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COMBINED EFFECTS ON RESIDUAL STRENGTH OF A HIGH PERFORMANCE CONCRETE EXPOSED TO FIRE

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ABSTRACT

Concrete structures exposed to fire suffer from damage, but can remain a certain degree of residual strength. International research has shown that the compressive strength of concrete decreases not only with temperature, but also by the way of cooling and the storage conditions after fire. Fast cooling introduces a thermal shock which, based on experiments by the authors, could result in a 30% additional strength loss with respect to the loss during heating. When storing the concrete after the fire in air or under water, additional strength losses of about 20-30 % are found within 14 days after the fire.

In this paper it is investigated for a high performance concrete what the combined effect is of heating, cooling and storage.

One of the conclusions – but with respect to the specific test conditions (e.g. slow heating, 550°C max, pre-dried samples) – is that superposing both expected strength losses of about 30% in case a fast cooling is followed by a period of post-cooling storage results in too conservative strength estimations. It is deemed that the cracks resulting from fast cooling, will act as expansion chambers for the newly produced portlandite, thus strongly reducing additional stresses, which results in expected lesser damage.

1 INTRODUCTION

The last decades, a lot of research has been performed worldwide in order to understand the remaining strength properties of concrete exposed to fire. For the particular case of high performance concrete, the studies presented in [1] and [2] can be mentioned. These studies show the importance on the remaining compressive strength of the specific test conditions after the heating cycle. Of major influence are the rate of cooling and the post-cooling environmental storage

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conditions. Such studies can be the basis to evaluate the remaining load-bearing capacity of a concrete structure exposed to fire by means of calculations.

Mostly the mentioned influencing parameters result in a further reduction of the compressive strength compared to the strength loss already induced by the temperature. The additional loss of the cooling rate can be explained by the introduction of a thermal shock in case of a rapid cooling method, resulting in additional cracks and therefore strength loss. The additional strength loss related to post-cooling storage conditions should be related to newly formed portlandite ($Ca(OH)_2$) which is an expansive reaction, and thus literally presses the concrete to failure from the inside.

On the other hand, in the cases presented in [2] a range of strength recovery with respect to the loss during the heating cycle is found of 3.4-18.62%, respectively 5.4-16.7%. These results were found on siliceous granite high performance concretes (with a variety in amount and kind of puzzolanic material) when exposed to 600°C and 800°C, followed by storage for 56 days in moist air. These recovery values should be multiplied by a factor of about 2-3 in case the samples were stored under water after heating for 56 days. In all cases, only a partial restore of bounds is found, no full recovery is obtained. These values can potentially be interesting for an assessment after fire, but seem to be in contrast with other research studies. Given these contradictions, it is clear the problem is not fully understood yet. This also implies practical problems when asked to assess the remaining load-bearing capacity of concrete structures.

Hence, the scope of this paper is to better understand this potential (and therefore also its limitation) of recovery. Additionally, it is questioned if this recovery can be found for heating to temperatures of 350-550°C. Based on the results of [2], one of the remaining research questions is if for an assessment both the negative effects of fast cooling and post-cooling storage should be superposed, or under which conditions this is not allowed to do.

For this purpose, in agreement with [2] a high performance concrete is cast and heated, after which it is cooled at different rates and stored in different climatic conditions. In addition to previous researches - where only one combination of these influencing parameters is studied - special focus is now given in this paper to the specific influence of each parameter and to the effect of the order of combination of the different parameters. As already explained, a good understanding of these effects is very important for practical use in assessments of the remaining load-bearing conditions after fire exposure.

2 TEST CHARACTERISTICS

2.1 Concrete mix

Table 1 presents the used concrete composition of a high performance concrete with Portland cement and siliceous aggregates. Cubic samples with size 150 mm are cast. These samples are cured for 4 weeks in an air-conditioned room at > 90% R.H. and a temperature of 20 ± 1°C, after which they are stored at 60% R.H. and 20 ± 1°C for drying till a testing age of 20 months. The density of sand and gravel is approximately 2625 kg/m³.

Table 1. Mix properties of high performance concrete (HPC)

sand [kg/m³]	650
gravel 2-8 mm [kg/m³]	530
gravel 8-16 mm [kg/m³]	720
Portland cement I 52.5 [kg/m³]	400
water [kg/m³]	132
superplasticizer [l/m³]	16.5
W/C [-]	0.33
fccub150,28d [N/mm²]	74.8
density at 28 days [kg/m³]	2430

2.2 Test programme

As reported in the introduction, the remaining compressive strength of concrete after exposure to fire is influenced by the exposed temperature level, the way of cooling and the post-cooling storage conditions. To study the combined effect of these three influence parameters, the following parameter characteristics are used:

- **Target temperature.** The cubes are heated till uniform temperature is obtained of 350°C or 550°C in the center of the cubes. The heating rate is fixed at 5°C/min and the maximum obtained furnace temperature is held constant for up to 950 minutes. This heating rate is considered as slow according to [3],as it is ≤ 5°C/min. The temperature level of 350°C is chosen as it can be regarded as the onset of strength loss due to loss of chemically bound water, whereas 550°C corresponds to the disintegration of portlandite.
- **Cooling regime.** After reaching uniform temperature, the samples are cooled under two different regimes.
  The first regime is a relatively slow cooling in air (20±3°C, 60±12% R.H.) by removing the furnace and directing a fan on the steel tube in which the samples are positioned (see also section 2.3 for the test setup). The temperatures inside the concrete drop below 200°C at a rate of about 3.5°C/min.
  The second regime is a fast cooling by immersing the hot samples in water of ~20°C, inducing a thermal shock of 13-17°C/min. This cooling regime is much faster as the temperatures inside the concrete drop below 40°C after 65 minutes, compared to 310 minutes for the cooling in air.
- **Post-cooling storage conditions.**The cubes are immediately tested for compressive strength (< 1 day after heating) or after storage for 28 days in air of 60% R.H. and 20±1°C, or under water of ~20°C.

It is noted that also the existence of an external compressive load can have an influence on the remaining compressive strength. The effect on the remaining compressive strength is out of the scope of this paper. However, it is noticed that if the load level is not too high in order to avoid compressive failure during heating, the mechanism of transient strain occurring during heating could potentially result in a less reduction of the compressive strength.

Prior experiments showed a risk for spalling of the concrete samples, even when heated slowly at 5°C/min. Hence, to be able to compare compressive strength results in agreement to the scope of the test programme, the concrete samples that will be heated to about 550°C are pre-dried at 50-70°C till constant mass was reached (drying period ≥ 2 weeks).

Table 2. Overview of studied combination of influence parameters

Target temperature	Cooling method	Post-cooling storage conditions		Designation
350°C	Air (A)	0 days		350°C,A,0d
		28 days	In air (A)	350°C,A,28d,A
			Under water (W)	350°C,A,28d,W
	Water (W)	0 days		350°C,W,0d
		28 days	In air	350°C,W,28d,A
			Under water	350°C,W,28d,W
550°C	Air	0 days		550°C,A,0d
		28 days	In air	550°C,A,28d,A
			Under water	550°C,A,28d,W
	Water	0 days		550°C,W,0d
		28 days	In air	550°C,W,28d,A
			Under water	550°C,W,28d,W

For each combination, two samples are heated. Hence, in total 24 HPC cubes are tested in this test programme. An overview of all combinations together with their designation further used in this paper is given in *Table 2*.

2.3 Oven characteristics

An electric split or mobile oven (*Fig. 1*) is used to heat the specimens. It allows to reach temperatures of up to 600°C according to a given constant heating rate of 5°C/min. The oven has an internal diameter of 220 mm and a height of 550 mm, hence it is possible to heat 2-3 concrete cubes simultaneously. During the test, the central opening is sealed with insulation (PROMAGLAF HTK 1260°C, high temperature glass fibers) to reduce heat losses. To avoid possible damage to the oven due to concrete spalling, the cubes are surrounded in the oven with an additional steel tube.

Fig. 1. The electric split oven

It is observed that when 3 cubes are positioned on top of each other in the oven, large differences in heating profiles inside the different cubes are found. To reduce this effect, only 2 cubes are heated which are positioned at mid-height of the oven. To have similar heating conditions for both cubes - meaning heating from 4 faces and conduction losses through concrete at the top and bottom face – half cubes are positioned on top of the top cube and below the bottom cube.

To determine the temperature evolution inside the concrete samples and control reaching of the uniform temperature, a dummy test is performed provided with K-type thermocouples at 35 mm and 75 mm (center) distance from the corners of the cubes.

3 TEST RESULTS

3.1 Remaining compressive strength

Table 3 presents, for the different combinations as outlined in *Table 2*, the compressive strength reduction in percentage of the initial strength before heating.

Table 3. Remaining compressive strength with respect to the initial strength ($f_{ccub,T}/f_{ccub,20°C}$ [%])

Test sample	350°C	550°C
xxx°C,A,0d	98.95	60.00
xxx°C,A,28d,A	71.18	38.65
xxx°C,A,28d,W	75.99	57.42
xxx°C,W,0d	64.40	29.96
xxx°C,W,28d,A	74.39	52.20
xxx°C,W,28d,W	64.59	46.53

The initial concrete strength is 74.8 N/mm² which corresponds to a compressive strength class of C55/67. According to EN1992-1-2 [4], this concrete class is considered as a Class 1 of High

Strength Concrete. The expected remaining ‘hot’ strength at high temperatures can then be found in Section 6 of EN1992-1-2 and is given as 80% for heating to 350°C and 53% for 550°C. It is noted that those values are smaller than the strengths found for test samples xxx°C,A,0d, which are from the available test data the ones with the most representative test condition for hot strength.

As expected, a larger decrease of the compressive strength with respect to air cooling is found when the concrete is immersed under water. The influence (about 30-35%) of this thermal shock can be seen from comparison of xxx°C,A,0d with xxx°C,W,0d.

3.2 Influences of cooling rate and post-cooling storage conditions

The effect of each influencing parameter is shown in *Table 4*. The influence of mainly the temperature (xxx°C,A,0d) is expressed with respect to the initial strength before heating, and is already presented in *Table 3*. This effect of the temperature is further used to study the effect of the other parameters. Thus, in this procedure, air cooling is the reference cooling method.

Table 4. Effect of the different influencing parameters on the compressive strength reduction

Parameter	Test sample	%
Temperature (with respect to 20°C)	350°C, A, 0d	98.95
	550°C, A, 0d	60.00
Water cooling (difference with ‘xxx°C,A,0d’)	350°C, W, 0d	-34.55
	550°C, W, 0d	-30.04
28 days storage in air (difference with ‘xxx°C,A,0d’)	350°C, A, 28d, A	-27.77
	550°C, A, 28d, A	-21.35
28d storage in water (difference with ‘xxx°C,A,0d’)	350°C, A, 28d, W	-22.96
	550°C, A, 28d, W	-2.58

The results of *Table 4* show an additional strength loss due to a fast cooling of about 35% and 30% for respectively heating to 350°C and 550°C. Furthermore, when the samples are air cooled and subsequently stored in air for 28 days, additional strength losses of about 28% and 21% are found for respectively 350°C and 550°C. In case the storage is in water, this additional loss is less with about 23% and 2.6% for respectively 350°C and 550°C. These observations indicate a potential importance of storage under water.

3.1 Superposition of the influencing parameters

Starting from *Table 4*, it is now possible to superpose the different influences to obtain the resulting total strengths as outlined in *Table 3*. For example, the post-cooling strength of ‘550°C,A,28d,W’ given in *Table 3* as 57.42% can be found as the sum of 60% (temperature effect) and -2.58% (storage effect) given in *Table 4*.

This superposition works for the combinations outlined in *Table 4*, because the different influences are derived with respect to the values corresponding to air cooling. However, in *Table 3* a few extra combinations are given: water cooling followed by storage in air or storage in water. When for these conditions the superposition is applied based on the values from *Table 4*, the derived strength losses are too large compared to the experimental data. In other words, the strength degradation is then assessed conservative, but too severe.

Table 5. Effect on strength of water cooling combined with storage

Combination of influencing parameters	Test sample	Sum of *Table 4* [%]	Difference with *Table 3*[%]	Difference with xxx°C, W, 0d[%]
Water cooling + storage in air	350°C, W, 28d, A	36.63	37.76	9.99
	550°C, W, 28d, A	8.61	43.59	22.24
Water cooling + storage in water	350°C, W, 28d, W	41.45	23.15	0.19
	550°C, W, 28d, W	27.38	19.15	16.57

For the concerning combinations, this exercise is presented in columns 3 of *Table 5*, while column 4 gives the percentage that is subtracted too much. The total of both columns results again in the experimental values mentioned in *Table 3*. This significant deviation is due to the effect of water cooling and subsequent storage which have both a negative effect on the strength if the values of *Table 4* (influences calculated with respect to air cooling) are considered.

In contrast, the experimental values indicate that after a strength loss from water cooling, the strength recovers partially during a subsequent storage in air or under water. This partial strength recovery is presented in column 5 of *Table 5* and is the highest for post-cooling storage in air. Due to this partial strength recovery, the values concerning storage derived from air are too conservative when studying combinations of water cooling and storage. In these cases, the values of column 5 of *Table 5* should be added to the values of ‘xxx°C,W,0d’ of *Table 4*.

Column 4 of *Table 5* is also the difference between strength loss during storage after air cooling (*Table 4*) and the strength recovery during storage after water cooling (column 5, *Table 5*). Due to this large recovery difference, some water cooled cubes have despite the thermal shock a higher post-cooling strength than air cooled specimens (see *Table 3*).

4 DISCUSSION

As explained in the introduction, the strength loss upon storage after air cooling is generally attributed to the regeneration of portlandite (for T > 450°C). Despite new portlandite is also formed for specimens which are cooled under water, the results presented in this paper show no further strength loss during this post-cooling period. This could be explained by 3 possible reasons: 1) the increased porosity due to the thermal shock gives expansion space for the newly formed portlandite, resulting in less stress development than for air-cooled specimens. 2) Due to water immersion a lot of water is available for further hydration of unhydrated cement grains, resulting in the observed partial strength regain. 3) When the samples are stored in air, they will dry. Such a displacement of the moisture to the surface accelerates the hydration process. This latter contribution could also explain why storage in air after water cooling yields higher recovery than storage under water.

From the resulted effect of the different influencing factors, the difficulty is clear of assessing the in-situ strength of a concrete building after fire as the exact exposure circumstances are very difficult to reveal. To deal with this uncertainty, it is recommended to calculate the load-bearing capacity with conservative values. It is noted that this paper focusses on the strength degradation of uniform heated concrete samples only. The complex interaction of restraint actions of connected members is out of the scope of this paper.

The samples used in this test programme are heated slowly (5°C/min) and to avoid spalling, the samples tested at 550°C are additionally pre-dried. In this way, potential cracks occurring due to restraint actions during heating that can potentially influence the remaining strength are not considered in the present study. Hence, the combination of a fast heating with a fast cooling and subsequent storage is out of the scope of this research program. In this way, the presented results can be interpreted as valid for a concrete element located further away from the fire.

For a complete diagnosis of the reuse possibilities of a concrete member after a fire, also durability should be controlled. Given the increase of porosity, this can be an issue.

5 CONCLUSIONS

- The specific test conditions have a large influence on the remaining compressive strength. The results presented in this paper are derived from slowly - till uniform temperature - heated (pre-dried) samples.
- The studied high performance concrete mix suffers from almost no strength loss when exposed to 350°C and about 35% additional reduction in case of water cooling. When heating to 550°C, respectively 40% and 30% of reductions are found.

- If the samples are cooled slowly (in air) and subsequent stored in air or under water for 28 days, additional significant strength losses (up to 28%) are found. This conclusion is in agreement with the general conception given in the introduction.
- On the other hand, if the samples are cooled fast (water immersion) and subsequently stored in water or air, a partial strength recovery is found which can be very significant (respectively 16.57 and 22.24%) for heating to 550°C and less (respectively 0.19 and 9.99%) for 350°C. This observation is in agreement with [2] and explains the potential, but also the limit of recovery.
- In conclusion: superposition of both negative influences due to fast cooling and subsequent storage results in too conservative predictions of the remaining strength as a recovery is expected.

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