Post-cooling Stress-strain Model of Traditional and High-Strength Concrete

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ABSTRACT

As concrete structures suffer from severe fire damage, but may retain a certain remaining loadbearing capacity, it is important to have material properties for assessment by calculation after fire. This paper proposes a full stress-strain model for post-cooling conditions of a traditional calcareous concrete (TCC) and a high strength siliceous concrete (HSSC).

1. INTRODUCTION

In a compartment fire, concrete structural elements can suffer from severe damage. Nevertheless, after the fire these structures or part of them often can be considered for further use after appropriate assessment, and possible replacement or repair. One way to assess the remaining loadbearing capacity of the elements is by calculation. In structural design codes, such as the Eurocodes, hot strength properties and simplified calculation methods are provided by which the loadbearing capacity can be estimated. However, these tabulated material properties are valid for the design during fire only. Hence, in order to perform an adequate analysis after fire, a database is needed for material properties valid for post-cooling conditions.

The last decades, a lot of research has been performed worldwide in order to understand the remaining strength properties of concrete exposed to fire. It is demonstrated that the post-cooling strength of concrete is complex and depends on the specific conditions during fire, such as heating rate, exposure temperature and

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duration, as well as the existence of an external load [1,2]. After fire, also the cooling rate and specific subsequent environmental storage conditions influence the remaining strength [1,2].

Mostly these influencing parameters after fire result in a further reduction of the compressive strength compared to the strength loss already induced by the temperature. For the HSSC used in this paper, after slowly heating (5°C/min) to uniform temperatures up to 550°C without sustained load, a fast cooling rate by water immersion (13-17°C/min) results in additional strength losses of about 30-35% [2]. And a post-cooling storage in air or under water results in an additional strength loss of 20-30% [2]. The additional loss induced by 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.

This paper contributes to the described specific research area by proposing a full stress-strain model for post-cooling compressive strength of a traditional calcareous concrete (TCC) and a high strength siliceous concrete (HSSC). In addition to other research programs found in literature, this paper not only studies the compressive strength, but also the stiffness. Reference is made to section 2.3 to understand the specific test conditions and therefore the application limits of the proposed stress-strain model. The work presented is part of a master thesis [3].

2. TEST PROGRAM

2.1. Concrete mix

Table I presents the composition of the concrete mixes used in present study. A traditional calcareous concrete (TCC) and a high strength siliceous concrete (HSSC) are studied. Cylindrical samples with diameter 106 mm and 320 mm height are casted.

TABLE I. CONCRETE MIXES

Constituent	TCC	HSSC
Sand [kg/m³]	664	650
Coarse aggregates [kg/m³]	1210	1250
CEM I 52.5N [kg/m³]	350	400
Water [kg/m³]	165	132
W/C [-]	0.47	0.33
Superplasticizer [l/m³]	-	16.5

2.2. Test setup

The test setup consists of an electrical split oven, a loading frame, a measurement system and a PC unit.

The oven has an internal diameter of 220 mm and a height of 550 mm, and can reach temperatures up to 600°C. The concrete sample is positioned inside the oven. Thermocouples K-type are used to measure the temperature at the surface of the concrete at 3 positions, namely 20 mm from the top and bottom of the sample, and at midheight of the sample. The central opening of the oven is sealed with fire protection 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 cylinders are surrounded in the oven with an additional steel tube.

The load from the hydraulic jack is transferred to the sample by means of a series of steel cylinders. Loading till target level is performed by a pump, after which the load is sustain during the test by an accumulator.

2.3. Test conditions

The following test conditions are used:

Preparation of samples. Concrete mix and casting is explained in section 2.1. Fire tests show a risk for spalling of the concrete samples due to the sustained load, even when heated at 1°C/min. Hence, to be able to compare material property results in agreement to the scope of the test programme, the concrete samples are pre-dried at 105°C till constant mass is reached.

Target temperature. The concrete samples are heated to uniform target temperatures inside the cylinders of 175°C, 350°C and 550°C. 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. It is noted that determining residual properties beyond 550°C exposure are less interesting, as given the expected damage the layers between 300-550°C are already expected to be removed in case of repair of a concrete element.

The heating rate (measured by thermocouples positioned on the concrete) is 1°C/min. This heating rate is slow to avoid additional internal damage due to large differences in thermal expansion over the cross section of the concrete samples.

For the residual properties, uniform temperature over the cross section of the sample is required. Dummy tests with registration of the temperature in the center of the samples, together with thermal FEM calculations are performed to determine the exposure time needed to obtain uniform temperature distribution inside the samples. The required time is 7h of heating after reaching the target temperature.

Loading, cooling and post-cooling conditions. Two type of tests are performed, for which each test condition is executed twice per concrete type:

Test 1 comprises heating of the samples under a compression load ratio of 0, 20 or 30% of the initial compressive strength (further in the text referred to as 'loading from start'). Cooling is slow in a closed oven under sustained load, reaching a temperature drop from 550°C till 100°C over 8 hours.

Test 2 consists of heating without load till target temperature, from where additional 3 hours of heating is performed under the same load ratios as stated above (further in the text referred to as 'delayed loading'). Cooling is fast, but naturally, by immediately opening of the oven after the test. In this way, a temperature drop from 550°C to 100°C is found at the surface of the concrete within 1 hour.

The samples of all tests are further stored for 5 weeks in a climate chamber at temperatures of 20±1°C and 60% R.H. without load, after which they are tested for

Young's modulus (displacement controlled test, according to B15203-1990: 0.002 mm/s).

It is noted that the difference between both test conditions explains the possible effect of delayed loading during heating, as can be expected in some cases from restraint actions in a real fire.

The load is not sustained after cooling. Hence, the possible influence of this parameter is not taken into account in the proposed stress-strain model. However, the expected influence with respect to a post-cooling storage without load is a significant increase of the Young's modulus, but without effect on the compressive strength. This estimation is based on experiments of heating a similar concrete as TCC (but with siliceous aggregates) to 500°C under the same conditions as Test 1, but by also keeping the 20% load level for the 12 weeks post-cooling storage in ambient air [2]. Nevertheless, attention is necessary as increasing the load level to 40% results in failure after a few days during the post-cooling storage under load.

3. RESULTS

3.1. Sargin model at ambient temperatures

Equation 1 describes the non linear stress-strain relationship of concrete at ambient conditions, as proposed by Sargin and adopted in EN1992-1-1.

$$\frac{\sigma}{f_{cm}} = \frac{k \cdot \eta - \eta^2}{1 + (k-2) \cdot \eta} \qquad (1)$$

With:

$\eta = \varepsilon/\varepsilon_{c1}$; $k = 1.05 \cdot E_{cm} \cdot |\varepsilon_{c1}|/f_{cm}$

ε_{c1} is the strain at peak stress ($= 0.7\, f_{cm}^{0.31} < 2.8$)

ε_{cu1} is the nominal ultimate strain

$\varepsilon_{cu1} = 2.8 + 27\, [(98 - f_{cm})/100]^4$ $\quad f_{ck} \geq 50$ N/mm²

$\varepsilon_{cu1} = 3.5$ $\quad f_{ck} < 50$ N/mm²

f_{cm} is the average cylinder compressive strength at age of 28 days [N/mm²]

Samples of TCC and HSSC are tested at an age of 28 days for Young's modulus. Table II summarizes the mechanical properties of both concretes with respect to the Sargin model.

TABLE II. MECHANICAL PROPERTIES AT AMBIENT TEMPERATURE

Concrete	$f_{ccub150}$ [N/mm²]	$f_{ccil106x320}$ [N/mm²]	ε_{c1} [10^{-3}]	$E_{ccil106x320}$ [N/mm²]	k_{sargin} [-]
TCC	59.04	47.96	2.02	36750	1.62
HSSC	74.06	70.83	1.98	45270	1.33

3.2. Modified Sargin model for post-cooling fire conditions

For post-cooling fire conditions, the model of Sargin (section 1) is modified as given in Equation 2, by adopting the parameters $f_{c,T}$, $\varepsilon_{c1,T}$ and k as function of temperature which are tabulated in Table III.

$$\frac{\sigma}{f_{c,T}} = \frac{k \cdot \eta - \eta^2}{1 + (k-2) \cdot \eta} \qquad \text{with} \quad \eta = \varepsilon / \varepsilon_{c1,T} \quad ; \quad \text{for } T \leq 550°\text{C} \qquad (2)$$

TABLE III. PARAMETERS MODIFIED SARGIN MODEL (VALID T $\leq$ 550°C)

Concrete	Test	α [%]	$\varepsilon_{c1,T}/\varepsilon_{c1}$ [-] ; $f_{c,T}/f_c$ [-] ; k [-]
TCC	1	0	$\varepsilon_{c1,T}/\varepsilon_{c1} = 7.195 \cdot 10^{-6} \cdot T^2 - 1.165 \cdot 10^{-3} \cdot T + 1.023$; $f_{c,T}/f_c = 3.230 \cdot 10^{-7} \cdot T^2 - 1.516 \cdot 10^{-3} \cdot T + 1.046$; $k = -7.752 \cdot 10^{-4} \cdot T + 1.455$
		20	$\varepsilon_{c1,T}/\varepsilon_{c1} = 4.205 \cdot 10^{-6} \cdot T^2 - 1.332 \cdot 10^{-3} \cdot T + 1.031$; $f_{c,T}/f_c = 3.174 \cdot 10^{-7} \cdot T^2 - 1.389 \cdot 10^{-3} \cdot T + 1.024$; $k = -6.195 \cdot 10^{-4} \cdot T + 1.430$
		30	$\varepsilon_{c1,T}/\varepsilon_{c1} = 2.990 \cdot 10^{-6} \cdot T^2 - 6.365 \cdot 10^{-4} \cdot T + 9.906 \cdot 10^{-1}$; $f_{c,T}/f_c = 6.998 \cdot 10^{-7} \cdot T^2 - 1.615 \cdot 10^{-3} \cdot T + 1.043$; $k = -7.660 \cdot 10^{-4} \cdot T + 1.482$
	2	20	$\varepsilon_{c1,T}/\varepsilon_{c1} = 5.821 \cdot 10^{-6} \cdot T^2 - 6.041 \cdot 10^{-4} \cdot T + 1.007$; $f_{c,T}/f_c = 2.476 \cdot 10^{-7} \cdot T^2 - 1.447 \cdot 10^{-3} \cdot T + 1.031$; $k = -9.682 \cdot 10^{-4} \cdot T + 1.530$
		30	$\varepsilon_{c1,T}/\varepsilon_{c1} = 5.995 \cdot 10^{-6} \cdot T^2 - 7.201 \cdot 10^{-4} \cdot T + 9.623 \cdot 10^{-1}$; $f_{c,T}/f_c = 3.428 \cdot 10^{-7} \cdot T^2 - 1.535 \cdot 10^{-3} \cdot T + 1.047$; $k = -6.809 \cdot 10^{-4} \cdot T + 1.446$
HSSC	1	0	$\varepsilon_{c1,T}/\varepsilon_{c1} = 8.220 \cdot 10^{-6} \cdot T^2 - 2.170 \cdot 10^{-4} \cdot T + 1.056$; $f_{c,T}/f_c = -2.368 \cdot 10^{-7} \cdot T^2 - 1.341 \cdot 10^{-3} \cdot T + 1.057$; $k = -3.398 \cdot 10^{-4} \cdot T + 1.228$
		20	$\varepsilon_{c1,T}/\varepsilon_{c1} = 4.392 \cdot 10^{-6} \cdot T^2 - 1.421 \cdot 10^{-4} \cdot T + 1.059$; $f_{c,T}/f_c = -6.453 \cdot 10^{-7} \cdot T^2 - 9.850 \cdot 10^{-4} \cdot T + 1.026$; $k = -4.170 \cdot 10^{-4} \cdot T + 1.262$
		30	$\varepsilon_{c1,T}/\varepsilon_{c1} = 4.481 \cdot 10^{-6} \cdot T^2 - 1.391 \cdot 10^{-4} \cdot T + 1.031$; $f_{c,T}/f_c = -4.478 \cdot 10^{-7} \cdot T^2 - 1.105 \cdot 10^{-3} \cdot T + 1.038$; $k = -3.785 \cdot 10^{-4} \cdot T + 1.244$
	2	20	$\varepsilon_{c1,T}/\varepsilon_{c1} = 9.179 \cdot 10^{-6} \cdot T^2 - 4.484 \cdot 10^{-4} \cdot T + 1.076$; $f_{c,T}/f_c = -4.225 \cdot 10^{-8} \cdot T^2 - 1.469 \cdot 10^{-3} \cdot T + 1.053$; $k = -4.426 \cdot 10^{-4} \cdot T + 1.259$
		30	$\varepsilon_{c1,T}/\varepsilon_{c1} = 5.253 \cdot 10^{-6} \cdot T^2 - 8.609 \cdot 10^{-4} \cdot T + 1.005$; $f_{c,T}/f_c = -3.913 \cdot 10^{-7} \cdot T^2 - 1.276 \cdot 10^{-3} \cdot T + 1.043$; $k = -4.421 \cdot 10^{-4} \cdot T + 1.276$

Figure 1 shows the experimental stress-strain test result, as well as the fit of the proposed stress-strain model. Generally, a good agreement is found between the experimental value and the proposed model. For target temperatures of 550°C, a smaller Young's modulus is often found for the experiments with respect to the proposed model. Probably, this should be related to the development of micro-cracking induced by the heating process. For instance: differences in thermal expansion between the aggregates and the cement matrix. Given this observation, although not further examined, it is expected that the proposed model will lose accuracy when adopted for temperatures much higher than 550°C.

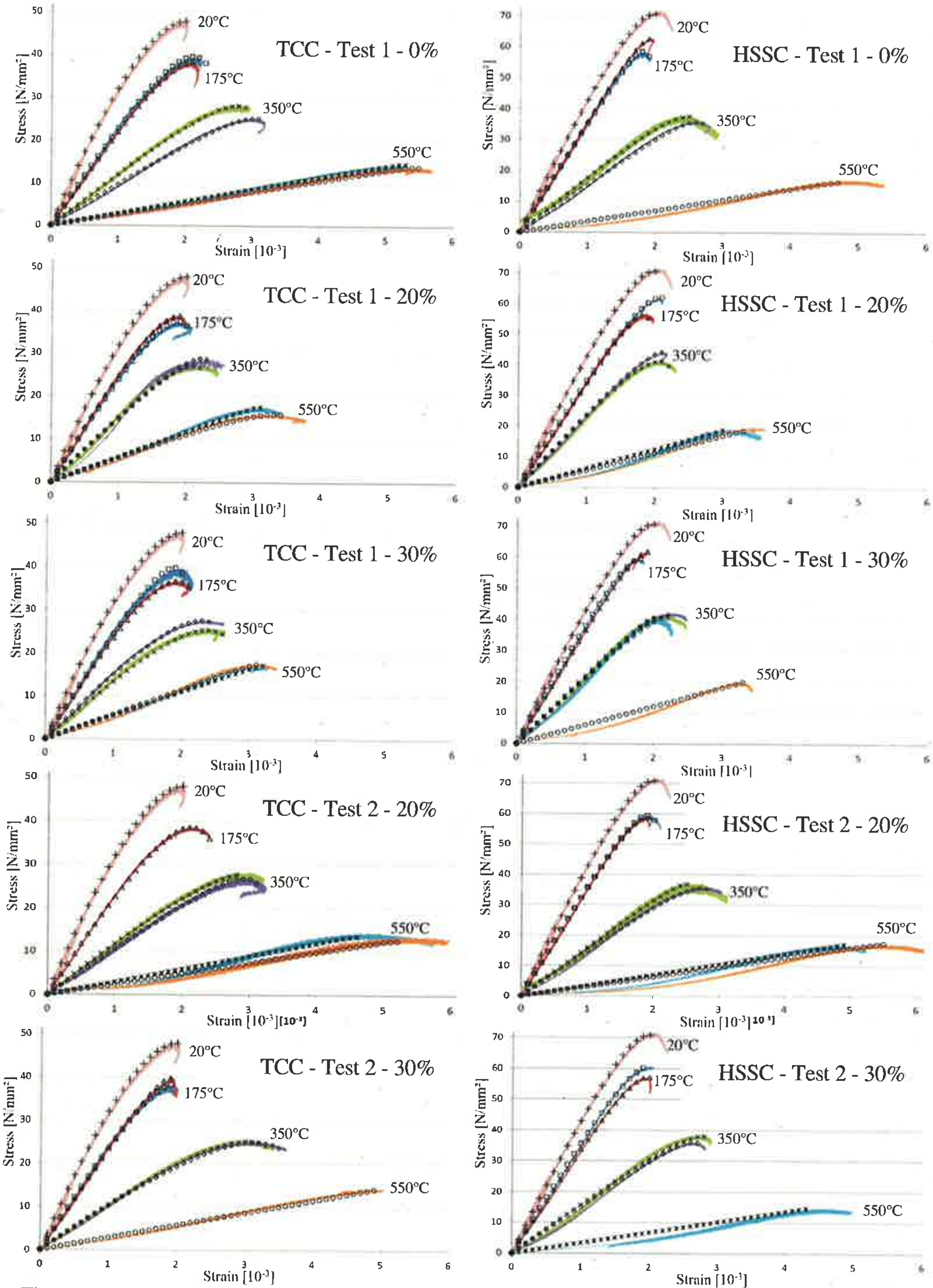

Figure 1. Stress-strain curve for TCC (left column) and HSSC (right column) for temperatures 20°C, 175°C, 350°C and 550°C. Full lines: experimental data; Shape designations: modified Sargin model.

3.3. Analysis of material properties

Figure 2 illustrates the reduction curves of compressive strength and Young's modulus for both concretes, as can be derived from the proposed model. Table IV presents the influence of the type of loading with respect to the values found for 0% loading of Test 1. Positive values indicate that the reduction with temperature is less than this reference.

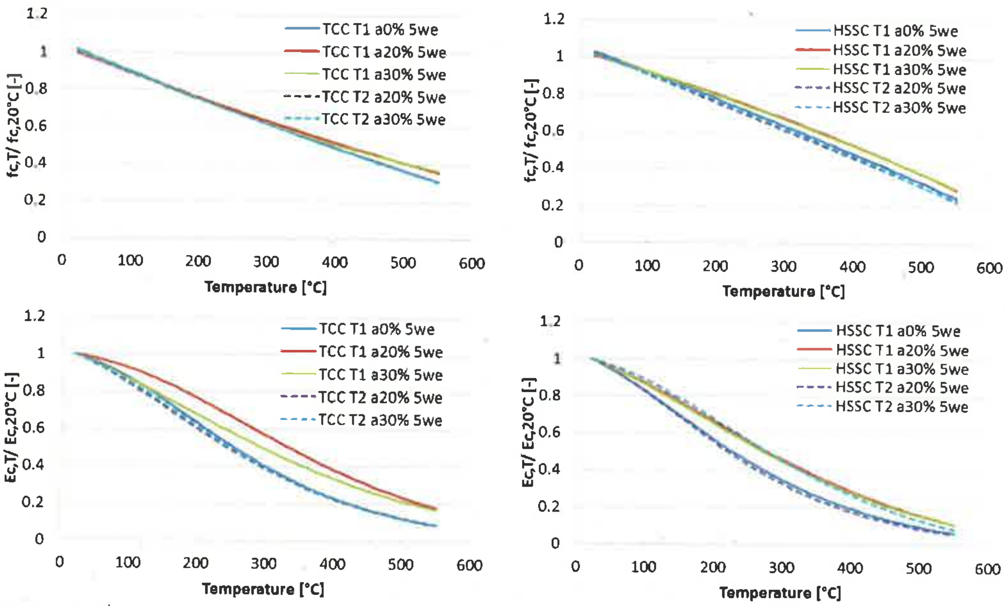

Figure 2. Reduction curves of compressive strength (top row) and Young's modulus (bottom row). Left column: TCC; right column: HSSC.

TABLE IV. INFLUENCE OF LOADING, WITH RESPECT TO 'TEST 1 – 0% load'

concrete	temp. [°C]	$f_{c,T}/f_{c,20°C\_T1/2\text{-}x\%}$ - $f_{c,T}/f_{c,20°C\_T1\text{-}0\%}$ [%] load from start 20%	30%	delayed loading 20%	30%	$E_{c,T}/E_{c,20°C\_T1/2\text{-}x\%}$ - $E_{c,T}/E_{c,20°C\_T1\text{-}0\%}$ [%] load from start 20%	30%	delayed loading 20%	30%
TCC	100	-0.9	-0.9	-0.9	-0.1	5.4	-0.5	-3.0	-1.8
	200	0.3	-0.8	-0.4	-0.2	13.2	4.3	-3.2	-1.7
	300	1.6	0.1	-0.1	-0.3	16.6	8.9	-1.7	-0.6
	400	2.8	1.8	0.1	-0.3	15.0	10.3	-0.6	0.2
	500	4.0	4.2	0.1	-0.4	11.2	9.3	-0.2	0.5
HSSC	100	0.1	0.2	-1.5	-0.9	4.1	3.5	-0.5	6.3
	200	2.4	2.0	-2.2	-0.7	9.5	8.3	-1.6	11.2
	300	3.9	3.3	-2.5	-0.8	11.1	9.9	-2.0	10.7
	400	4.6	4.2	-2.4	-1.3	9.3	8.5	-1.8	7.3
	500	4.5	4.6	-1.9	-2.0	6.2	6.0	-1.2	3.6

Figure 2 shows no large differences between the different test conditions for the reduction of the compressive strength, whereas for the Young's modulus significant differences are notable. Table IV presents an increase of both compressive strength and Young's modulus when load is applied from the start of the heating. On the other hand, delayed loading introduces a (limited) decrease for both properties, with exception of Young's modulus of HSSC 30% load. Observed differences can be explained by the activation of transient strain in case load is applied from the start.

Assuming a spread of 5% as being significant (corresponding to the spread found on compressive strength tests at ambient conditions), Table IV presents only significant differences for the Young's modulus. An increase is found for both TCC and HSSC, which is temperature dependent and has a maximum of respectively 16.6% and 11.1% at 300°C in the case of 20% loading applied from the start. For the 30% load, the increase is smaller.

Table V presents the difference in reduction with temperature of compressive strength and Young's modulus between both concretes. Negative values indicate that the reduction with temperature is larger for HSSC. Regarding the compressive strength, about 300-400°C can be observed as a shift from HSSC having less to more reduction with temperature than TCC. For the Young's modulus, larger differences are found, indicating a steeper reduction of stiffness of HSSC for all test conditions, except delayed loading and 30% load level.

TABLE V. DIFFERENCE OF MATERIAL PROPERTIES BETWEEN HSSC AND TCC

Temp. [°C]	$f_{c,T}/f_{c,20°C\_HSSC} - f_{c,T}/f_{c,20°C\_TCC}$ [%]					$E_{c,T}/E_{c,20°C\_HSSC} - E_{c,T}/E_{c,20°C\_TCC}$ [%]				
	load from start			delayed loading		load from start			delayed loading	
	0%	20%	30%	20%	30%	0%	20%	30%	20%	30%
100	2.3	3.3	3.5	1.7	1.5	-4.5	-5.7	-0.5	-2.0	3.7
200	2.4	4.4	5.1	0.6	1.8	-6.6	-10.3	-2.6	-5.0	6.3
300	1.3	3.7	4.5	-1.1	0.8	-5.4	-10.9	-4.4	-5.8	5.8
400	-0.9	1.0	1.5	-3.3	-1.8	-3.7	-9.4	-5.5	-4.9	3.3
500	-4.1	-3.7	-3.7	-6.1	-5.8	-2.7	-7.7	-6.0	-3.7	0.5

4. 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 under load. No load after cooling.
- A stress-strain model is developed for post-cooling conditions ($T \leq 550°C$).
- With respect to the studied test conditions, heating under load has a positive effect on both post-cooling compressive strength and Young's modulus, although only significant values are found for the latter. On the other hand, a small decrease is found for delayed loading.
- Generally, a faster decrease of Young's modulus is found for HSSC than for TCC. For compressive strength HSSC has less reduction till about 300-400°C.

5. REFERENCES

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