October, the 18th of 1993.

This report describes the work that has been done at the University of Liège with the financial support of the ***National Fund for Scientific Research (Belgium)*** through the grant ***Prix Ferdinand de Waele du F.N.R.S.*** .

I. Thermal elongation of concrete during heating up to 700°C and cooling.

The aim of this work was to measure the thermal elongation of concrete during the heating up to a maximum temperature, as well as the evolution of this elongation during the cooling down to ambient temperature. Those curves of elongation versus temperature were to be established for different maximum temperatures.

The concrete.

Raw materials.

Coarse aggregate	:	Calcareous aggregates, 7-14 mm.
Fine aggregate	:	Sand of the river Rhine.
Cement	:	HK 400.
Water		

Proportions.

The composition aimed at was;

Cement:	350 kg/m³,
Coarse aggregate:	1215 kg/m³
Sand:	675 kg/m³
Water/cement:	0.5

	2415 kg/m³

As the average specific mass calculated from the actual weight and dimensions of 6 samples was 2386 kg/m³,
the actual composition finally was;

Cement :	346 kg/m³,
Coarse aggregate :	1200 kg/m³
Sand :	667 kg/m³
Water/cement :	0.5

Specific mass.

The specific mass was measured on 6 samples.

Sample	Mass (g)	Volume (cm³)	Specific mass (kg/m³)
1H	1238.7	520.67	2379
1B	1245	520.92	2390
4H	1257	520.16	2417
7B	1239	519.12	2387
7H	1234.6	519.88	2375
9H	1237.7	522.26	2370
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	7452 g	3123 cm³	

Mean specific mass = 7452/3.123 = 2386 kg/m³

Resistance.

The resistance of concrete has been measured after 105 days at 20°C, 100% HR on 3 cylindrical samples - height = 100 mm, diameter = 81 mm -.

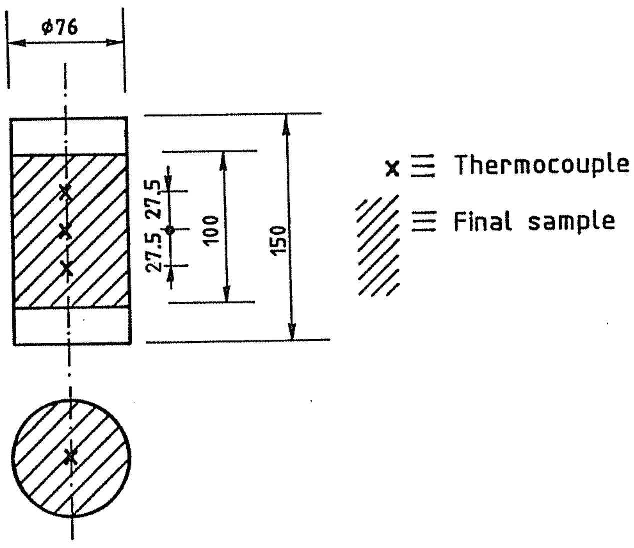
Sample	Resistance (MPa)
1B	54.9
4H	59.0
7B	58.8

Average	57.6 MPa

<u>The samples.</u>

Moulded sample.

One sample (N° 1) has been directly moulded in a PVC cylinder with an internal diameter of 76 mm.
Three thermocouples could be placed on the axis of the concrete cylinder, one at mid level, and two that were 27.5 mm above or bellow the mid level (see Fig. 1).



<u>Figure 1 : moulded sample.</u>

A height of 150 mm was filled with concrete and the whole thing was placed on a vibrating beam for 5 seconds.
The cylinder remained in the laboratory for 2 days under a PVC cover.
The sample was eventually sawed and its faces mechanically adjusted as to have a height of 100 mm.
It was then placed in a room at 20°C at 100% HR.

Drilled samples.

PVC cylinders with a diameter of 125 mm and a height of 300 mm were filled with concrete and placed on a vibrating beam for 5 seconds.
They remained in the laboratory for 2 days under a PVC cover.
Two cylinders with a height of 100 mm were then sawed out of each 300 mm cylinder and one cylinder with a diameter of 81 mm was drilled from each of those cylinders (see Fig. 2).

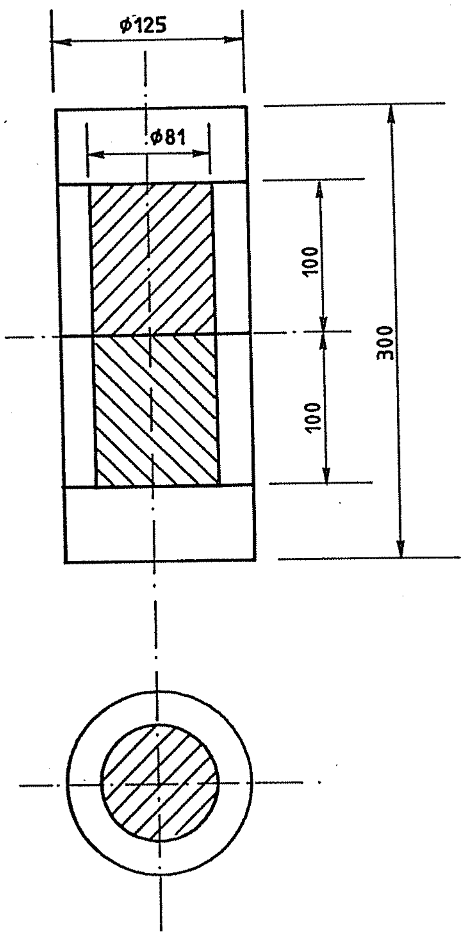


Figure 2 : drilled samples.

The faces were mechanically adjusted and the samples were placed in a room at 20°C and 100% HR.

Maximum aggregate size.

According to § 3.2. of **Schneider 1990**, the maximum aggregate diameter d for concrete samples should be limited to

$$d < \frac{V^{1/3}}{5}$$

i.e. d < 15 mm for the moulded sample,
d < 16 mm for the drilled samples.

This condition is fulfilled for the specimens used in this work.

Equipment.

Furnace.

The furnace - type U.O. 841 -, with its electrical alimentation - type 681a - and temperature regulation system - type TR 596 -,has been made by Amsler A J. & Co., Switzerland.
The electrical furnace is made of two separate parts which are placed side by side. This makes it possible to place the furnace around the testing system when it has been arranged. The heating is provided by three horizontal electrical resistance placed in each half of the furnace. Heat is transmitted to the sample by radiation as well as by convection. Due to the fact that the heating resistance are located only in the longitudinal walls of the furnace it appeared that the specimen removed from the furnace after a preliminary test had not been uniformly heated. The effect of excessive radiation could be observed on two opposite zones on the concrete cylinder. It was therefore decided to place a steel cylinder around the concrete specimen in order to form a screen between the specimen and the radiating resistance. The screen has a high thermal conductivity and its temperature is supposed to be uniform. This screen will therefore heat the specimen in a more uniform manner than previously, which could indeed be observed on the specimens after the tests made with this new arrangement.
The resistance are connected two by two as to form three independent horizontal heating sources, one at mid level, one at a higher level and one at a lower level. Reducing the tension in one or two of the resistance allows to obtain more homogeneous temperature distributions in the furnace, and hence in the sample.
The internal dimensions of the furnace are 280 mm in length, 105 mm in width and 130 mm in height.

Temperatures.

For each test, the temperatures have been measured by three thermocouples Ni-NiCr connected by compensated cables.
For the moulded sample, the temperatures were measured within the concrete cylinder (see Fig. 1) whereas for the drilled samples, the temperatures were measured close to the steel cylinder (at mid level, 30 mm bellow and 30 mm higher than mid level).

Displacements.

Elongation of the concrete cylinders were measured by three mechanical transducers with graduations every 0.001 mm placed outside the furnace.

General layout.

A general layout of the measuring and heating systems can be found on Fig. 3.
a layer of rigid insulating material is placed on the supporting table. A cylindrical hole has been drilled in the this plate.
A small steel cylinder filled with refractory concrete is placed on the supporting table, in the aforementioned hole. Mineral fibres fill the space between the steel cylinder and the furnace.
A disk made of vitro-ceramic material is placed on three points of the steel cylinder. The diameter of this disk is slightly larger than the diameter of the concrete specimen.
The concrete sample is placed on the ceramic disk as well as the steel cylinder, with their axes concurrent.

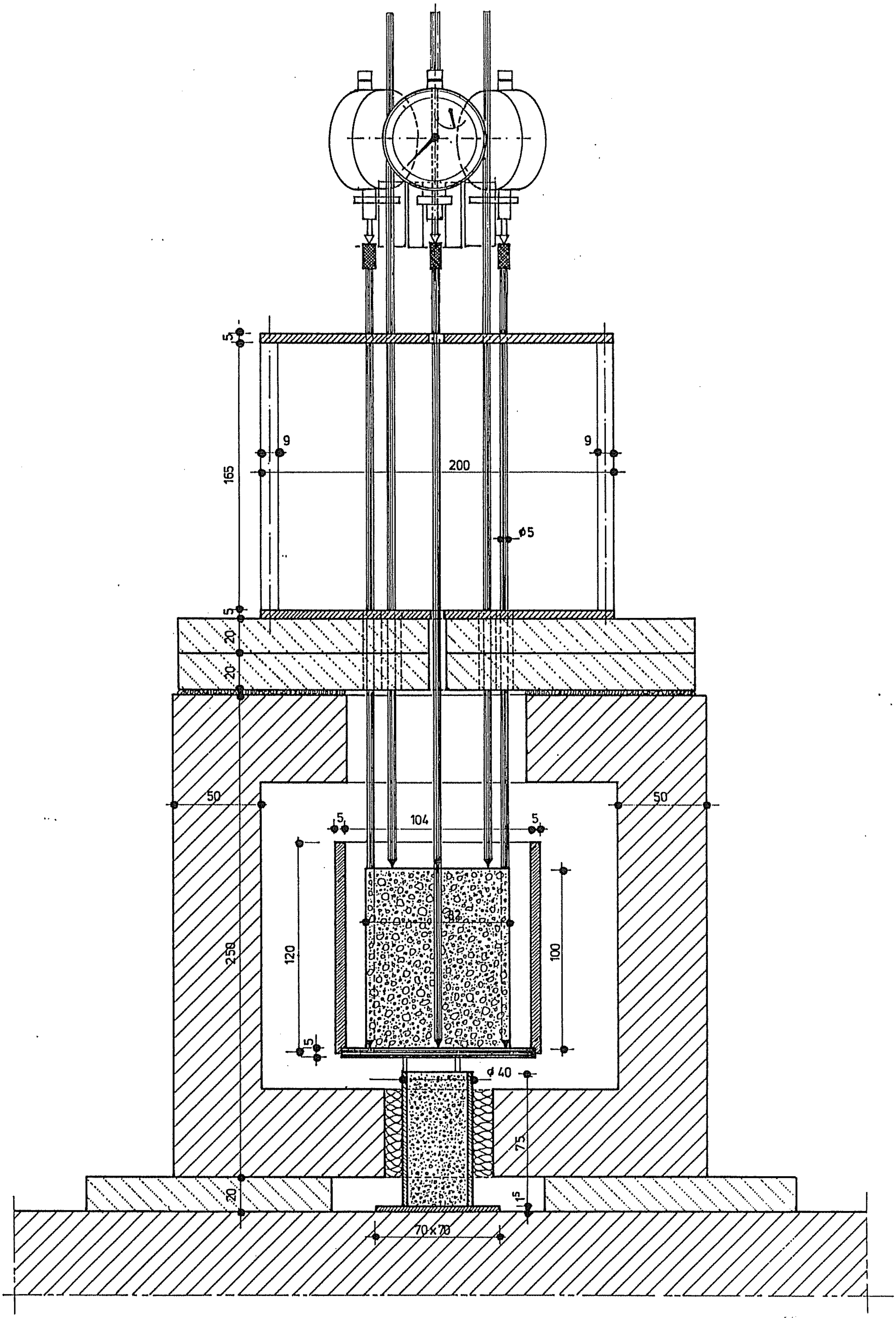


Figure 3 : equipment.

Three exterior quartz rods are placed on the disk, close to the concrete sample. Three interior quartz rods are placed on the top surface of the concrete sample, each of them vis-a-vis with an exterior rod. Those six rods serve as displacement transducers. If the temperature is the same in the rods at each level in the apparatus, the thermal expansion of the exterior rods automatically compensates for the expansion of the internal rods, except for a length equal to the height of the concrete specimen. In this region, the temperature is uniform and the thermal elongation of the exterior rods can be evaluated. It is in fact much smaller than the elongation of the specimen.
The furnace is placed on the insulating plates, with a cylindrical hole in the lower face to receive the steel supporting cylinder, and a cylindrical hole in the upper face to allow the rods to extend outside the furnace.
Two plates of rigid insulating material are placed on the furnace to close the upper hole. Six small holes allow the rods to pass through this plate.
The rods are laterally guided at two points when passing through two thin steel plates
One mechanical transducer is placed on each of the interior rods and measures the relative displacement of the related exterior rod. The system fixing the transducer on the rods is designed as to introduce as few bending moment as possible in the rods.

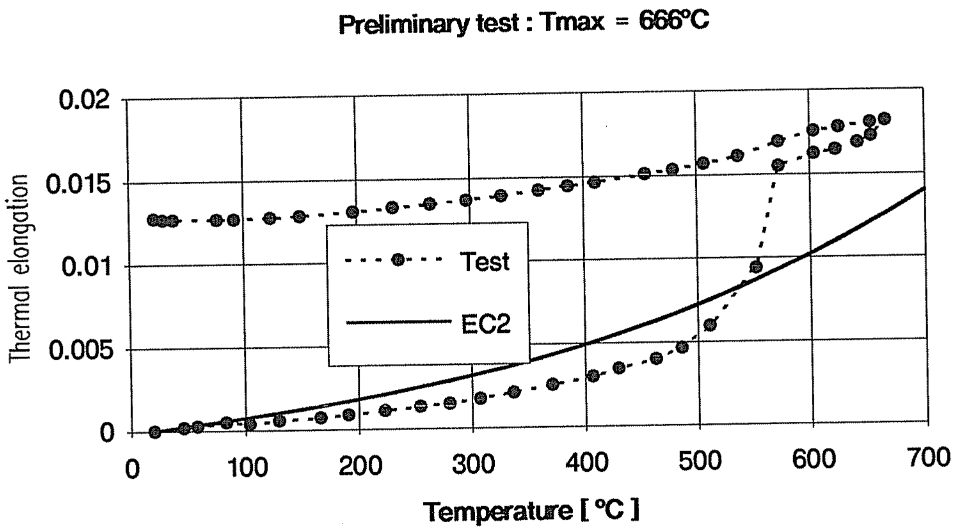
Procedure.

The test procedure is according to **Schneider 1990.**
From 20°C, the electrical power is raised as to reach the temperature of 40°C in the furnace. The preliminary test with moulded thermocouples indicated that this temperature has to be maintained for 90 minutes in the furnace before the temperature is also stabilised at 40°C in the core of the concrete sample. The elongation is measured and the temperature in the furnace is increased by another step of 20°C. This procedure is repeated until the measurement has been made at 100°C. The temperature step is then allowed to be of 30°C which makes it necessary to wait for 120 minutes before the temperature is stabilised in the concrete.
The cooling down is also made by progressive temperature steps and measurements after stabilisation has been obtained.
The exact height of each sample has been measured : H.
The mean value of the measured displacement is calculated : dH = (dH1 + dH2 + dH3)/3.
The thermal elongation is calculated taking into account the elongation of the quartz rods;

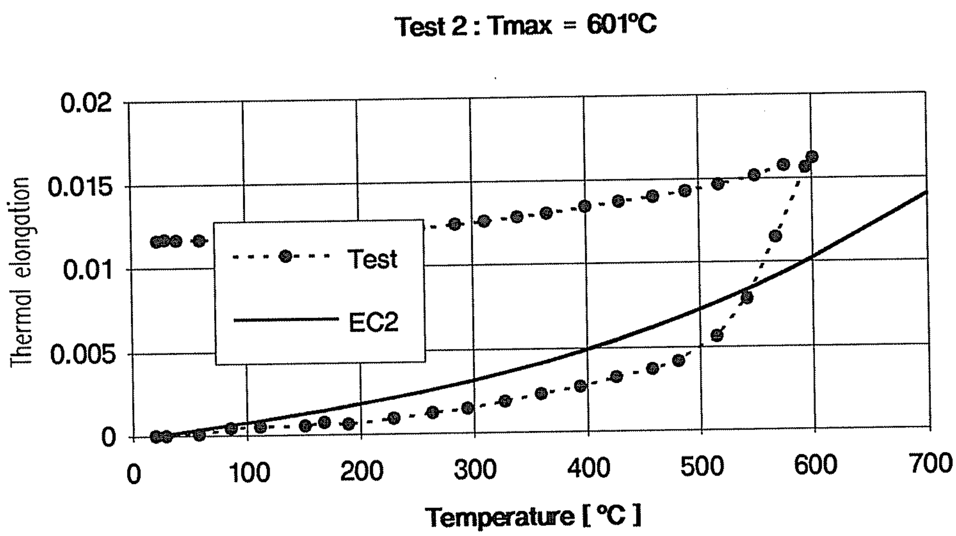
$$e_{test} = [dH + H\ 0.55\ 10^{-6}\ (T - 20)\ ] / H \qquad (1)$$

Results.

The results are graphically presented on Fig. 4 to Fig. 9. On those figures are plotted the experimental thermal elongation according to equation 1, during heating up and cooling down, as well as the thermal expansion of concrete according to the analytical expression proposed for siliceous concrete in annexe 1 of **EC2 part 1-2. 1993.**



<u>Figure 4 : Tmax = 666°C.</u>



<u>Figure 5 : Tmax = 601°C.</u>

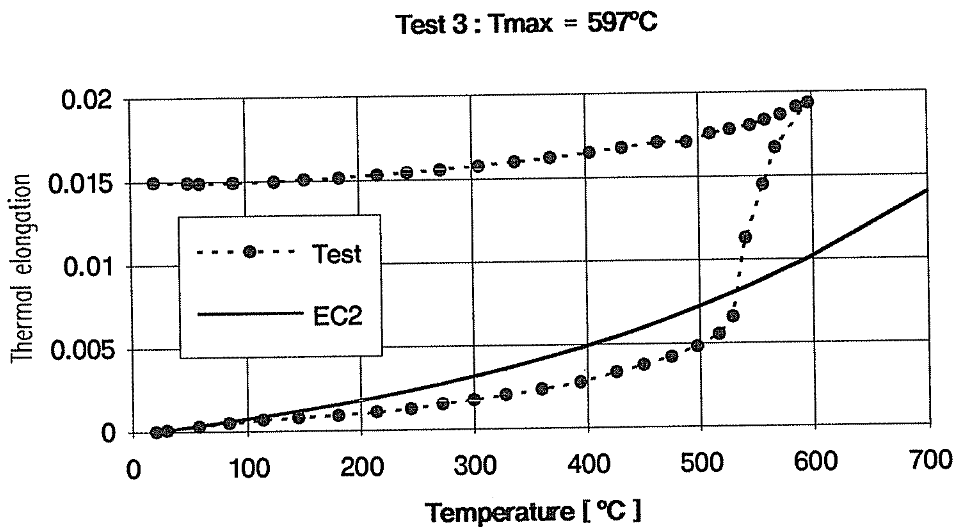


Figure 6 : Tmax = 597°C.

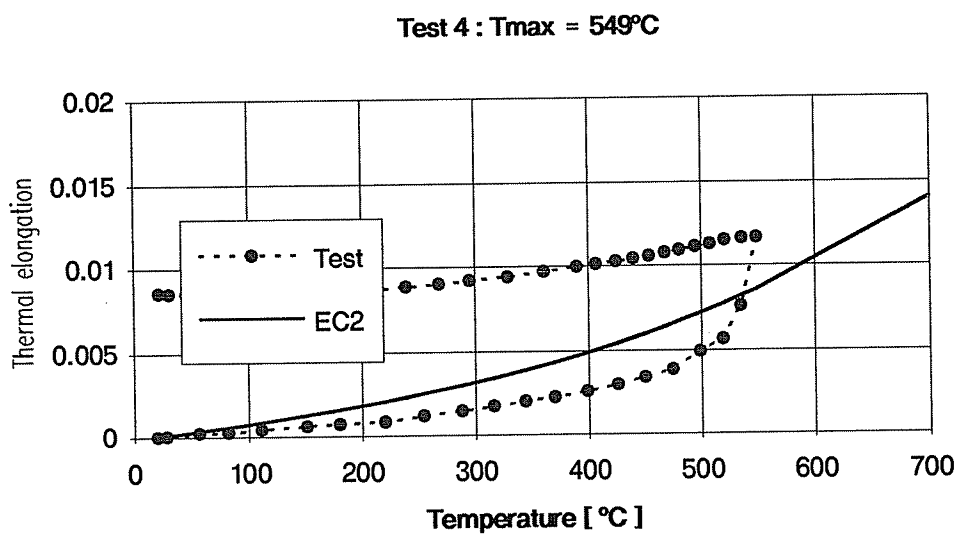
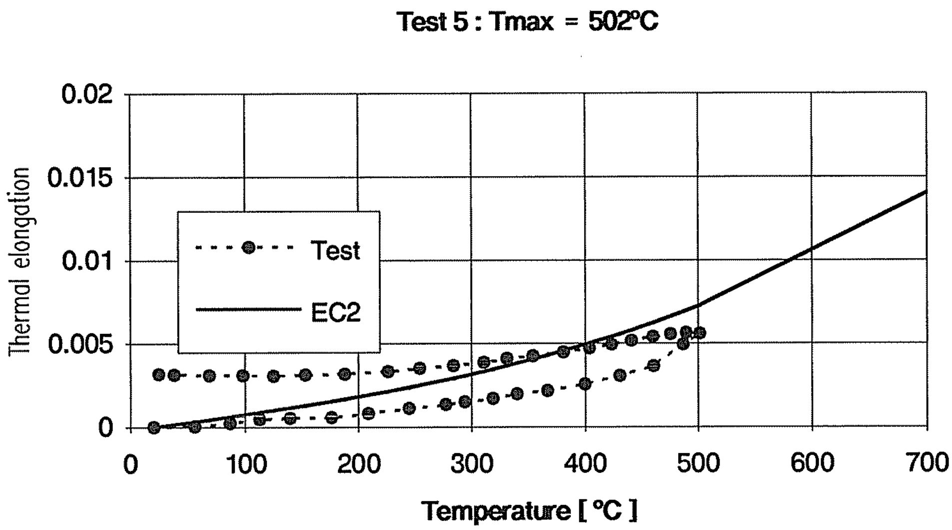
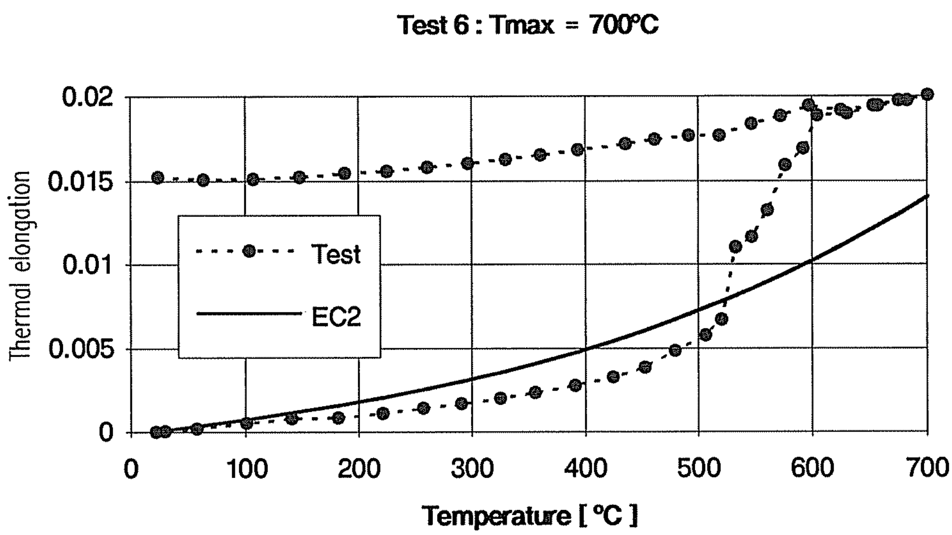


Figure 7 : Tmax = 549°C.



<u>Figure 8 : Tmax = 502°C.</u>



<u>Figure 9 : Tmax = 700°C.</u>

There appears that the tests are reproducible. The important increase of the thermal expansion that is observed between 500 and 600°C is probably due to macro cracking caused by thermal stresses existing in concrete between aggregates and the cement paste. Those macro cracks could indeed be observed on the specimen after the tests. In our tests, the thermal stresses are not hidden by mechanical stresses as would normally be the case in a real structure. Even if low compression stresses are present, they tend to close the thermal cracks in concrete and the observed thermal elongation could be much closer to the analytical expression. One must bear in mind that the duration of each test presented here is several days, which leaves time to the chemical reactions causing thermal stresses to fully develop in concrete. This is not the case in real structures submitted to fire.

The fact that the thermal elongation does not recover when the material cools down is in agreement with what other authors have reported. The above discussion concerning macro cracks put the question on the table whether it is really the thermal expansion of concrete that is not recovered or the opening of the cracks. Our observation of the specimen after the tests clearly indicates that some unclosed cracks remain, which have nothing to do with thermal expansion. Let us assume the following model for unloaded concrete:

$$e_{test} = e_{th} + e_{crack} \quad (2)$$

where e_{test} : experimental value of the elongation,

e_{th} : real thermal expansion,

e_{crack} : elongation due to thermal cracks.

If e_{th} during heating is given by the analytical expression of **EC2 part 1-2. 1993**, then e_{crack} during heating is given by;

$$e_{crack} = e_{test} - e_{th} \quad (3)$$

If there is no recovery of the elongation due to thermal cracks, i.e.

$$e_{crack}(T) = e_{crack}(Tmax) = e_{test}(Tmax) - e_{th}(Tmax) \quad (4)$$

where T : actual temperature of the material,
Tmax : maximum temperature reached by the material,

then the thermal expansion during cooling down is given by

$$e_{th} = e_{test} - (e_{test}(Tmax) - e_{th}(Tmax)) \quad (5)$$

The thermal expansion during the cooling down according to equation 5 has been plotted on Fig. 10 where the curves of the 6 tests are drawn. One hypothesis of the model, i.e. the fact that the thermal expansion during heating follows the analytical expression of **EC2 part 1-2. 1993**, leads to the fact that the curves of thermal expansion during cooling down start on the analytical curve for T = Tmax.

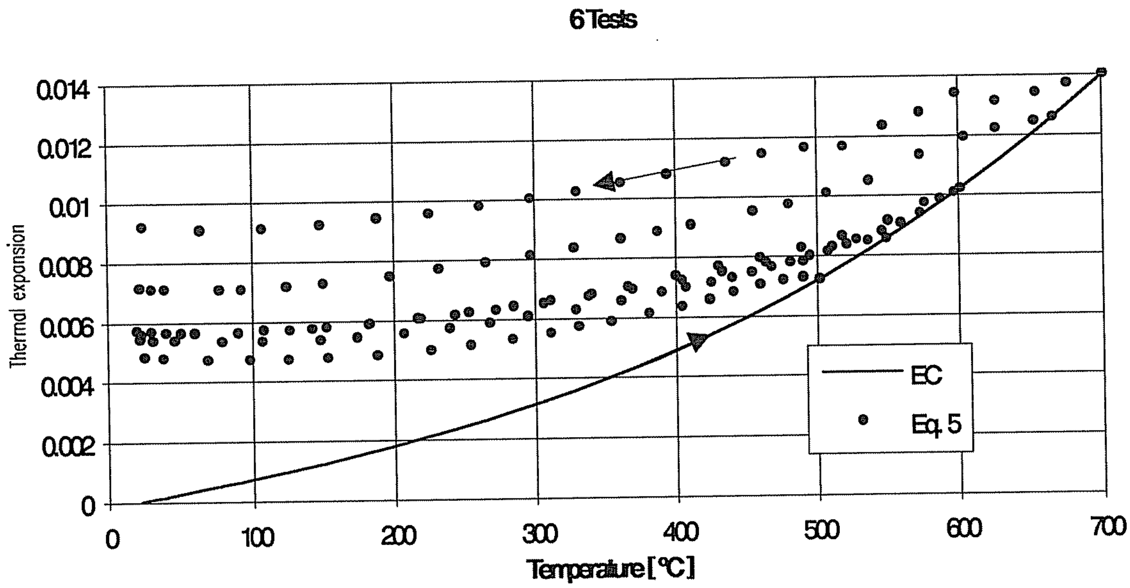


Figure 10 : Thermal expansion during cooling down.

If the above model is accepted, where the difference is made between observed elongation considered as a structural effect and thermal expansion considered as a material property, the results appear as very reproducible.

The material model for concrete during cooling down has been adapted in the code SAFIR according to the results presented in Fig. 10.

II Stress strain relationship of Tempcore steel after heating up to 650°C and cooling.

A research project on the fire behaviour of reinforced concrete columns submitted to fire has been running at the universities of Liège and Ghent with the financial support of the Fund for Joint Basic Research (Belgium). One part of this project consisted in the measurement of the stress strain relationship of Tempcore steel re-bars at ambient temperature, as well as the stress strain relationships at elevated temperatures (steady state tests) and the yield strength at elevated temperatures (transient tests). The system of displacements transducers that has been designed for the tests at elevated temperatures included several steel re-bars of the same diameter as the tested re-bar, but those one being unloaded.
I was decided to test those heated but unloaded bars after cooling down in order to investigate the residual properties of Tempcore steel.

The bars at 20°C.

Two diameters have been used : 12 mm and 25 mm.
The measured yield strength at 20°C are
- 616, 618 and 599 MPa for the 12 mm bars. The mean value is 612 MPa.
- 541, 561 and 562 MPa for the 25 mm bars. The mean value is 562 MPa.

Fig. 11 shows a typical load strain diagram for a 12 mm bar at 20°C

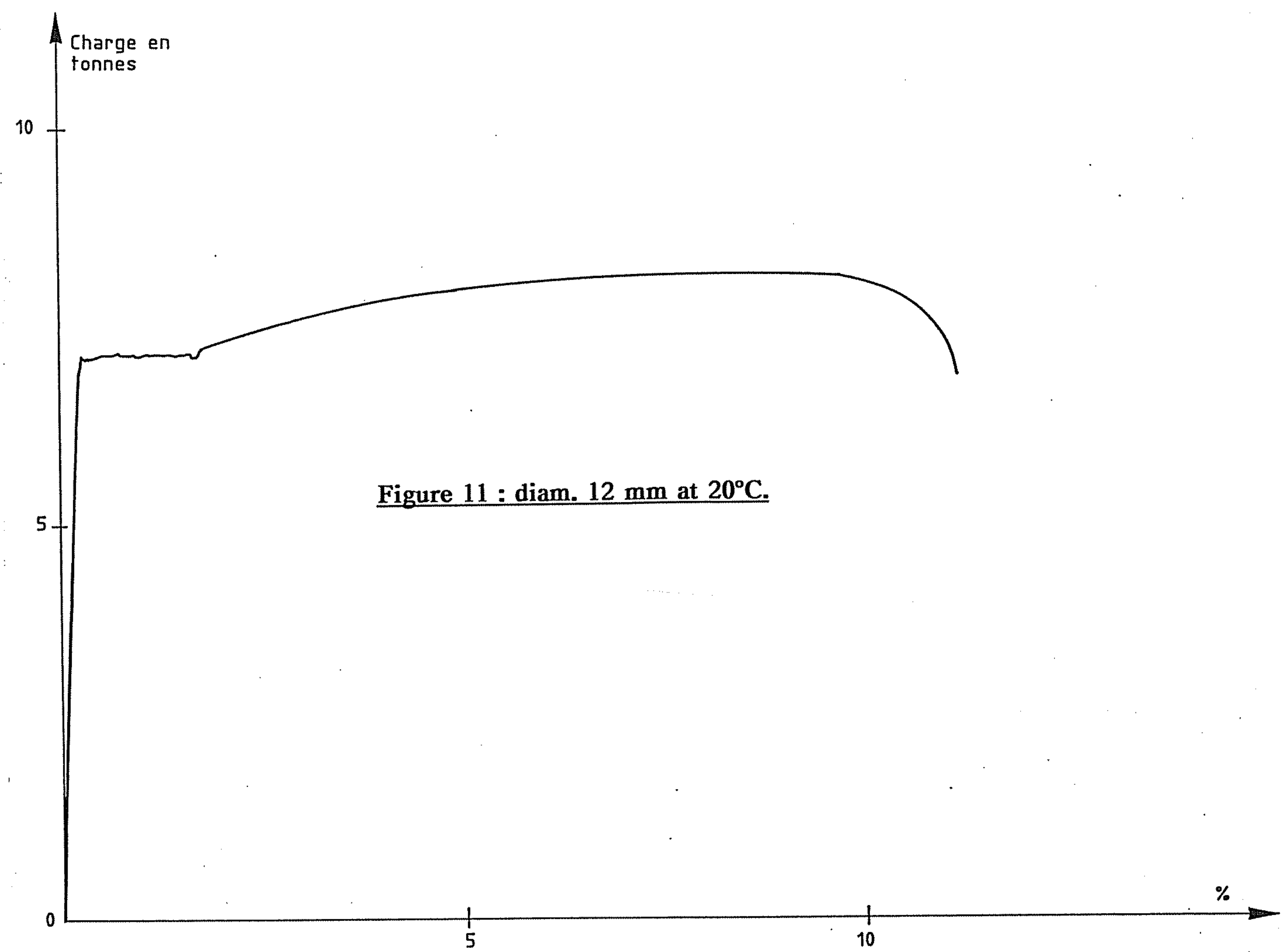


Figure 11 : diam. 12 mm at 20°C.

Fig. 12 shows a typical load strain diagram for a 25 mm bar at 20°C

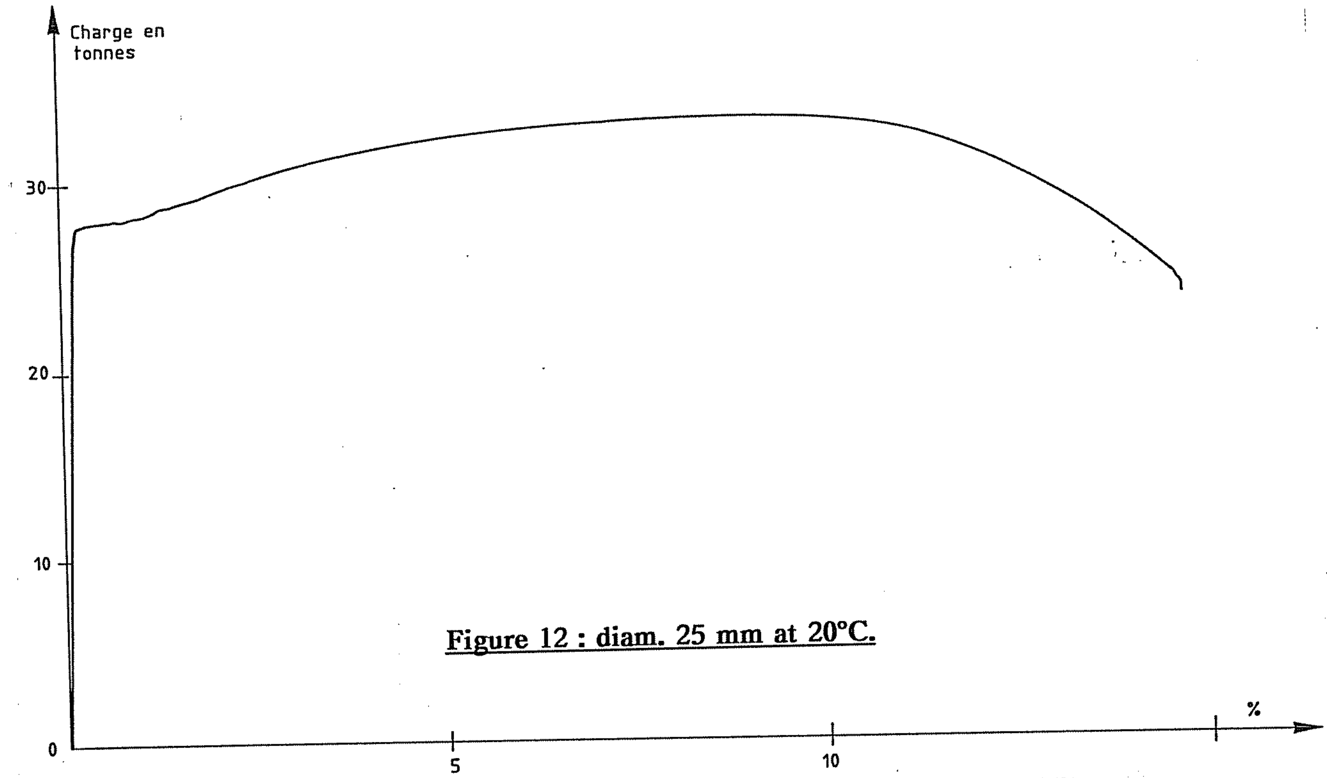


Figure 12 : diam. 25 mm at 20°C.

The bars at elevated temperatures.

Fig. 13 shows a typical stress strain diagram for a 12 mm bar at 570°C, obtained from a steady state test.

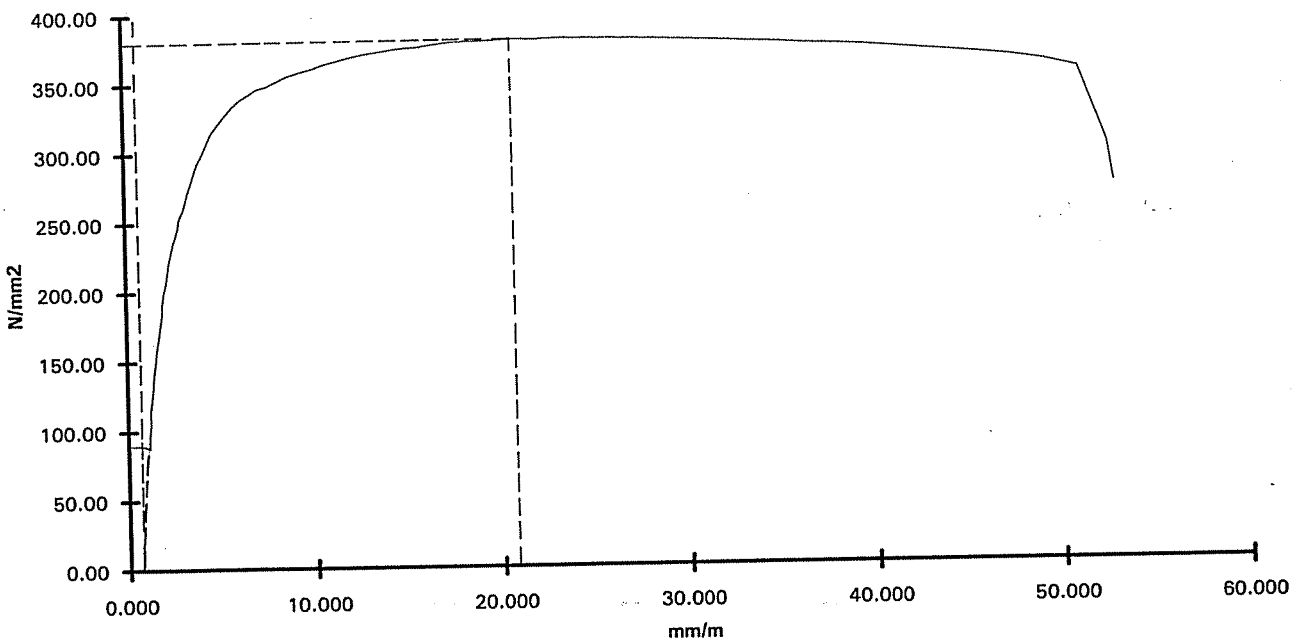


Figure 13 : diam. 12 mm at 570°C

Fig. 14 shows a typical stress strain diagram for a 25 mm bar at 520°C, obtained from a steady state test.

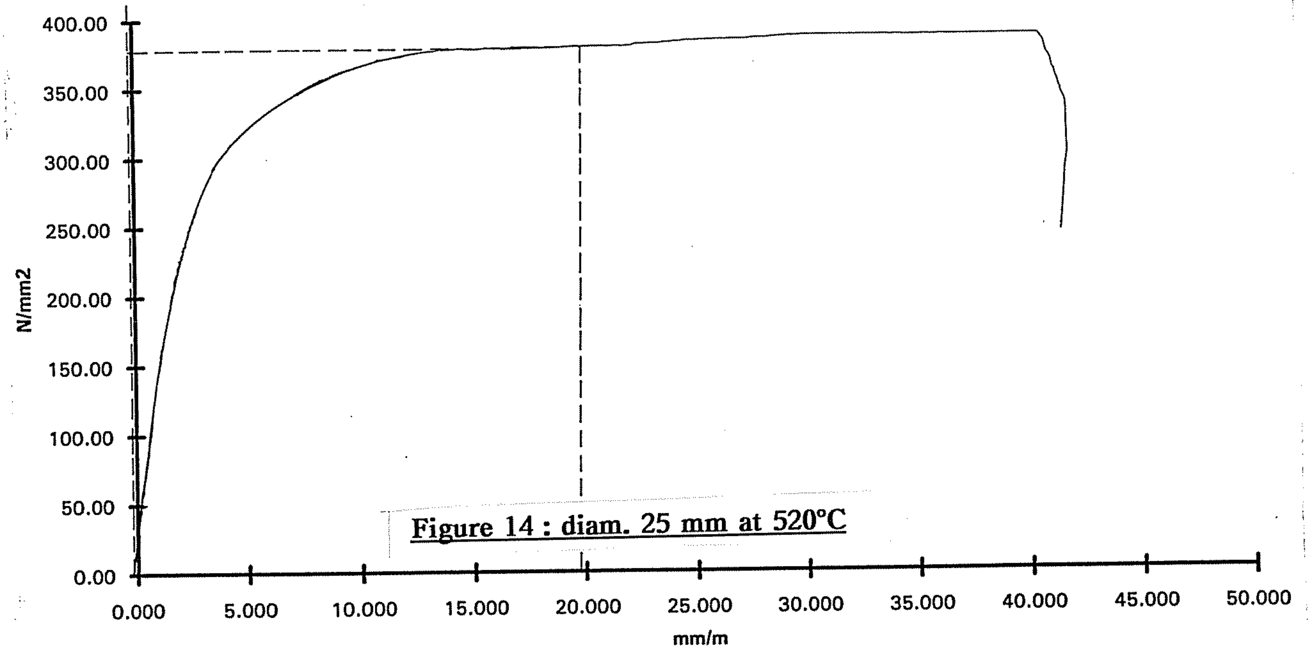


Figure 14 : diam. 25 mm at 520°C

Those figures are from **Dotreppe et al. 1993.**
It appears that the behaviour of steel, which was elasto plastic at ambient temperature, has become highly non linear at elevated temperature. Of course, the yield strength is reduced by elevated temperatures. The question is to know what this diagram becomes after heating and cooling, and what does the yield strength become.

The bars after cooling down.

Fig. 15 shows a typical load strain diagram after cooling for a 12 mm bar that had been heated up to 680°C.

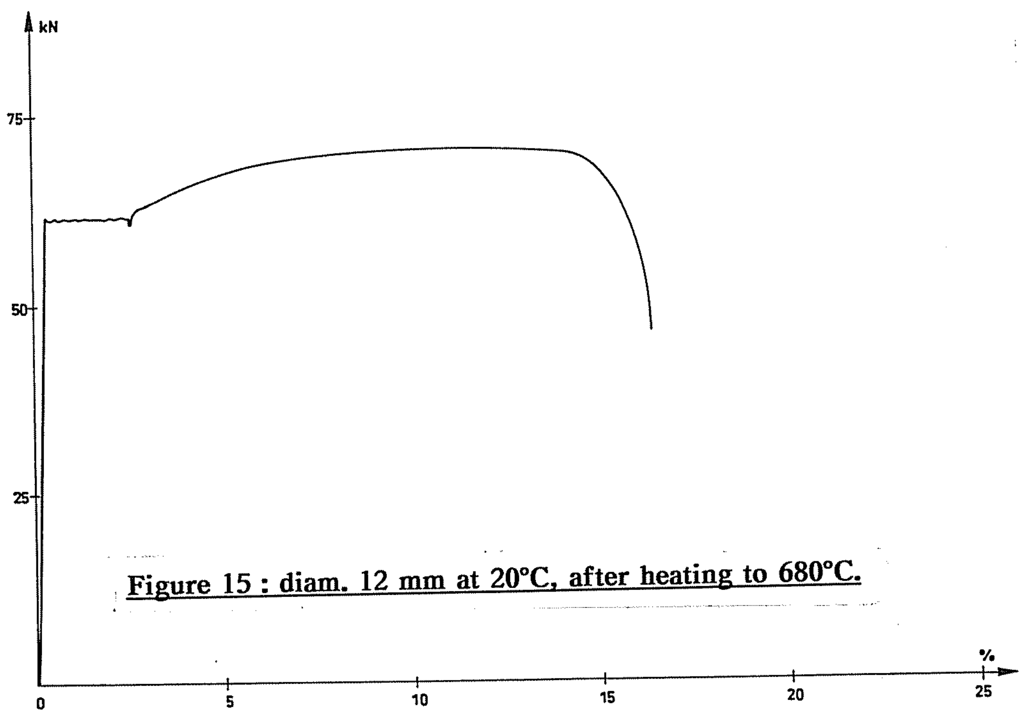


Figure 15 : diam. 12 mm at 20°C, after heating to 680°C.

Fig. 16 shows a typical load strain diagram after cooling for a 25 mm bar that had been heated up to 680°C.

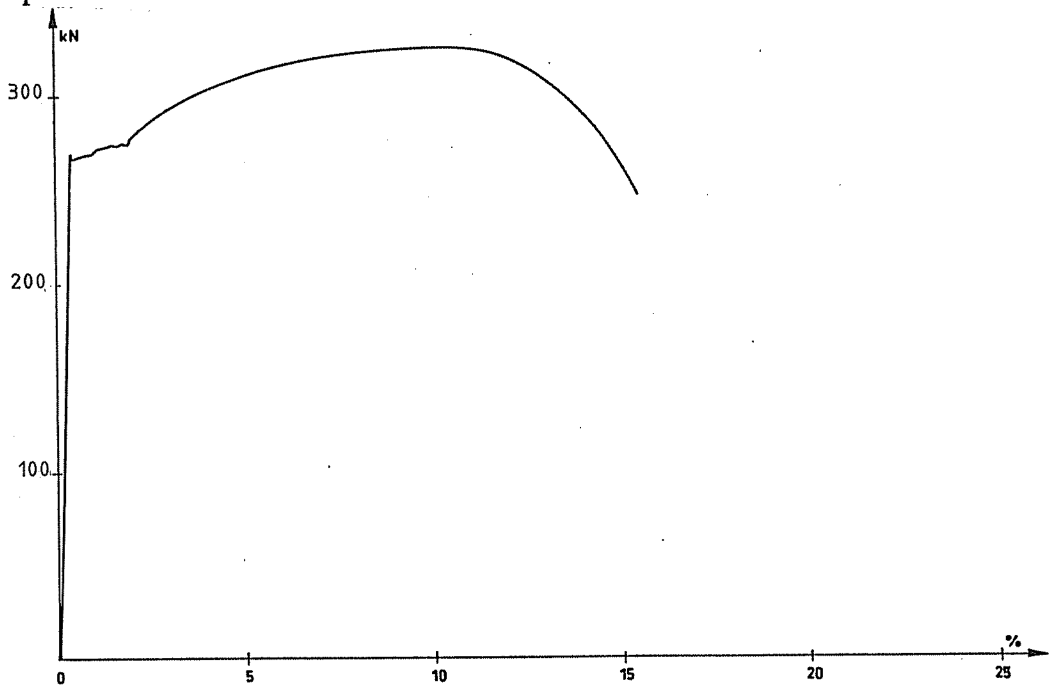


Figure 16 : diam. 25 mm at 20°C, after heating to 680°C.

The shapes of the load - strain diagrams are very similar to the shapes that the re-bars presented prior to heating. As those diagrams (as well as two other diagrams for bars heated up to 680°C and four other ones for bars heated to 650°C) have been obtained for the bars submitted to the highest temperatures, it is likely that the shape of the diagram would remain unchanged also for the bars heated to ltemperatures lower than 650°C. That is why the load - strain diagrams have not been determined for the remaining bars.
For bars heated to lower temperatures, only the residual yield strength has been measured.

In **table I** are presented the results of the tests made on 12 mm bars, in term of yield strength (in MPa) as well as the ratio between the yield strength at T °C and the yield strength at 20 °C.

d = 12mm				
fy(T)/fy(20°C)	Steady	Transient	Residual	Residual
T [°C]				
20	1.00			
475		0.80	1.00	1.04
480	0.70		1.00	1.00
510		0.60	1.03	1.00
570	0.49		0.99	0.99
590		0.40	1.03	1.02
600	0.40		0.98	0.99
650			0.88	0.89
680		0.20	0.93	0.93
fy(T) [MPa]				
20	612			
475		488	613	639
480	429		613	615
510		366	632	610
570	300		604	608
590		244	631	623
600	243		600	605
650			536	542
680		122	570	567

Table I : 12 mm bars.

- The second column presents the yield strength obtained from steady state tests at elevated temperature. T is the temperature of the test.
- The third column presents the yield strength obtained from transient tests at increasing temperatures. T is the temperature when steel reached a mechanical strain rate of 10^{-4}/sec (see **Dotreppe et al. 1993**).
- The fourth and fifth columns present the residual yield strength at 20°C. T is the maximum temperature reached by the bar during the heating.

Fig. 17 graphically presents the evolution of the ratio $f_y(T)/f_y(20°C)$ as a function of T.

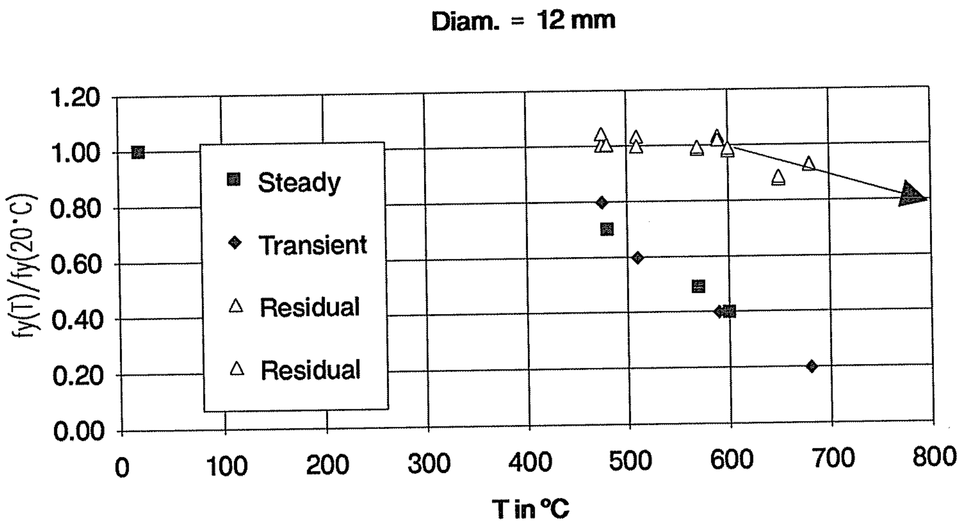


Figure 17 : residual strength.

In **table II** are presented the results of the tests made on 25 mm bars, in term of yield strength (in MPa) as well as the ratio between the yield strength at T °C and the yield strength at 20 °C.

d = 25mm				
fy(T)/fy(20°C	Steady	Transient	Residual	Residual
T [°C]				
20	1			
475	0.57829181		1	1.00711744
520	0.54270463		1.02313167	1.01779359
555		0.58718861	0.99644128	0.99644128
570		0.39145907	0.9519573	0.97153025
580	0.3024911		1.01067616	1.0088968
660		0.19572954	0.96441281	0.92170819
680	0.14412811		0.73843416	1.03024911
fy(T) [MPa]				
20	562			
475	325		562	566
520	305		575	572
555		330	560	560
570		220	535	546
580	170		568	567
660		110	542	518
680	81		415	579

Table II : 25 mm bars.

Fig. 18 graphically presents the evolution of the ratio $f_y(T)/f_y(20°C)$ as a function of T.

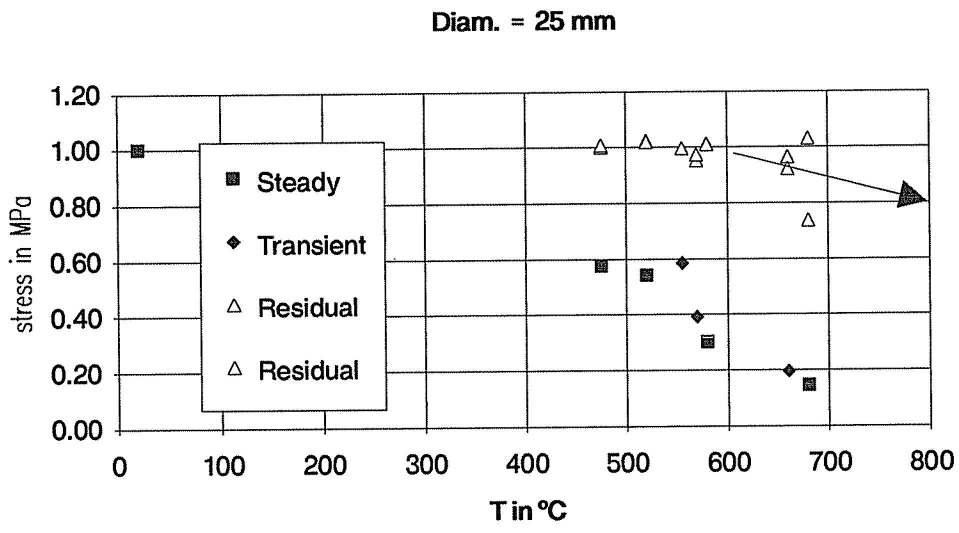


Figure 18 : residual strength

Conclusions.

The stress strain diagram of Tempcore steel is not modified by a heating up to 680°C under a zero stress condition and cooling down to 20°C.
The yield strength is not modified provided that the maximum temperature is limited to 600°C. From 600°C to 680°C, a reduction of 30 MPa/100°C should be considered.

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