuvent engendrer de hautes résistances, de faibles porosités et perméabilités, et donc un risque d'éclatement thermique accru. L'objet de cette publication est de présenter l'étude menée par EDF dans le but de définir un essai simple et rapide permettant de guider le choix de formules béton durant la phase d'étude. Les conditions d'essais ont été choisies pour favoriser les phénomènes d'instabilité thermique : les échantillons initialement saturés en eau sont chauffés à 10°C/min jusqu'à 550°C. Les propriétés de différents bétons ont été suivies avant et après sollicitation thermique. Les phénomènes d'éclatement thermique ont également été analysés.

Abstract :

Concrete structures can be subjected to elevated temperatures in accidental situations. Fire is the best-known situation but the nuclear field may also involve some specific situations inducing elevated temperatures (loss of coolant accident, core meltdown severe accident). The concrete designer may have to reduce the risk of thermal spalling of concretes in such situations. This input data is usually a portion of many others that not all go in the same way : the high durability requirements can induce high strength, low porosity, low permeability and therefore an increased thermal spalling risk. The aim of this paper is to present the study performed by EDF in order to define a simple test that guides the choice of concrete formula during the design stage. The test conditions were chosen to promote the development of thermal instability phenomenon : the initially water saturated specimens are heated at a 10°C/min rate up to 550°C. The properties of several concretes were followed before and after the thermal tests. Thermal spalling occurrence was also analyzed.

Keywords : Concrete, Non destructive testing, Thermal spalling

1 Context

Thermal spalling of concrete may be an issue when structures can be accidentally exposed to elevated temperatures. Fire is the best-known situation but the nuclear field may also involve some specific situations inducing high temperatures (loss of coolant accident, core meltdown severe accident). It is recognized that thermal spalling generally occurs below 500°C [1, 2]. Adding polypropylene fibers is the most common solution for reducing the risk of thermal spalling [3, 4]. Polypropylene fibers lead to an increase of permeability and a decrease of interstitial pressure related to their melting around 170°C. It is known that high performance concretes are more subjected to thermal spalling than ordinary concretes [5, 6]. When some high strength and/or high durability requirements are also given, the concrete designer has to select the concrete formula in such a way that it satisfies the demonstration of resistance to high temperatures. The resistance to elevated temperatures is generally evaluated from representative tests (representative scale of the concrete structure and representative thermal exposure). Given that this type of test is complicated and cumbersome, it usually comes at the far end of the concrete design process. Thus, in order to reduce the risk of unsuccessful results and to help the designer in the selection of the concrete formula, it appears useful to have a simple and fast test to assess the propensity of concrete to spall at elevated temperature.

2 Experimental program

An experimental protocol has been defined by the concrete laboratory of EDF (Ceidre/TEGG department dedicated to the expertise in civil engineering materials) in order to evaluate the sensitivity of concretes to thermal spalling. This protocol is based on some thermal tests performed on cylindrical 11 x 22 cm specimens. Concrete specimens are not dried in order to improve interstitial overpressure phenomenon during heating. The device used is a radiant heat oven. The small working volume of the furnace (9 litres) allows to test one specimen for a given temperature plateau. This has the advantage to provide uniformity and repeatability. The tests are performed up to 550°C with various intermediate temperature plateaus (250°C or 300°C, 400°C, 500°C). The effect of temperature on the mechanical properties is in particular evaluated trough non destructive tests. Ultrasonic pulse velocity (54 kHz cylindrical transducers generating compression waves) and flexural resonant frequency (Grindosonic) are measured on each specimen before and after the thermal tests if it remains integral. Knowing the density it is also possible to use the value of the resonant frequency for calculating the dynamic modulus. At the end, compressive strength is measured and can be compared to the initial value obtained on witness specimens tested without thermal treatment.

The detailed protocol is defined as follows :

- Storage of 11 x 22 cm cylindrical surfaced specimens according to NF EN 12390-2 (temperature = 20°C+/- 2 and relative humidity > 95%)
    - At least 90 days for concretes containing ground granulated blast-furnace slag (GGBS), fly ash or any other pozzolanic component
    - At least 60 days for the other ones
- Initial measurements on the tested specimen in a water saturated state (*ie.* just at the exit of the storage room)
    - Dimensions
    - Weight
    - Volume (hydrostatic weighing)

    - Ultrasonic pulse velocity (UPV)
    - Flexural resonant frequency
- Thermal test on the water saturated specimen (if necessary the specimen can be protected from drying after the initial measurements and before to put it in the furnace)
    - T0 → Start of heating at a rate of 10°C/min until the chosen maximum heating temperature. The limit for the maximum heating temperature is 550°C
    - T1 = T0 + 3 hours → End of the heating. The specimen is held in the furnace
    - T2 = T1 + 24 hours → The specimen is removed from the furnace, protected from humidity (in a waterproof bag for example) and disposed in a controlled room (temperature = 20°C+/-2)
    - T3 = T2 + 24 hours → Measurements on the specimen :
        - Weight
        - Ultrasonic pulse velocity (UPV)
        - Flexural resonant frequency
        - Compressive strength

Several types of high and very high performance concretes have been selected for this study. A description of theses mixes is given in the Table 1.

Table 1: Concrete mixes description

Mix designation		M0	M1	M2	M3	M4	M5
CEM I 52,5 N cement (kg/m^3)		350	400	240	80	370	400
Ground granulated blast-furnace slag (kg/m^3)		-	-	160	320	-	-
Silica fume (kg/m^3)		-	40	40	40	30	80
Polypropylene fibers (kg/m^3)		-	-	-	-	2	-
D_{max} of aggregates		20 mm	20 mm	20 mm	20 mm	8 mm	2 mm
Total water content	kg/m^3	185	138	138	138	155	250
	% wt of concrete	7,8	5,6	5,6	5,6	5,9	11,0

The description of these different mixes could be explained as follows :

- The mix M0 is relatively close to the composition of an ordinary concrete (ratio of the effective water content to cement content W/C = 0,5, no silica fume) but has a compressive strength greater than 60 MPa. It can be considered as a concrete at the border between ordinary and high performance concretes.
- The mix M1 has a very low W/C ratio (< 0,35) and contains also silica fume in addition of the CEM I cement. The compressive strength of this mix is greater than 100 MPa.
- The mixes M2 and M3 are derivatives from the mix M1 by replacing cement with GGBS in different proportions: 40% for the mix M2 and 80% for the mix M3.
- The mix M4 is a high performance micro-concrete containing some polypropylene fibers. This concrete has been originally designed for a specific structure of the EPR nuclear power plant called the core catcher. This structure should be exposed at very high temperatures in case of severe accident and the risk of thermal spalling of the concrete has to be reduced.

- The mix M5 is a high performance fine mortar containing a high content of silica fume. Its compressive strength is largely greater than 60 MPa

The initial mechanical properties of hardened concretes (before thermal tests) are given in the Table 2.

Table 2: Initial mechanical properties of the different mixes

Mix designation	M0 (*)	M1 (*)	M2 (**)	M3 (**)	M4 (***)	M5 (*)
Flexural resonant frequency (Hz)	6310	6590	6535	6390	6520	6000
Ultrasonic pulse velocity (m/s)	4970	5260	5300	5210	5030	4600
Dynamic modulus (GPa)	48,0	53,4	53,5	51,0	55,5	43,0
Porosity accessible to water (%)	13,0	7,6	6,6	8,7	10,0	15,0
Compressive strength (MPa)	64,8	108,4	112,5	91,2	83,7	93,3

(*) at 60 days, (**) at 90 days, (***) at 5 years

We can see that the initial properties of these mixes are comprised between :

- 64,8 MPa and 112,5 MPa for the compressive strength
- 6,6 % and 15,0 % for the porosity accessible to water
- 43,0 GPa and 55,5 GPa for the dynamic modulus
- 4600 m/s and 5300 m/s for the ultrasonic pulse velocity

These values are consistent with the kinds of materials tested (high and very high performance concretes). We can note the special properties of the mix M5 : its compressive strength is very high despite its high porosity accessible to water. This is due to the fact that the components of this mix are very fine (cement, silica fume, fillers, fine sand) inducing a specific pore structure (*ie.* very small pore diameters).

3 Test results

The Figures 1 and 2 show the residual values of ultrasonic pulse velocity and resonant frequency measured after the thermal tests. Some specimens were sometimes destroyed. In this case, the measurements were not made and that is illustrated in pictures with dotted lines pointing to zero.

The variation of UPV and resonant frequency with temperature is globally the same for all the mixes when the specimens remain integral. Even if some specimens were destroyed at a given maximum temperature, the evolution of UPV and resonant frequency at a lower temperature do not reveal any particular sensitivity of a mix to thermal spalling.

Some specimens were destroyed for some thermal tests with some heating temperatures comprised between 400 and 500°C.

No specimen was destroyed for some 250 or 300°C thermal tests. The mixes M3 and M5 were destroyed for a maximum temperature of 400°C and the mixes M1 and M2 for a maximum temperature of 550°C. The mixes M0 and M4 remained integral even after the thermal tests at 550°C. A surface and local spalling has been observed for the mixes M1 and M2 for the thermal tests at 500°C. This did not prevent in this case to make the measurements after the thermal tests.

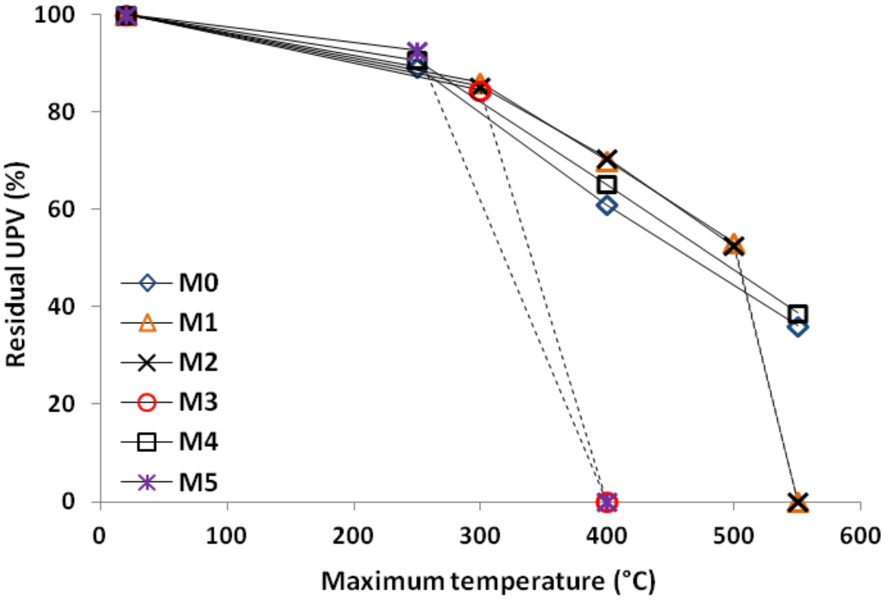

Figure 1: Residual ultrasonic pulse velocity versus maximum heating temperature

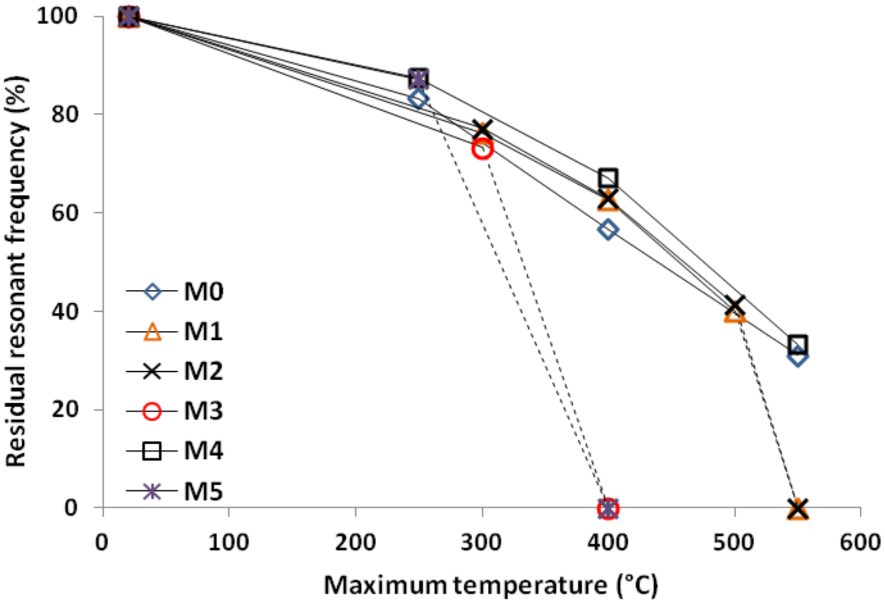

Figure 2: Residual resonant frequency versus maximum heating temperature

The calculation of the dynamic modulus is possible from the values of resonant frequency and density.

The Figure 3 illustrates the results of dynamic modulus versus temperature.

We can see that the dynamic modulus significantly decreases with temperature. The dynamic modulus is systematically less than 10 GPa as soon as the maximum temperature reached 500°C.

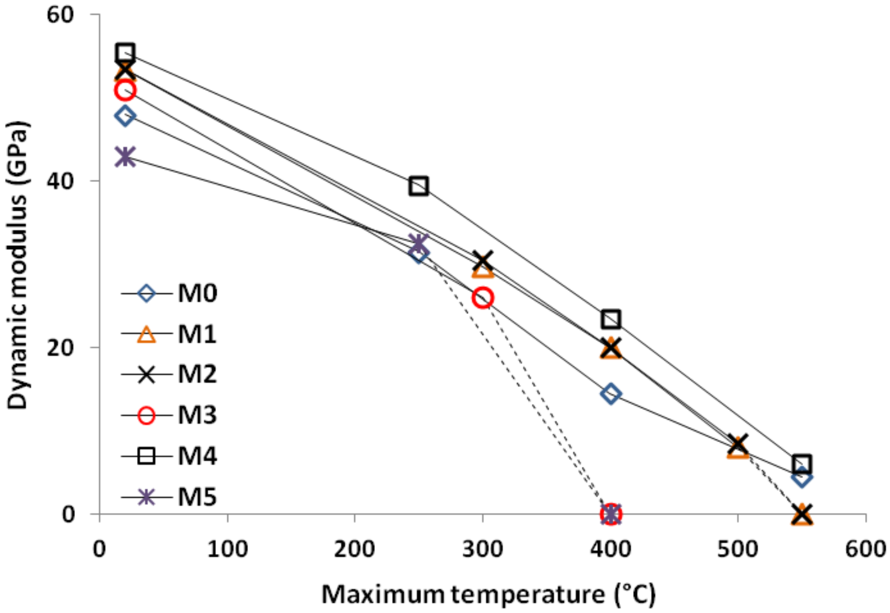

Figure 3: Dynamic modulus versus maximum heating temperature

Destructive compressive strength tests were performed on thermally treated specimens after NDT measurements. The Figure 4 shows the values of residual compressive strength of the different mixes. We can see that some bell-shaped curve tendencies are observed especially for the mixes M0, M3 and M5.

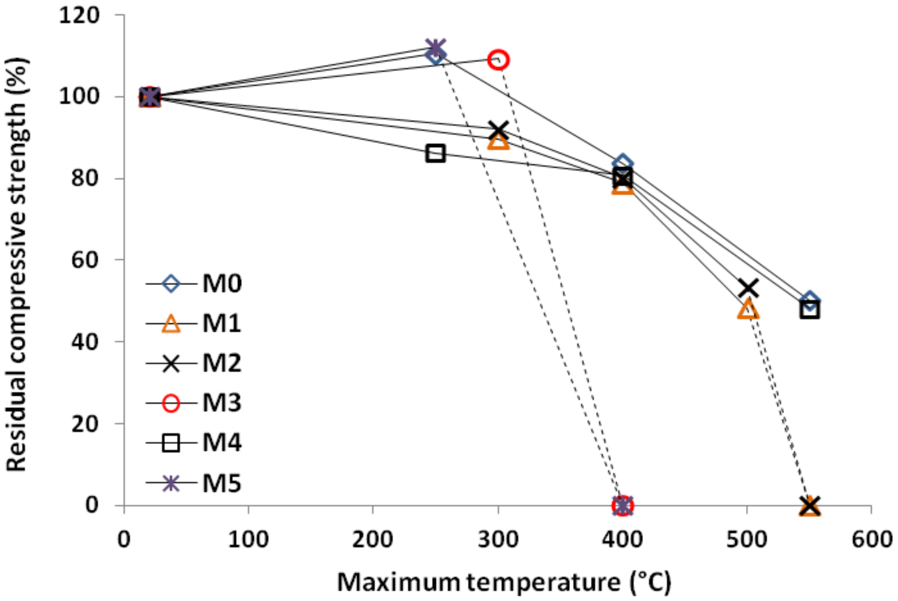

Figure 4: Residual compressive strength versus maximum heating temperature

4 Discussion

The concrete mechanical properties have been measured before and after thermal tests when the specimens didn’t explode. The variations of the measured residual properties with the maximum heating temperature are related to changes in the microstructure. Different mechanisms can be considered : drying (loss of free water), dehydration (loss of bonded water) and cracking. Globally these mechanisms tend to reduce the residual mechanical properties of concretes. Their combined action makes it difficult to evaluate the damage evolution of the mixes with temperature. Microstructural observations could certainly provide information to assess their damage degree.

All the results obtained allow analyzing some correlations between the different mechanical properties. The Figures 5 and 6 illustrate UPV and dynamic modulus versus compressive strength. The results obtained during the following of hydration for some mixes have been added for having more values before thermal tests.

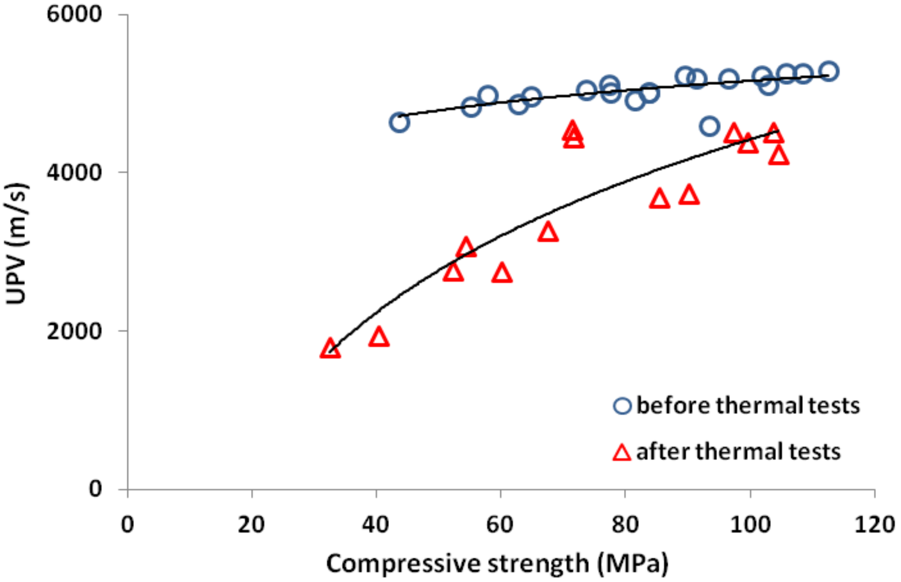

Figure 5: Ultrasonic pulse velocity versus compressive strength

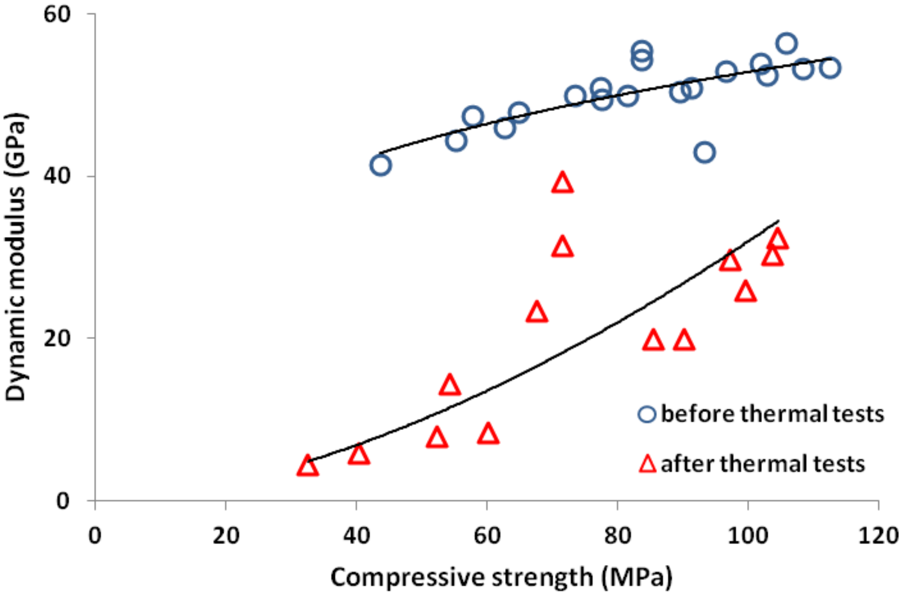

Figure 6: Dynamic modulus versus compressive strength

It can be noted that thermally treated concretes do not follow the same tendencies as initial sound concretes. This conclusion is valid for the UPV and also for the dynamic modulus and is compliant with some results already obtained by Hager et *al.* [7]. Water can play a major role in what is observed. Indeed the initial sound concretes are in a water saturated state while the thermally treated concretes are dried and more and less dehydrated. It's not sure that the observed tendencies would be the same if the specimens had been rehydrated after the thermal tests.

On the other hand we can see in the Figure 7 that the dynamic modulus varies in the same way with UPV whether the specimens are sound and water saturated or not.

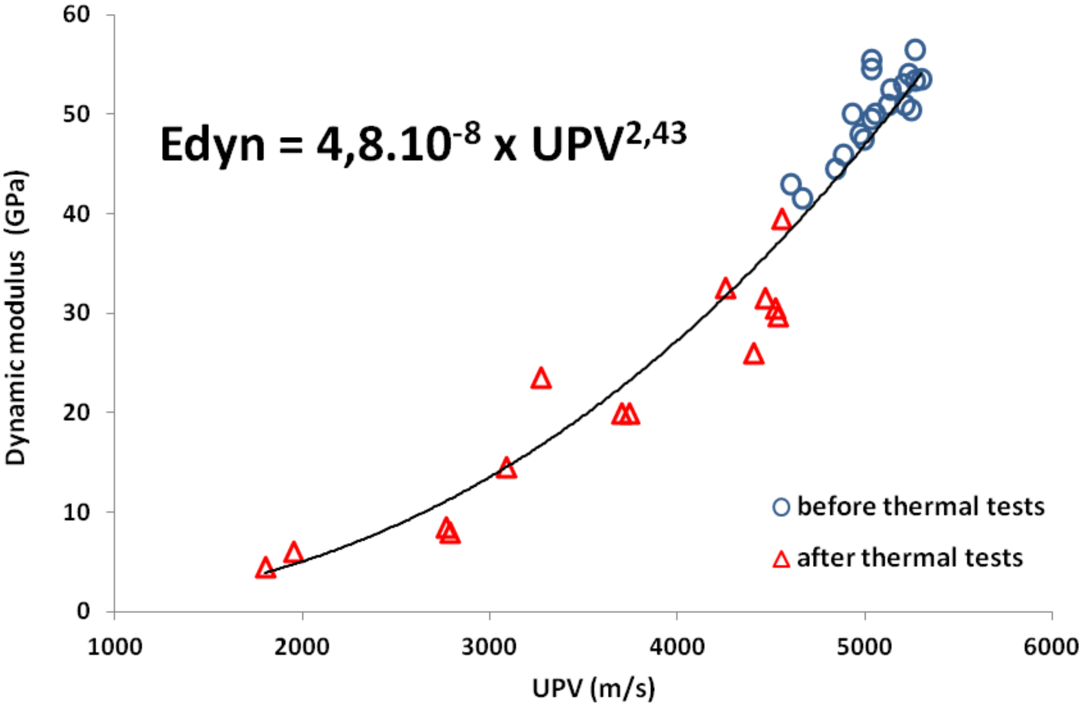

Figure 7: Dynamic modulus versus ultrasonic pulse velocity

Concerning thermal spalling of the concretes, three different phenomena have been observed :

- Explosive spalling : this violent and noisy phenomenon was observed during the heating stage. The samples were systematically found in small pieces after cooling in the furnace.
  This phenomenon has been for example observed with the mix M5 for the 400°C thermal tests.
- Non-explosive spalling : The specimens were found destroyed but no violent explosion occurred during the heating stage. The pieces of concrete were systematically larger than those mentioned above.
  This phenomenon has been for example observed with the mixes M1 and M2 for the 550°C thermal tests and with the mix M3 for the 400°C thermal tests.
- Surface spalling : some specimens had a local loss of material along the specimens.
  This phenomenon has been for example observed with the mixes M1 and M2 for the 500°C thermal tests.

Some photos of the spalling phenomena are given in the Figure 8. It has been in particular observed that the kind of thermal spalling phenomenon could vary with the maximum temperature level. As the maximum heating temperature increases, these phenomena tend to appear in this order: no spalling, surface spalling, non-explosive spalling then explosive spalling.

The temperature level at which these phenomena can occur depend on the kind of concrete tested :

- Mixes M0 and M4 : no spalling observed up to 550°C

- Mixes M1 and M2 : no spalling for 300 and 400°C thermal tests, surface spalling for 500°C thermal tests and non-explosive spalling for 550°C thermal tests
- Mix M3 : no spalling for 300°C thermal tests, non-explosive spalling for 400°C thermal tests, explosive spalling for 500 and 550°C thermal tests
- Mix M5 : no spalling for 250°C thermal tests, explosive spalling at 400°C and beyond

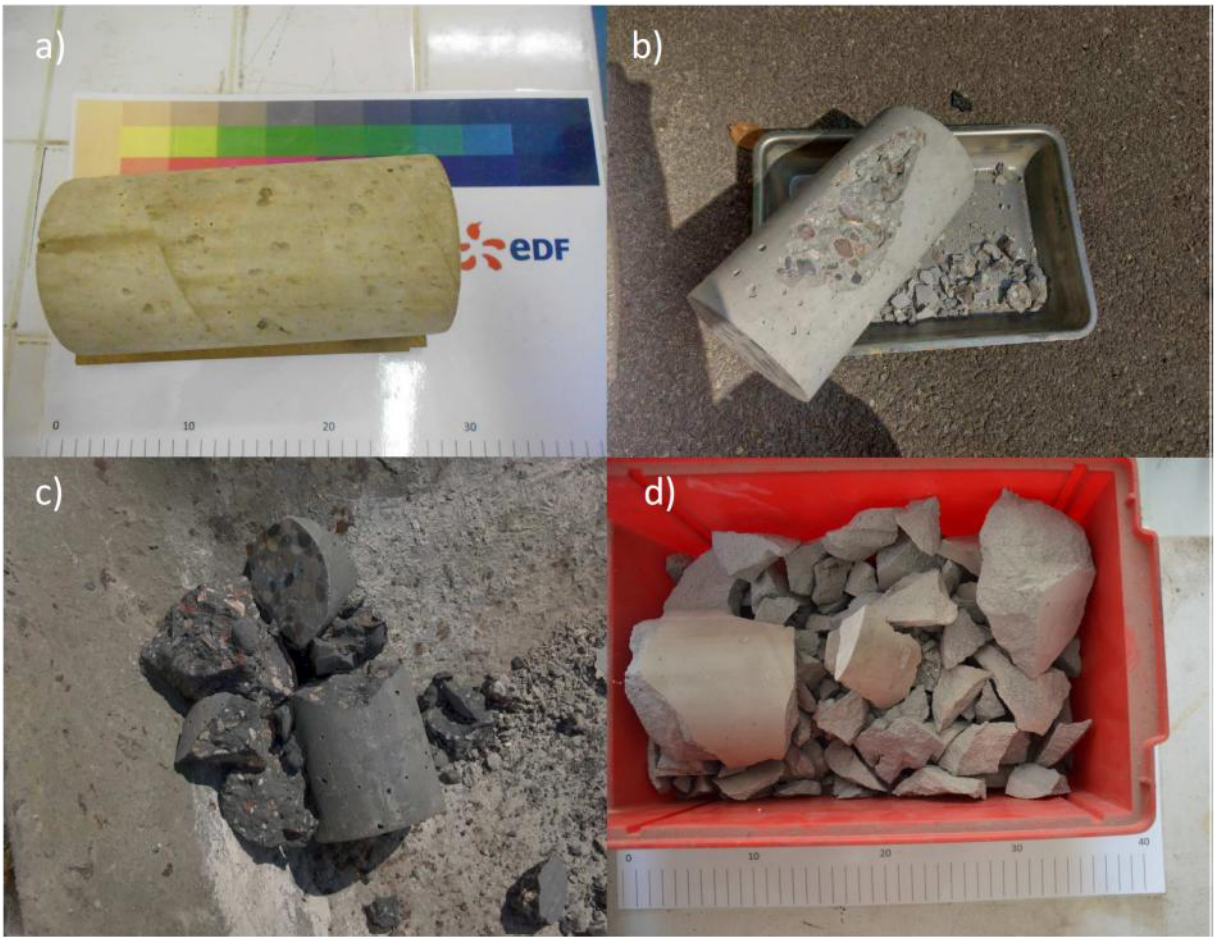

Figure 8: Photos of thermal spalling phenomena: a) no spalling / b) surface spalling / c) non-explosive spalling / d) explosive spalling

We can consider a growing harmfulness according to whether it is observed no spalling, surface spalling, non-explosive spalling and explosive spalling. By combining the observed phenomena with the temperature level at which they appear, an evaluation grid has been defined in order to classify the propensity of concrete material to spall at elevated temperature (see Table 3). Four classes have been defined: low, moderate, high and very high propensity to spall.

The resulting ranking for the different mixes is as follows: low for the mixes M0 and M4, moderate for the mixes M1 and M2, high for the mix M3 and very high propensity to spall for the mix M5.

This classification appears coherent with certain theoretical elements. The mix M0 close to the composition of an ordinary concrete and the mix M4 containing polypropylene fibers are ones that end up with the lowest propensity to spall. On the contrary the highest propensity to spall is obtained for the mix M5 that is the finest material while containing the most water. Concerning the mix M3, the greater sensitivity to thermal spalling with respect to the mixes M1 and M2 could provide from its lower compressive strength.

Table 3: Evaluation grid – application to the 6 studied mixes

	MAXIMUM HEATING TEMPERATURE		
	400°C	**500°C**	**550°C**
EXPLOSIVE SPALLING	🟥 M5	🟧 M3	🟧 M3
NON-EXPLOSIVE SPALLING	🟧 M3	🟧	🟨 M1 M2
SURFACE SPALLING		🟨 M1 M2	🟨
NO SPALLING	M0 M1 M2 M4	M0 M4	🟦 M0 M4

Propensity of concrete to spall at elevated temperature			
🟦 **Low**	🟨 **Moderate**	🟧 **High**	🟥 **Very high**

To go further in understanding the phenomena, it has been decided to highlight the ability of these concrete mixes to release water during the heating. The determination of the water permeability should be indeed more relevant than the porosity because we have seen that the pore structure could significantly influence the hydraulic behavior. Unfortunately, the tests performed with a permeameter do not allow an accurate assessment of the water permeability for high and very high performance concretes. An alternative method based on the unidirectional drying of concrete specimens is currently being studied by EDF. This method could be promising for determining and classifying the values of low-permeability concretes.

5 Conclusions

This paper deals with the temperature effect on high and very high performance concretes. The experimental protocol developed by the EDF concrete laboratory was exposed. It has been in particular mentioned that an evaluation grid was developed in order to assess the propensity of concrete material to spall at elevated temperature. This classification is based on the observed phenomena (no spalling, surface spalling, non-explosive spalling and explosive spalling) and the temperature level at which they occur. This test method is a simple and fast way to classify concrete formulas. This can be particularly useful during the design stage for helping to select some concrete mixes. This test method does not replace representative tests which are usually performed at the end of the concrete design process. By reproducing some real expected conditions (concrete structure with representative dimensions, reinforcement, external load, thermal exposure…), this can affect the thermal spalling occurrence. The evaluation of the propensity of concrete to spall at elevated temperature reduces the risk of unsuccessful representative tests (the higher the propensity to spall, the higher the risk of thermal spalling occurrence in real conditions).

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References

[1] R. Haniche, Contribution à l'étude des bétons portés en température – Evolution des propriétés de transfert : étude de l'éclatement, Doctoral Thesis, INSA Lyon, 2011

[2] L.T. Phan, J.R. Lawson, F.L. Davis, Effects of elevated temperature exposure on heating characteristics, spalling, and residual properties of high performance concrete, Materials and Structures, Vol. 32, march 2001, pp. 83-91

[3] I. Gaweska-Hager, Comportement à haute température des bétons haute performance : évolution des principales propriétés mécaniques, Doctoral Thesis, ENPC, 2004

[4] R. Jansson, Fire spalling of concrete – Theoretical and experimental studies, Doctoral Thesis, Stockholm, 2013

[5] J.C. Mindeguia, Contribution expérimentale à la compréhension des risques d'instabilité thermique du béton, Doctoral Thesis, Université de Pau et des Pays de l'Adour, 2009

[6] A. Noumowe, Effet des hautes températures sur le béton. Cas particulier du béton à hautes performances, Doctoral Thesis, INSA Lyon, 1995

[7] I. Hager, H. Carré, Ultrasonic pulse velocity investigations on concrete subjected to high temperature with the use of cylindrical and exponential transducers, 7th International Conference on Structures in Fire, Zurich, June 6-8, 2012