AALBORG WHITE®

Concrete Hardening

August 2006

032-1704-121e-06a

COWI

AALBORG WHITE®

Concrete Hardening

COWI A/S

Parallelvej 2
DK-2800 Kongens Lyngby
Denmark

Tel +45 45 97 22 11
Fax +45 45 97 22 12
www.cowi.dk

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1 Introduction

The white concrete is attractive aesthetically. As white concrete also has a higher compressive strength potential than the grey concrete, this adds new perspectives to the use of white concrete.

White cement develops considerately more heat during hydration than traditional grey cement. This could lead to a conclusion that there is a higher risk for cracks developing when white concrete is used compared to when grey concrete is used. Calculations however indicate that this is not the case, maybe on the contrary. The present note describes considerations regarding thermal cracking and presents results from thermal and stress simulations supporting the above statements.

Document no.	P-54631-A-4
Issue no.	0
Date of issue	15-08-2006
Prepared	HEJ
Checked	BBU
Approved	BBU

2 Conclusion

White cement concrete develops more heat during hydration and hence induces higher temperatures differences during hardening than the grey cement concrete.

The investigated white concrete can however endure larger temperature difference than the grey reference concrete.

This means that the risk of cracks forming during hydration is comparable for white and grey concrete, respectively

As demonstrated in this memo using only temperature requirements in planning against cracks forming are misleading for grey as well as for white concrete

The use of white cement concrete would - as is often also the situation for grey concrete - require documentation for the hardening requirements (crack control) depending on the geographical traditions in relation to crack and temperature control.

3 General concrete hardening problems due to hydration heat

During hardening concrete develops heat due to the hydration of the cement.

Under adiabatic and unrestrained conditions the concrete will expand as a result of the heat development. During this condition without interaction to the surrounding environment the concrete is in a state without internal stresses.

In a real construction situation a cast concrete will however loose heat to the surroundings and the cast concrete will often be joined to other previously cast structural elements. Stresses are therefore generated.

3.1 Internal restraint

During hardening the concrete temperature will raise. Loosing heat to the surroundings will result in a temperature difference between the surface (cold) and the core (warm) of the concrete. Due to the coefficient of expansion and the temperature difference, internal stresses will occur. The stresses will develop following the development of the stiffness (E-modulus) of the concrete; the higher stiffness the higher stress. This situation is defined as internal restraint.

A colder surface results in tensile stresses developing in the surface of the section and compression in the core. As long as the tensile stresses in the surface do not exceed the tensile strength of the concrete, no cracking will take place.

When the cast concrete has reached thermal equilibrium with the surrounding environment the stresses will disappear.

If the tensile stresses generated in the surface exceed the tensile strength of the concrete cracks will form. As the core is in compression the cracks will only become surface cracks. When thermal equilibrium is reached the core contracts too and the surface cracks will be closed.

3.2 External restraint

The increase in temperature will cause the entire cast section to expand. If the casting is joined to a previously cast structure, the expansion will be restrained by the joining structure as the joining structure is in or closer to a thermal equilibrium with the surroundings than the newly cast structure. This restraint will cause tensile stresses in the older structure and compressive stresses in the newly cast concrete structure. During expansion the new concrete is "soft" as the E-modulus is not yet fully developed and the compressive stresses will be small.

When the new concrete cools to thermal equilibrium it contracts. The concrete has now become stiffer due to the continuously development of the E-modulus. The tensile stresses developed during contraction are larger than the stresses developed during the expansion. The final state will be tensile stresses in the newly cast concrete and compressive stresses in the joining structure. These stresses are permanent stresses and they reach maximum when the new concrete is in thermal equilibrium with the surroundings.

If the permanent tensile stresses exceed the tensile strength of the concrete then permanent cracks will develop. These cracks will form through the entire cross-section.

3.3 Maximum temperature

Massive bulk structures can experience maximum hardening temperatures exceeding 70 ^{0}C. Hardening temperatures above approx. this level can result in a future risk of delayed ettringite formation. The ettringite formation depends not only on temperature but also on the composition of the cement. Tests can be carried out to document a specific cement behaviour upon hardening at high temperatures.

While the temperature problems in relation to internal and external restraint are relative problems, the maximum temperature reached in a concrete structure depends not only on the heat development, but also the casting concrete temperature and the ambient temperature.

4 The State-of-the-art situation

The problems related to internal restraint, external restraint and maximum temperature are traditionally dealt with by means of average temperature requirements based on experience or finite element computer simulations.

4.1 Temperature requirements

It is common practice that one would expect no problems in relation to internal restraint as long as the difference between the average sectional temperature and the minimum concrete temperature (typically the surface temperature) does not exceed 15 ^{0}C.

For external restraint it is generally recommended (e.g. in Danish Code DS 411) that the temperature difference between the average temperatures of the newly and previous cast structures does not exceed 15 ^{0}C in order not to cause problems.

The two temperature requirements and the maximum temperature can be calculated before casting based on information of the adiabatic heat development of the concrete. Measurements on site are performed to document that the requirements are met. In this situation the stress situation is unknown.

4.2 Stress requirement

Some specifications, typically for larger infrastructure projects, require that the stresses are calculated in order to demonstrate that a planned hardening regime effectively reduces the stresses and hence the risk of cracking to a sufficiently low level.

To be able to calculate the stresses the following concrete parameters as a function of the concrete maturity are required:

- Structural geometry
- Adiabatic heat development
- Tensile strength development
- E-modulus development
- Shrinkage
- Creep

Other input parameters, e.g. poisons ratio are required to perform a realistic calculation, but these can be found in the literature.

Shrinkage is a contraction of the concrete. In relation to internal stresses the structure can not distinguish between thermally induced contraction or shrinkage induced contraction. Furthermore the structure cannot distinguish between autogeneous, chemical and drying shrinkage.

Creep is a time-dependent deformation induced by stresses. Creep reduces the internal stresses and for that reason it is important to include creep to achieve a realistic simulation of the hardening stresses.

4.3 Measures to reduce thermal stresses

There are a number of measures to take into consideration in order to reduce stresses induced by heat development e.g.

- Cooling pipes embedded in the concrete
- Heat wires in the older structure
- Chilled fresh concrete e.g. by Nitrogen or ice
- The choice of formwork e.g. steel vs. wood. Insulation using mats or sheets etc.
- Time between two castings (reduction will reduce temperature difference and hence stresses formed)

By these measures the temperature difference due to heat development can be reduced or theoretically removed.

Assuming that the temperature difference is reduced to zero, shrinkage still introduces stresses. While the temperature difference contributes to the stresses within the first 2-7 day, shrinkage will contribute to the stresses for decades, relieved only by creep.

From a structural point of view there is no difference whether a structure cracks within a week or within a year. A crack is a crack and it is impossible to distinguish between a crack induced by primary heat development or shrinkage. In both cases the crack can have a detrimental effect on the overall durability of the structure.

5 Comparisons between white and grey concretes

Aalborg Portland has conducted various tests on different mixes using low-alkali-sulphate-resistant as well as Aalborg White Portland cement. The test results are presented in [1] and the mix compositions shown in Table 1.

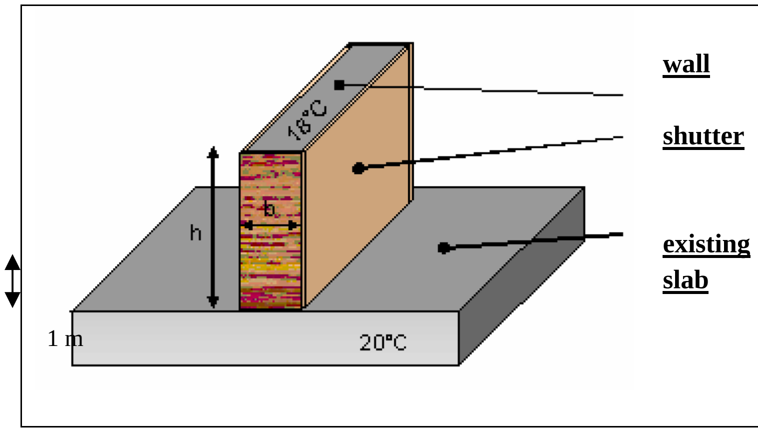
In the following, the results of investigations using a reference grey concrete (Ref. A) compared to a batch using Aalborg White (mix B1) cement has been investigated in relation to temperature development, stress induction and measures to reduce thermal stresses. The Ref. A concrete is a high performance concrete similar to the concrete used on The Great Belt Bridge. The cement used for Ref. A is a low heat cement. The input parameters are reported in [1].

		Ref. A	Mix B1
Aalborg White cement	kg/m^3		371
Low-alkali sulphate cement	kg/m^3	312	
Microsilica	kg/m^3	20	20
Fly ash	kg/m^3	59	-
Zinc Stearate	kg/m^3		
w/p-ratio	-	0.36	

Table 1 Mix-design of the binder phase of the concretes investigated. Further information about aggregate and additives used can be found in [1].

In the calculations below a beam (or wall) cast against an existing slab is considered. Temperature and stresses have been estimated using a finite element (FEM) analysis using the program 4CTemp & Stress [2], ref. Appendix.

In Figure 1 a principal sketch of the structure considered is shown, together with the physical assumptions for the calculations.



Assumptions:
Dimensions on wall:
b = 0.2; 0.4; 0.6 and 1.0 m
h = 3 m
Casting temperature**:** 18°C
Temperature for existing concrete slab: 20°C
Temperature air: 20°C
Shutter **material:** 19 mm plywood with thermal conductivity 20 kJ/m2/h/°C

Figure 1. Principal sketch of the structure used for calculations

The calculations are based on an assumed casting temperature of 18 ^{0}C and environmental temperature of 20 ^{0}C.

The following definitions are used when evaluating the test results:

The utilization ratio in the following is defined as the ratio between tensile stresses and tensile strength. A utilization ratio larger than 1 means that the tensile stress is larger than the tensile strength, and theoretically the concrete will crack.

The utilization ratio combines the influence of shrinkage, heat development, the development of the E-modules and the subsequent stresses and the development of tensile strength into one parameter, which tells whether the concrete cracks or not.

Geometrical restraint ratio is in the following defined as the ratio between the cross section of the new and the old structure.

The white concrete Mix B1 is compared to the reference concrete (Ref.A) at different wall thickness and form stripping time. Hereby the risk of crack induction can be assessed, among other as a result of internal restraint and external restraint. Calculations for different wall thickness and geometrical restraint ratios have been conducted as shown in Table 2. Results are given in Appendix.

The thicker the wall the less heat can leave the structure and as a consequence the temperature rise is larger for thicker walls than for thinner walls. The conclusion of the present investigations is that the thickness of the casting has the same effect for white concretes as for grey concretes. This means that that the white concrete showed no different behaviour than the grey in relation to the utilization ratio.

A wall thickness of 400 mm corresponds to the in practise most common structural size in relation to the behaviour investigated.

Calculation no.	Mix no.	Geometrical restraint ratio [3]	Wall thickness (mm)
a_200	Ref. A	6.67	200
a_400	Ref. A	3.33	400
b1_400	Mix B1	3.33	400
a_600	Ref. A	2.22	600
b1_600	Mix B1	2.22	600
a_1000	Ref. A	1.33	1000
b1_1000	Mix B1	1.33	1000
a_400s	Ref. A	0.4	400
b1_400s	Mix B1	0.4	400
a_400_cooled [1]	Ref. A	3.33	400
b1_400_cooled [1]	Mix B1	3.33	400
a_400_no_heat [2]	Ref. A	3.33	400
b1_400_no_heat [2]	Mix B1	3.33	400

1) Contains 6 nos. of Ø20 mm cooling pipes with 15^{0}C cooling water.
2) No heat development only shrinkage.
3) Ratio between cross section of new and old structure, ref. Figure 1
Table 2. Survey of calculations conducted. Results are given in Appendix

5.1 Internal restraint

Stripping the formwork after 32 hours will cause utilization-ratio of 1.10 for the grey concrete (Ref. A) and 1.05 for the white (Mix B1). In this situation there is no practical difference between the two concretes concerning stresses. The temperature difference between the average and the minimum temperature is 19^{0}C for the grey and 25^{0}C for the white. It is noted that both the temperature difference and the utilization ratio indicate that there is a risk that cracks may develop in both the grey and the white mix.

Stripping the formwork after 72 hours will cause a temperature difference of 15^{0}C for both concretes as common practice would allow as maximum temperature difference. At that stripping time the utilization ratio is 0.5 and 0.4 for the grey and the white concrete, respectively, hence no risk of cracks forming.

The above findings are presented in Figure 2. Figure 2 indicates that the maximum temperature difference resulting in internal restraint cracking (utilization ratio exceeding 1) is 18^{0}C for the grey concrete (Ref. A) and 24^{0}C for the white (Mix B1).

The internal restraint for concrete mixes using white cement is not higher than for traditional grey concretes. The amount of internal restraint has to be investigated each time for both grey and white concretes if a realistic evaluation of crack formation is required.

The investigated white concrete can endure larger temperature difference than the grey reference concrete.

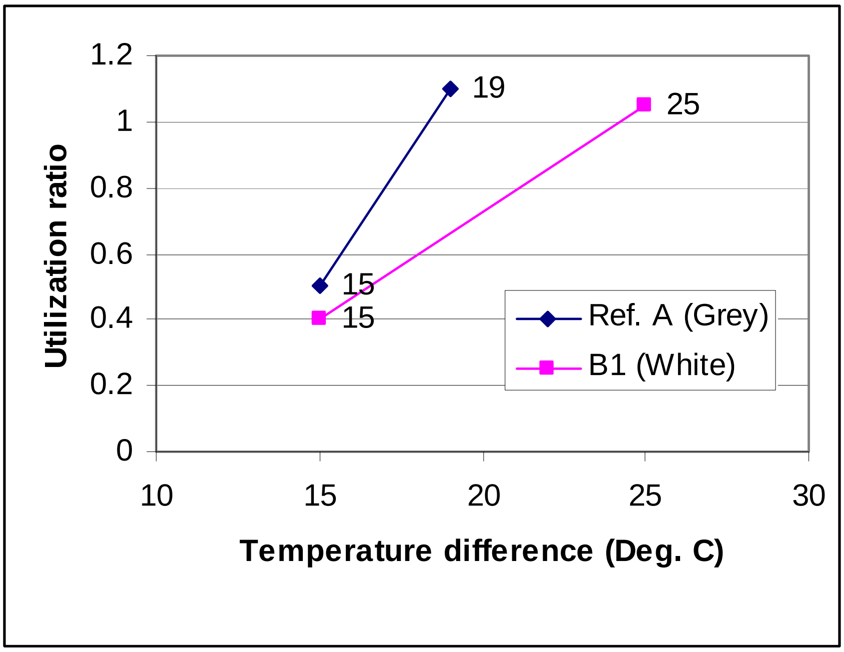


Figure 2 Utilization ratio vs. temperature difference for concretes based on grey and white cement, respectively.

5.2 External restraint

Comparing Ref. A concrete and Mix B1 concrete for different wall thicknesses in relation to external restraint it is found that the external restraint results in approximately the same utilization ratio for both the white (Mix B1) and the grey concrete. However the white concrete develops a maximum utilization ratio faster than the grey concrete, but 28 days after casting the ratio is approximately the same. This is illustrated in Figure 3.

In the case where the maximum utilization ratio is 1.7, the white concrete exceeds a utilization ratio of 1.0 (crack criterion) after 50 hours while the grey concrete exceeds the utilization ratio of 1.0 after 139 hours. The maximum temperature difference is 22^0C for the grey and 34^0C for the white concrete. This situation is related to a geometrical restraint ratio (the ratio between the cross section of the new and the old structure) of 3.3. Reducing the geometrical restraint ratio to 0.4 will result in a reduced utilization ratio from 1.7 to 0.7. The maximum temperature difference for the white and grey concretes, respectively remains the same.

Despite the significantly higher temperature of the white concrete there is no impact on the utilization ratio (stress/strength ratio), compared to that developed in the grey concrete. In other words that there is not a higher risk of cracks forming for the white concrete than the grey concrete despite the higher temperature.

The stress/strength development is illustrated in figure 3. The abbreviations are:

- a_400: Ref. A (grey) concrete. Wall thickness 400 mm and geometrical restraint ratio 3.33
- b1_400: White concrete, Mix B1. Wall thickness 400 mm and geometrical restraint ratio 3.33
- a_400_s: Ref. A (grey) concrete. Wall thickness 400 mm and geometrical restraint ratio 0.4
- b1_400_s: White concrete, Mix B1. Wall thickness 400 mm and geometrical restraint ratio 0.4

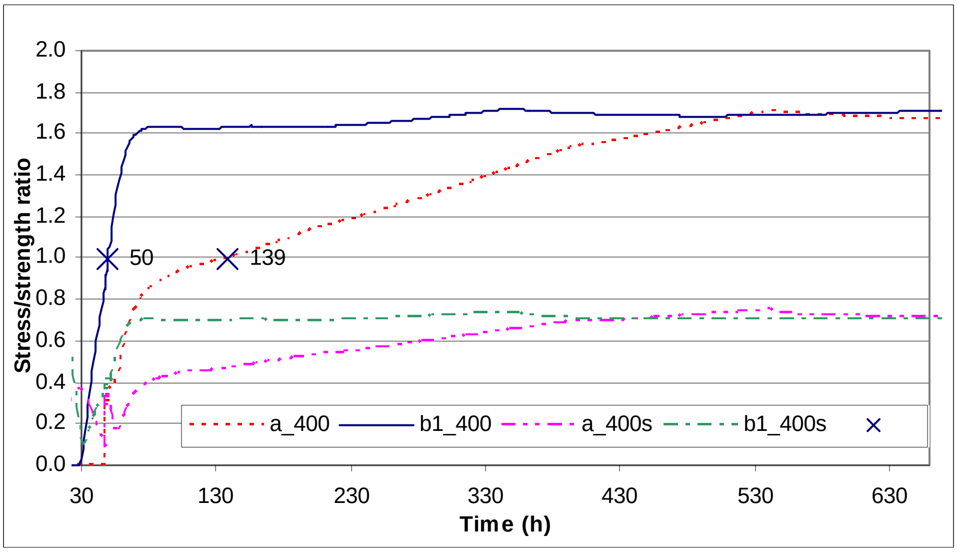


Figure 3. Stress/strength ratio vs. time of grey and white cement concrete walls, thickness 400 mm, at geometrical restraint ratios 0.4 and 3.33 respectively.

The external restraint for concrete mixes using white cement is not higher than for traditional grey concretes. The amount of external restraint has to be investigated each time for both grey and white concretes if a realistic evaluation is required.

The investigated white concrete can endure larger temperature difference than the grey reference concrete.

5.3 Maximum temperature

Under adiabatic conditions the grey concrete will reach a maximum temperature of 68^{0}C while the white (Mix B1) concrete will reach 78^{0}C, when the casting temperature is 18^{0}C. Adiabatic conditions are only prevailing in bulk massive concrete structures.

Casting at 18^{0}C and for ambient temperatures of 20^{0}C the grey concrete will reach a maximum temperature of 56^{0}C while the white will reach 70^{0}C for a wall thickness of 1000 mm.

5.4 The influence of shrinkage

In figure 4 and 5 the effect from shrinkage and temperature is separated. A shrinkage utilization ratio on 1.4 for the Ref. A concrete and 1.2 for the Mix B1 concrete is the effect when assuming that no heat develops and only shrinkage prevails. The influence of cooling with the same amount of cooling pipes and with the same cooling water temperature shows that the utilization can be reduced from 1.7 to 1.5 for the grey Ref. A concrete, and from 1.7 to 1.4 for the white Mix B1 concrete.

In this particular situation it is demonstrated that even cooling to zero temperature difference would have no effect as cracking would still appear due to shrinkage.

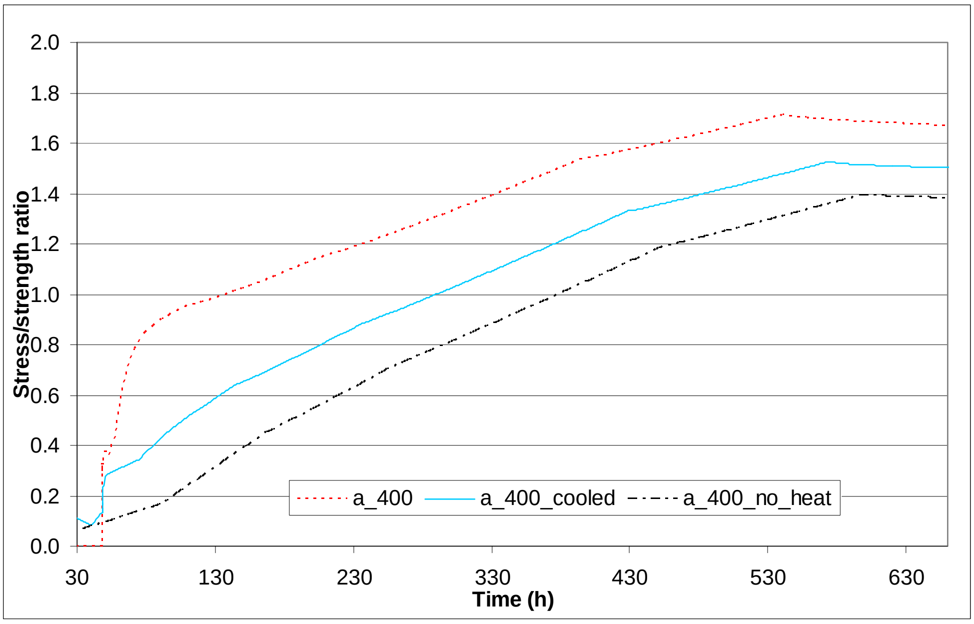


Figure.4: Utilization of Ref. A concrete for uncooled, cooled and theoretically cooled to zero temperature difference, i.e. only influenced by concrete shrinkage.

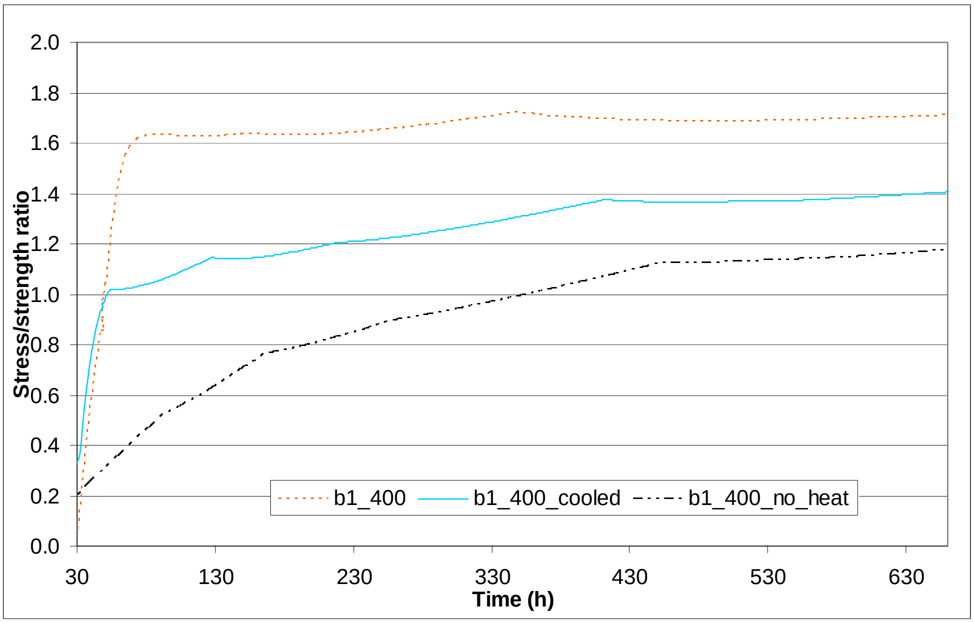


Figure 5 Utilization of mix b1 concrete for uncooled, cooled and theoretically cooled to zero difference, i.e. only influenced by shrinkage.

6 References

[1] . "White Concrete for Aggressive Environment" Aalborg White®; Aalborg Portland; September 2003

[2] 4CTemp&Stress

7 Appendix

Selected calculation results

COWI A/S CONSULTING ENGINEERS		4C-Temp & Stress Calculation Results	
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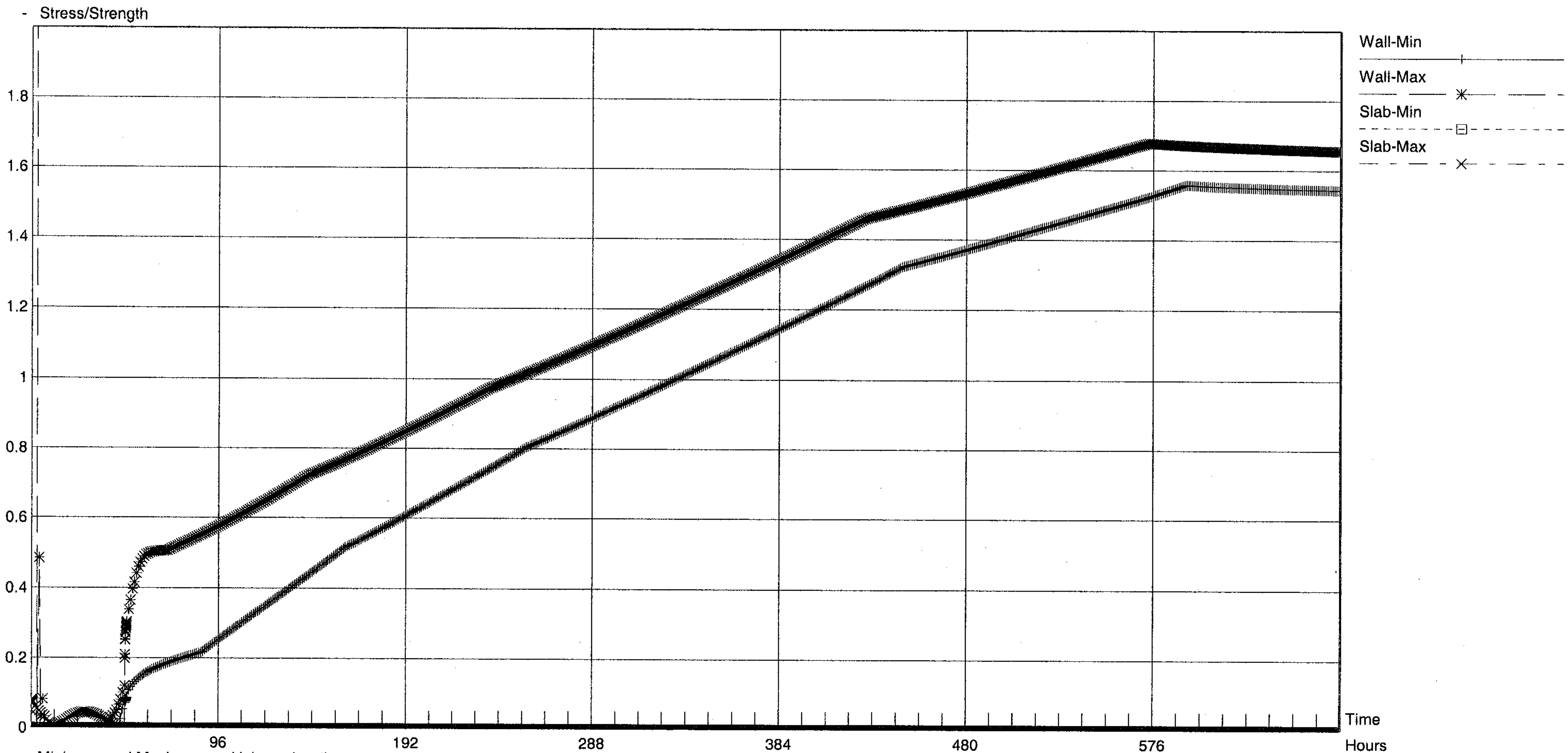

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Results

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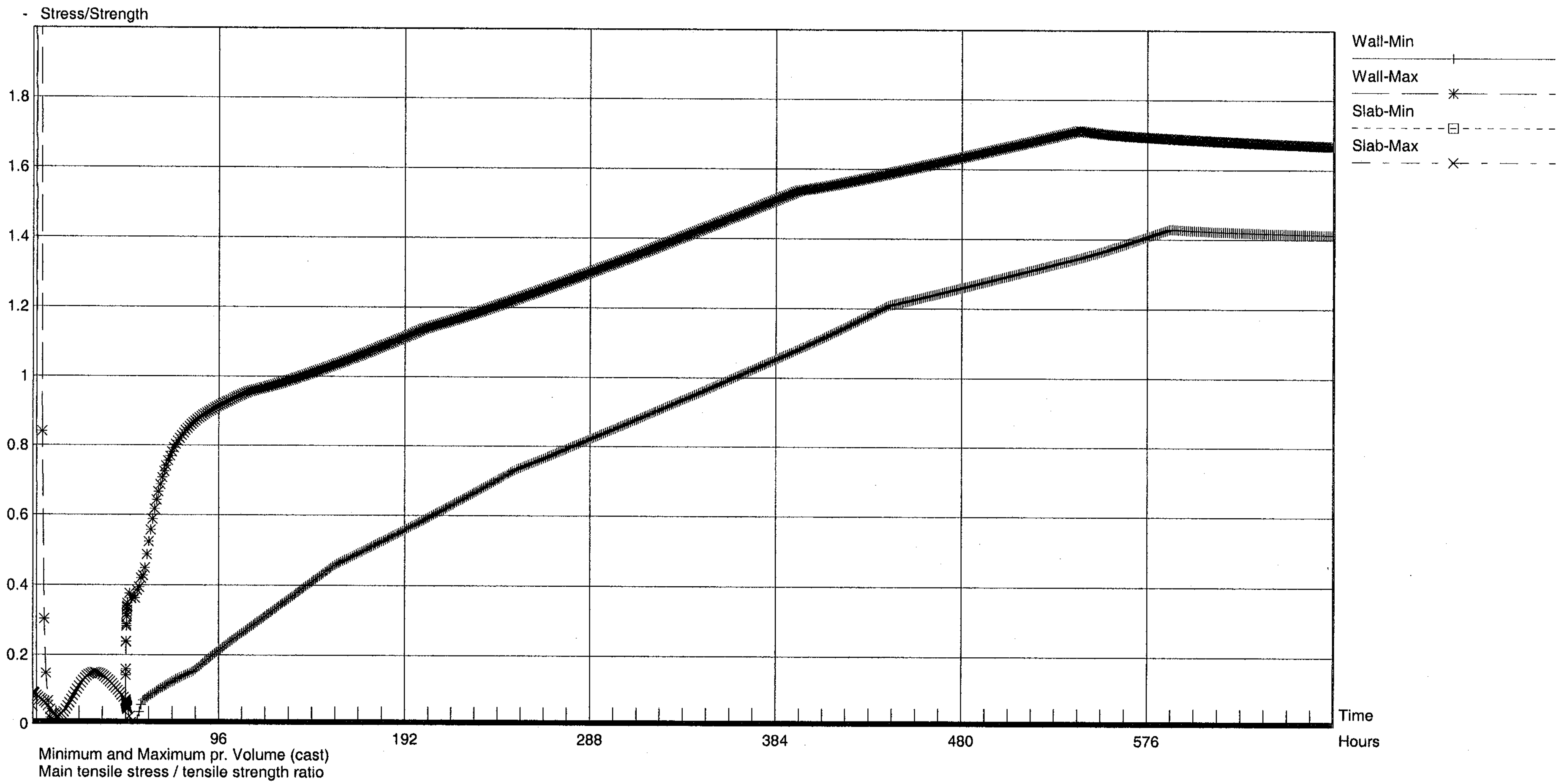

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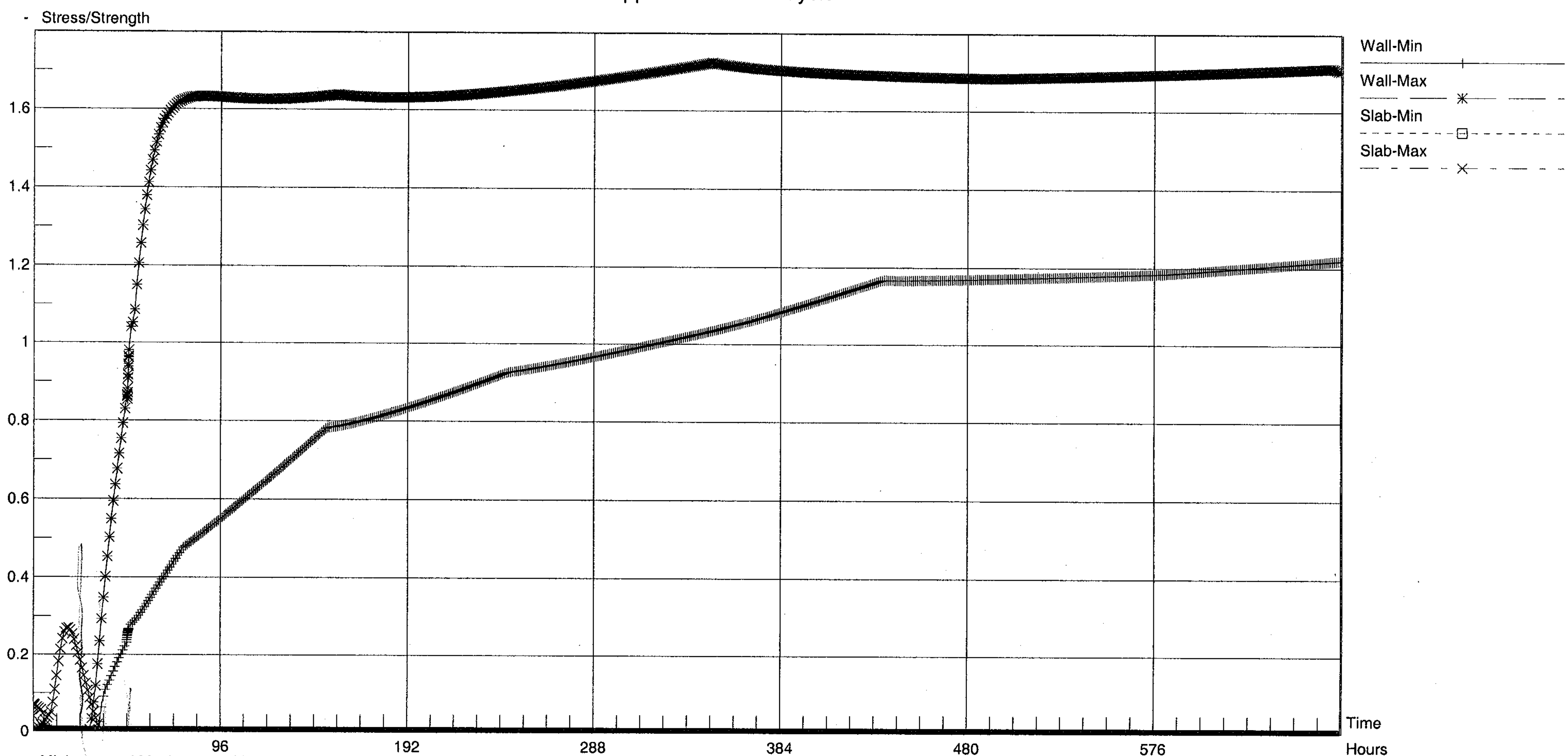

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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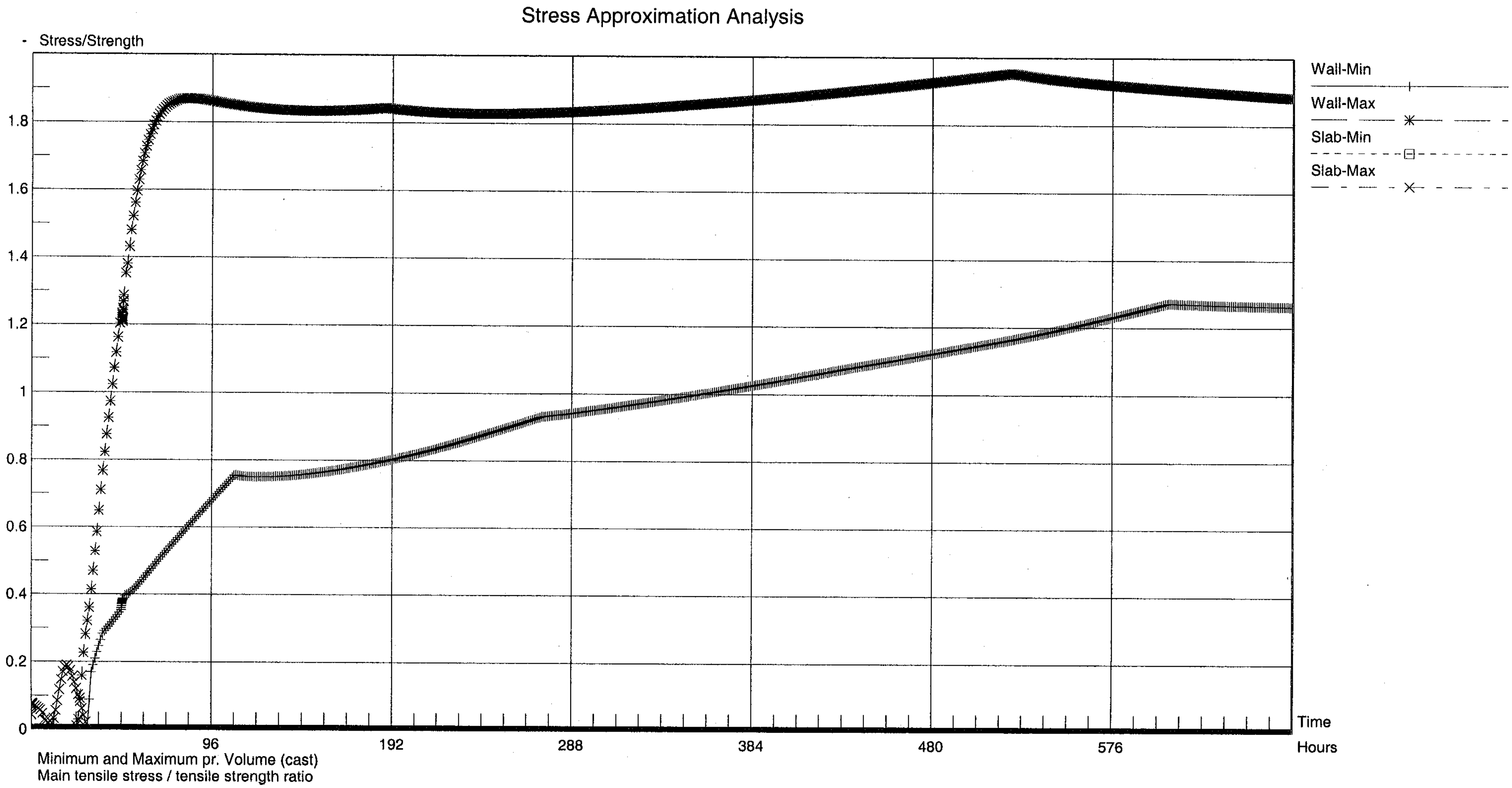

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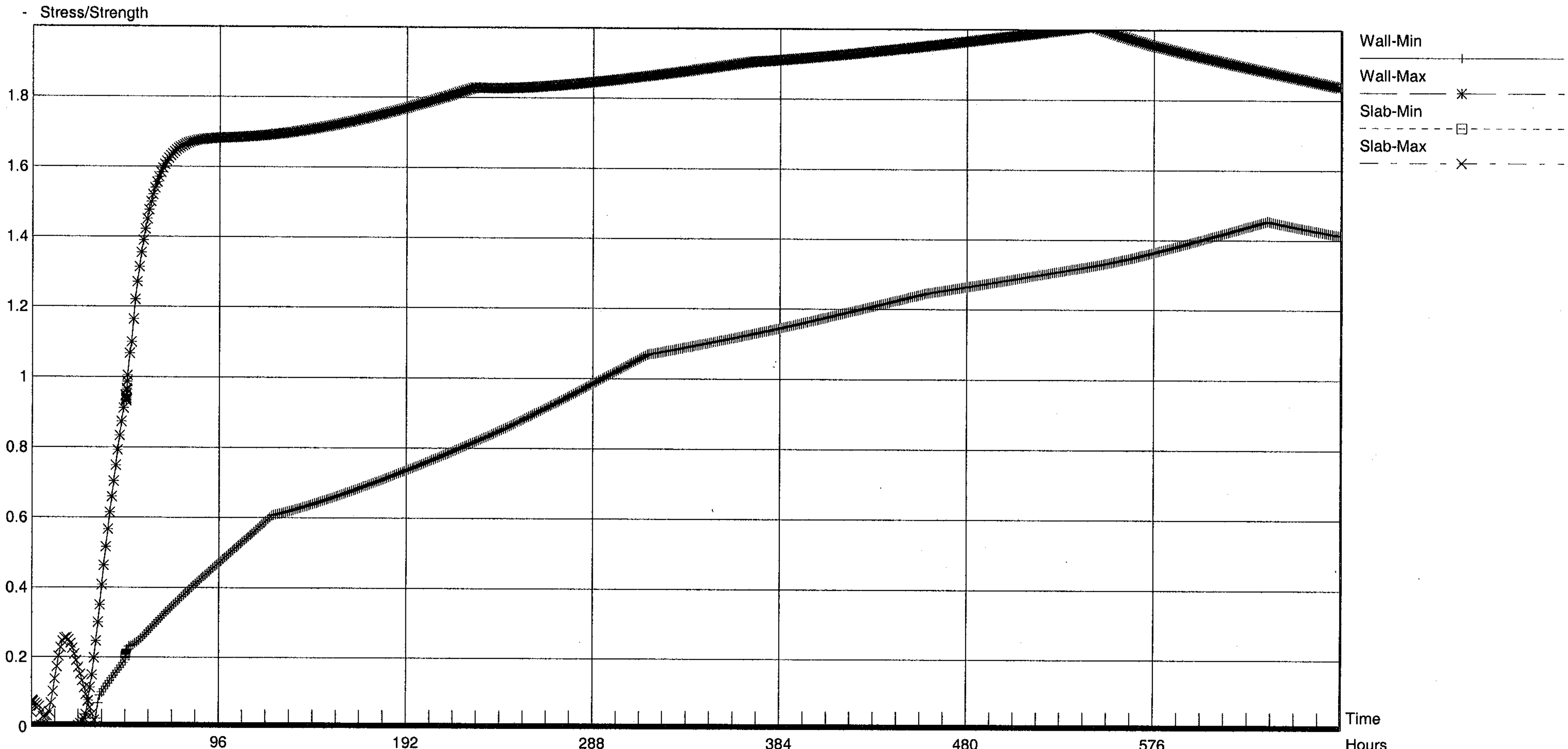

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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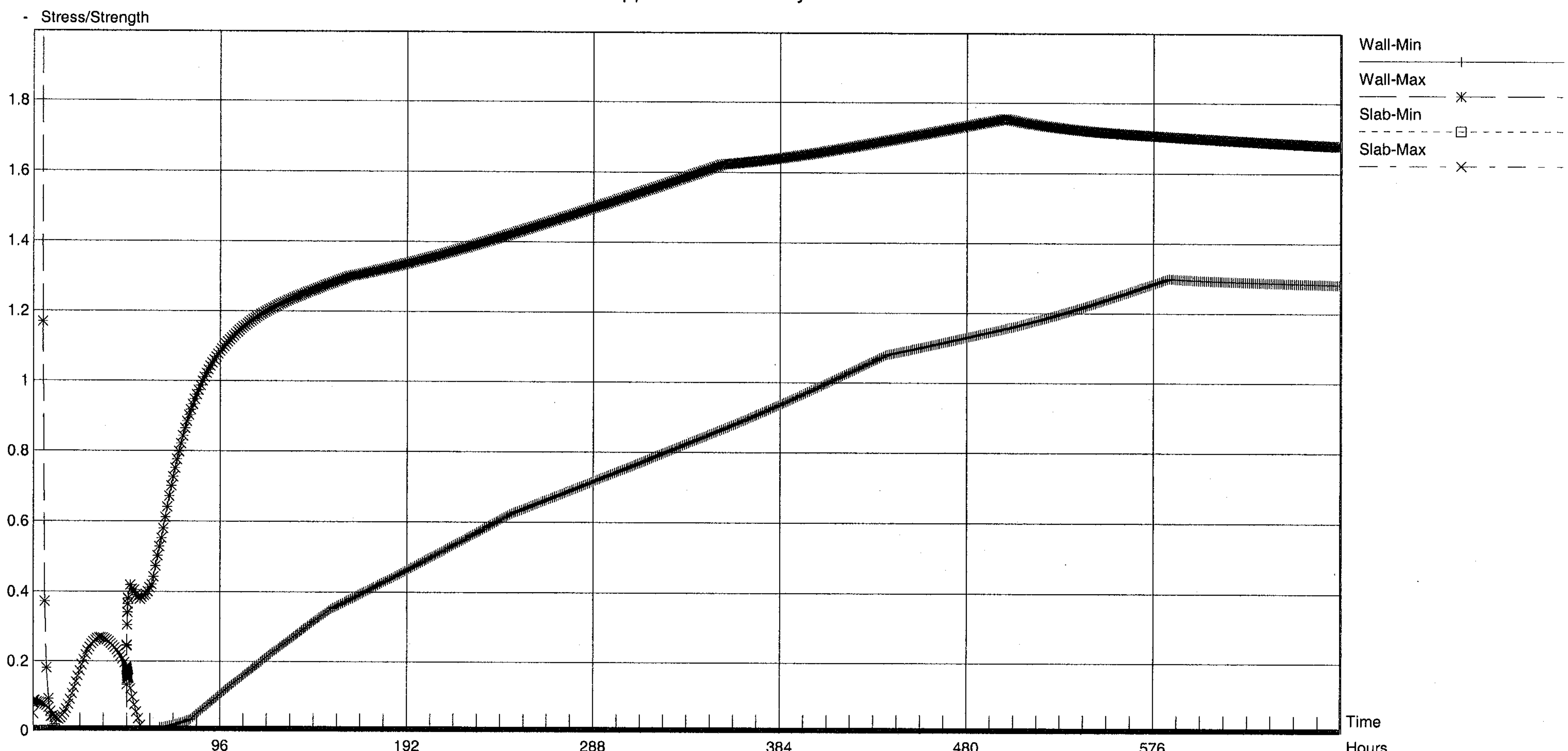

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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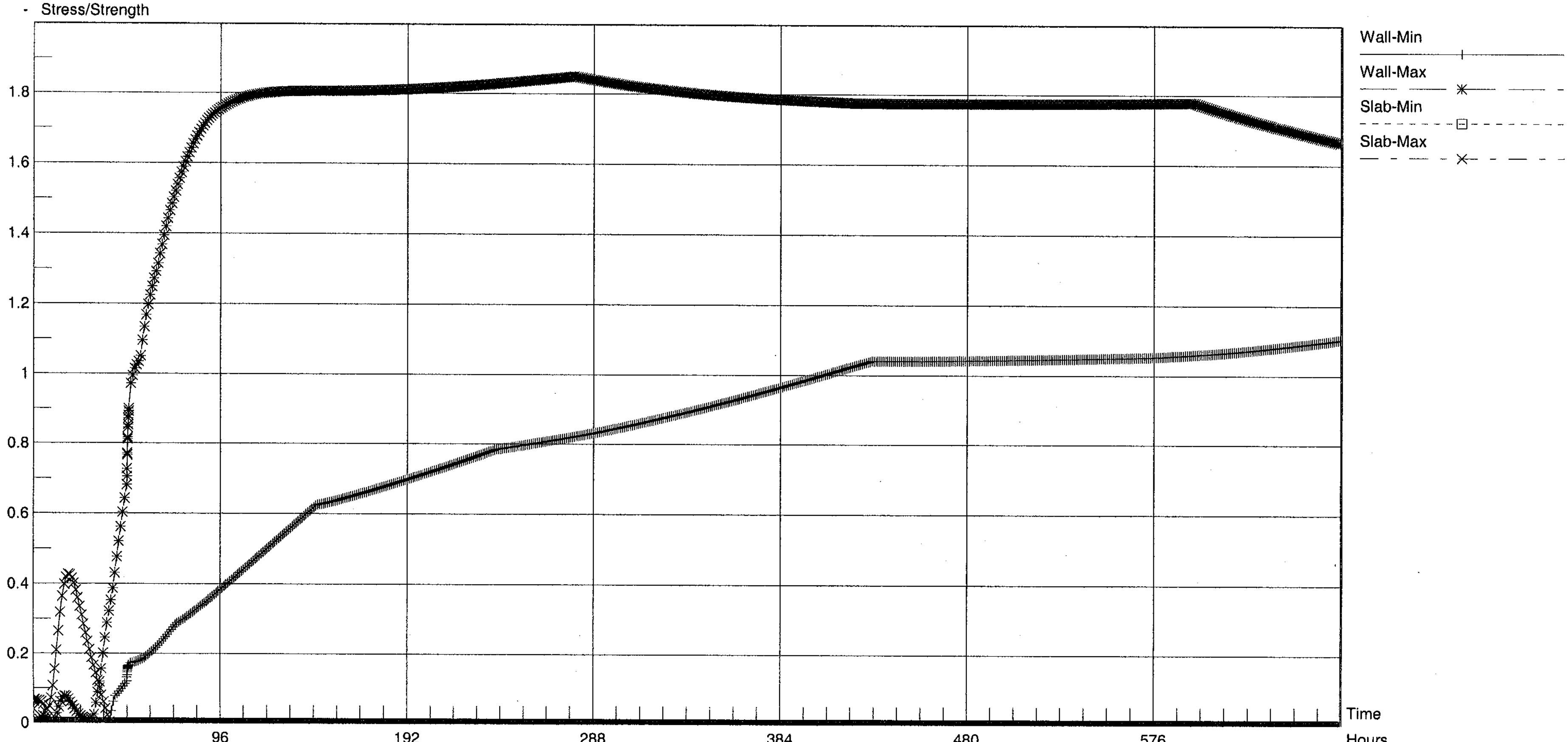

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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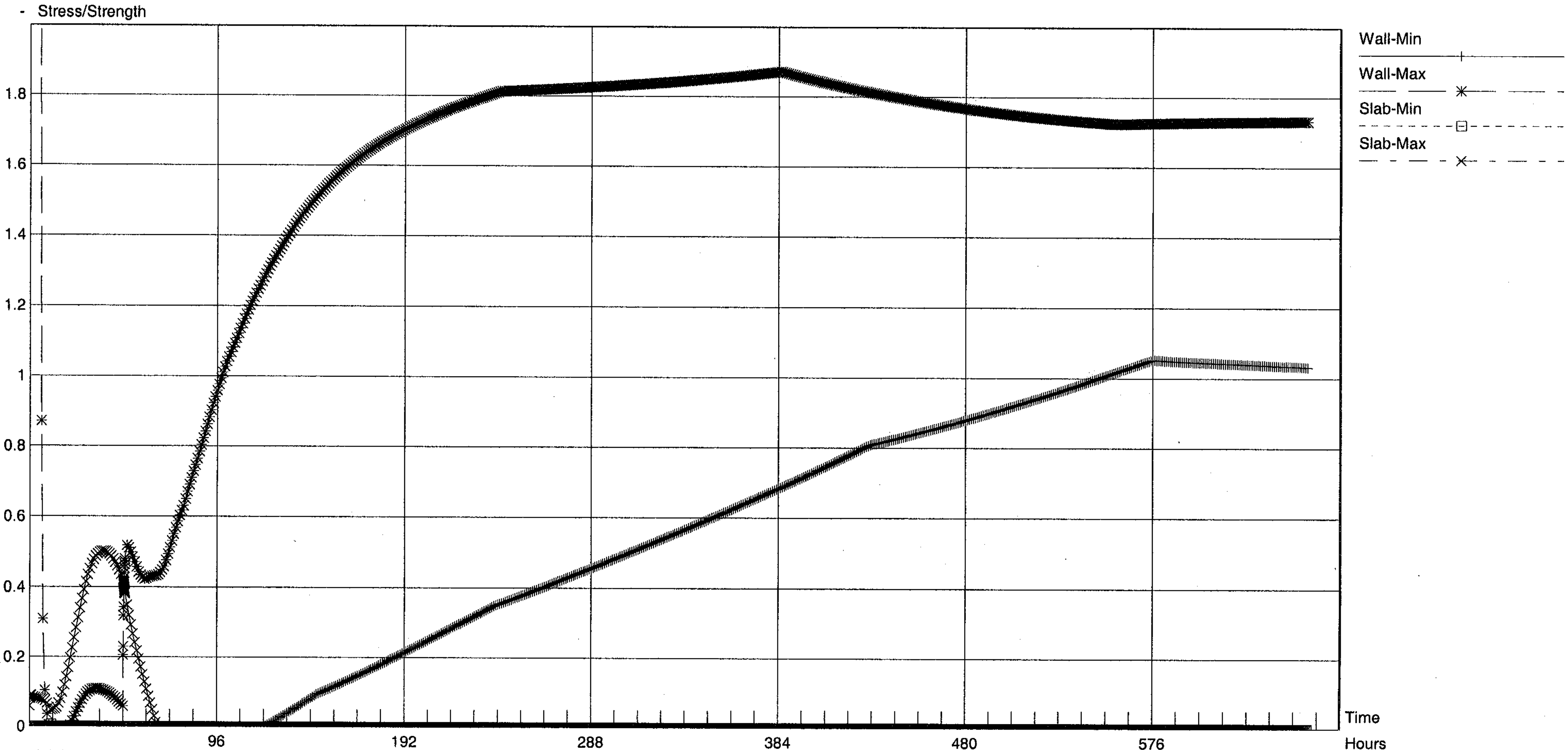

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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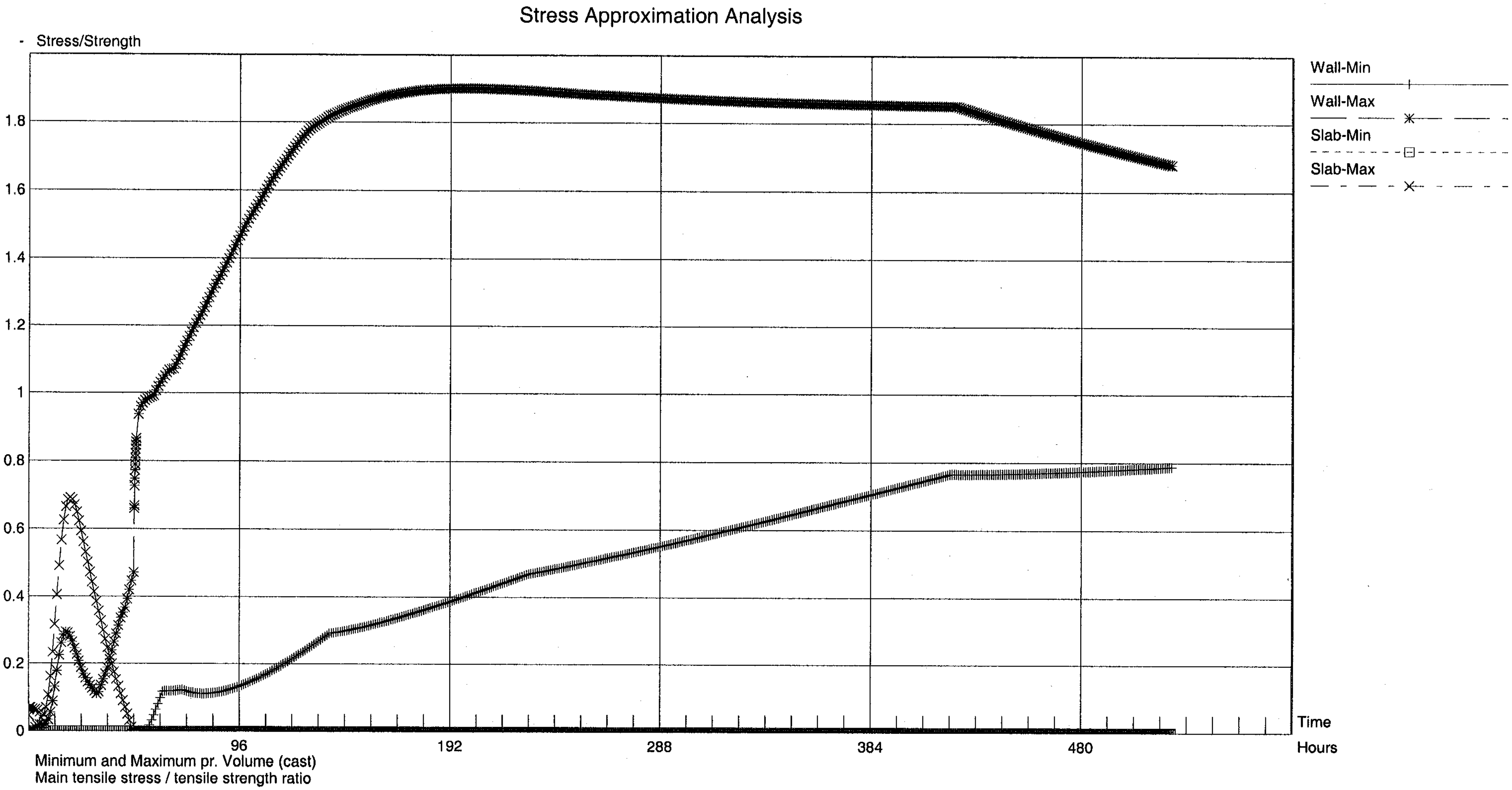

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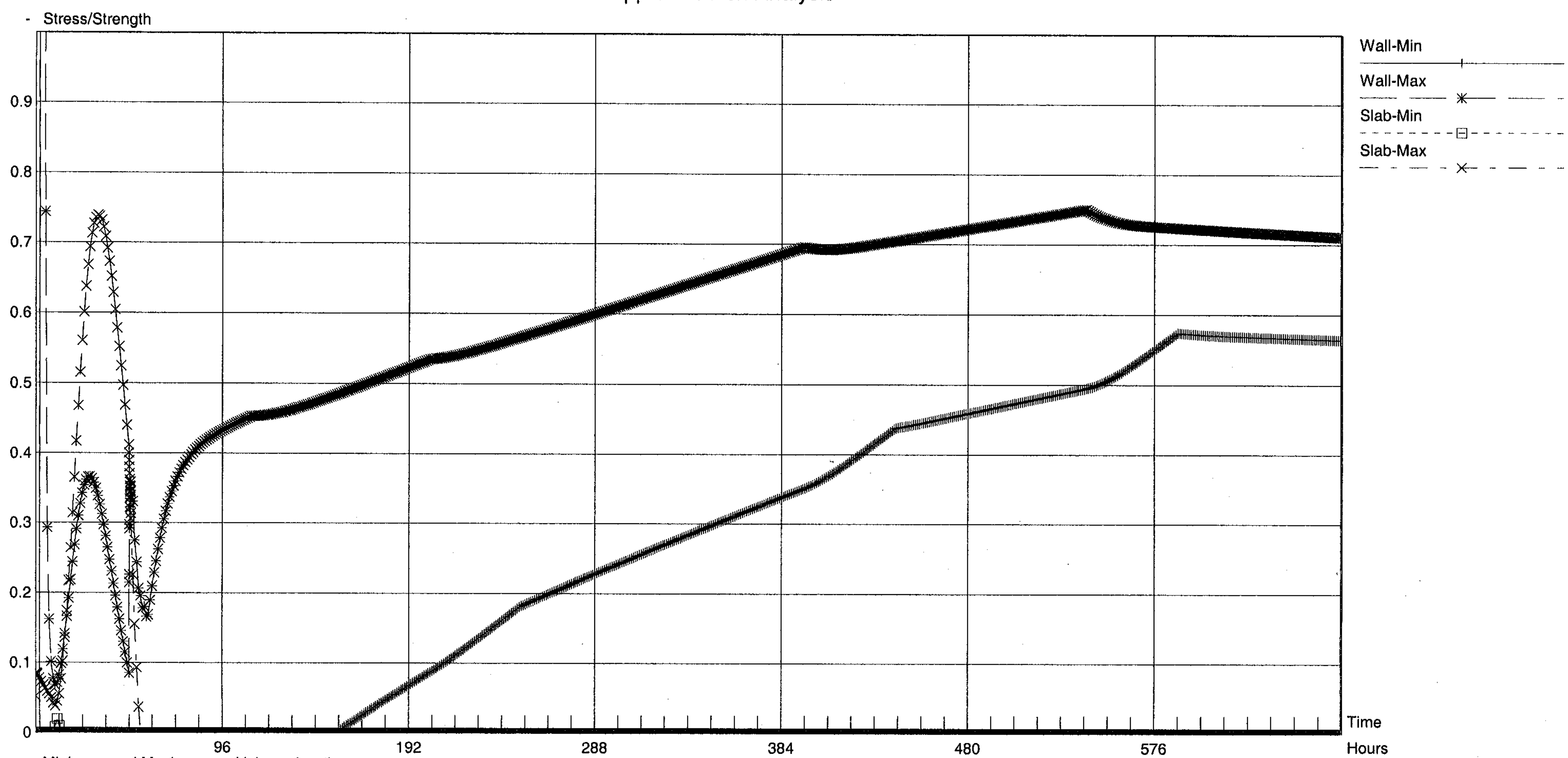

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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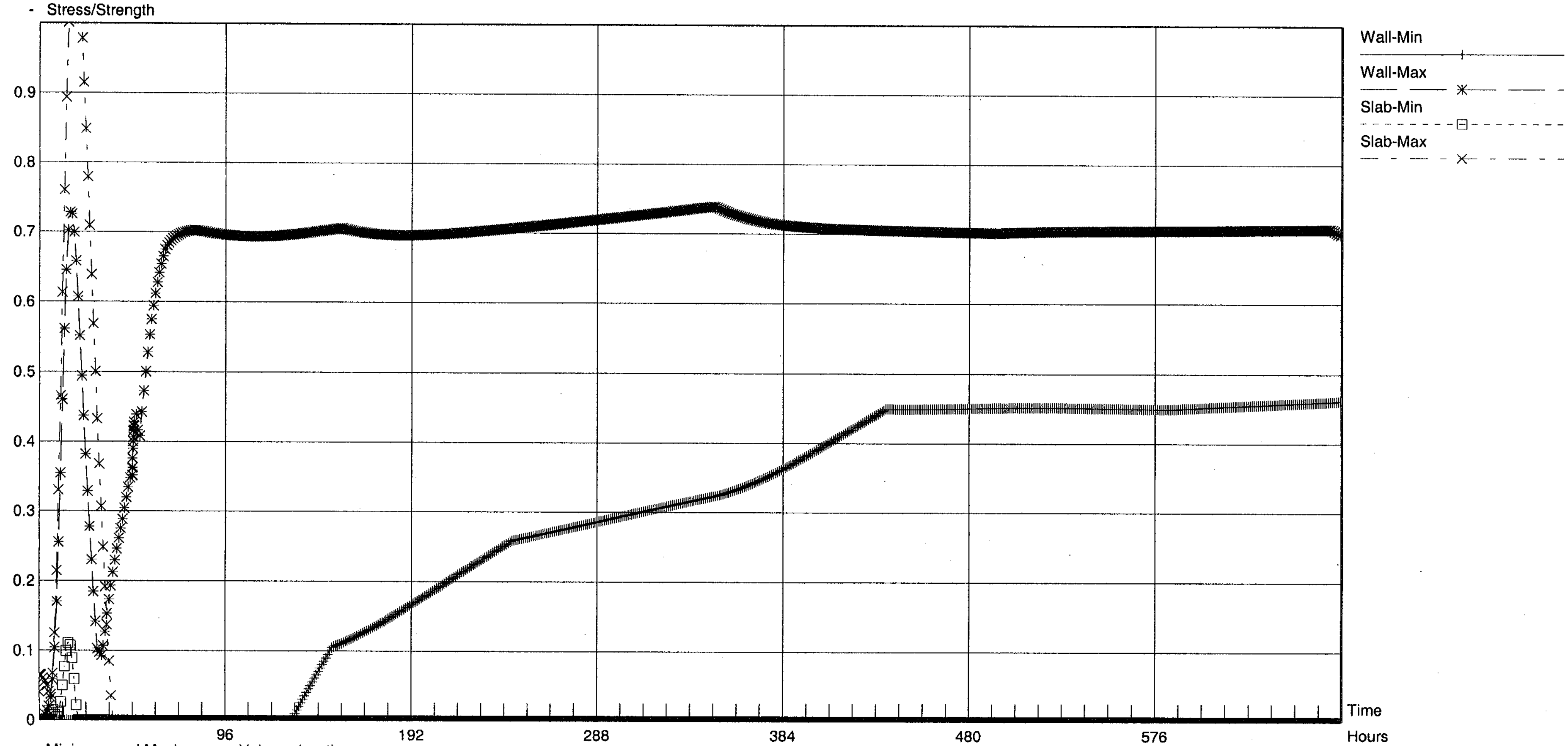

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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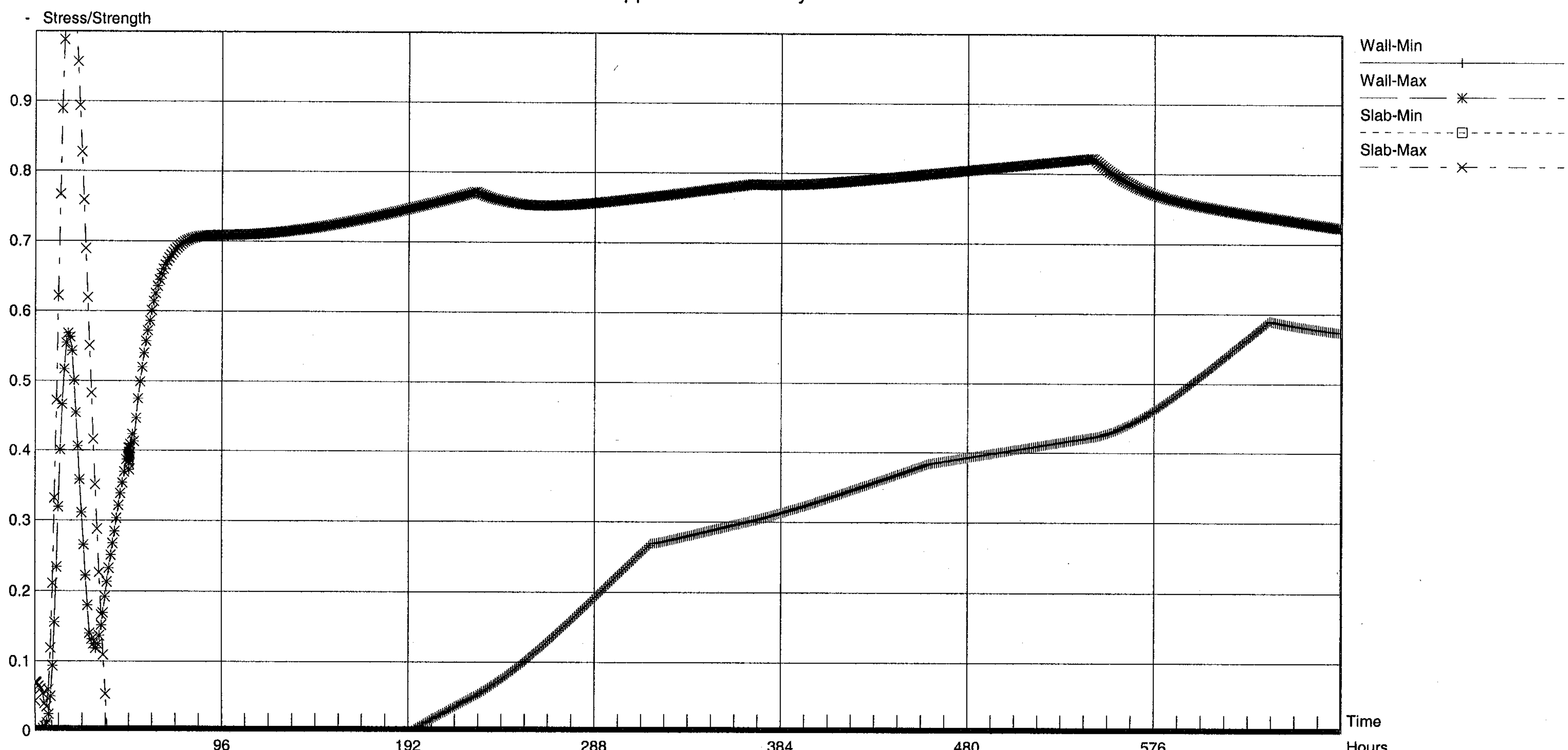

Minimum and Maximum pr. Volume (cast)
Main tensile stress / tensile strength ratio

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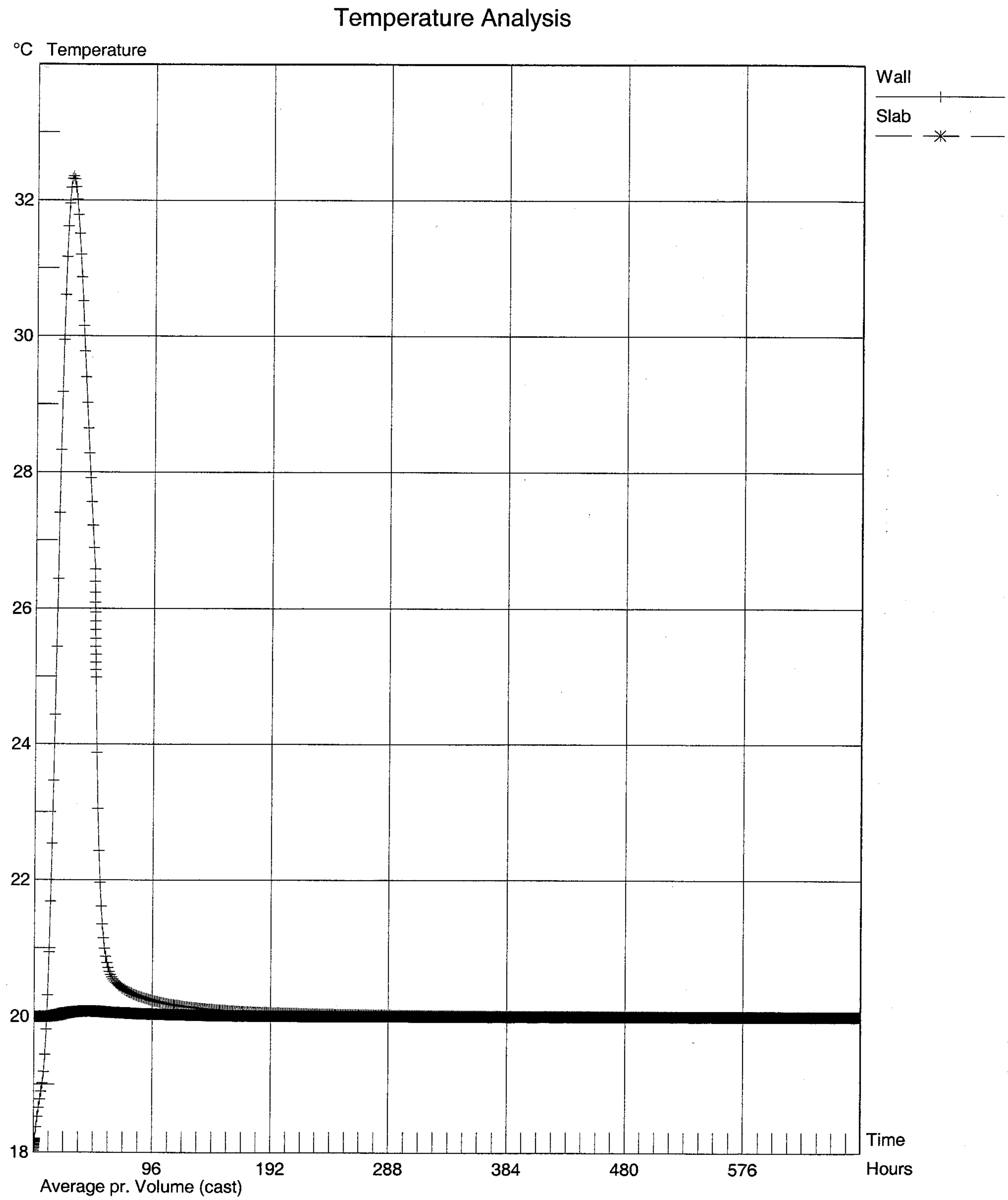

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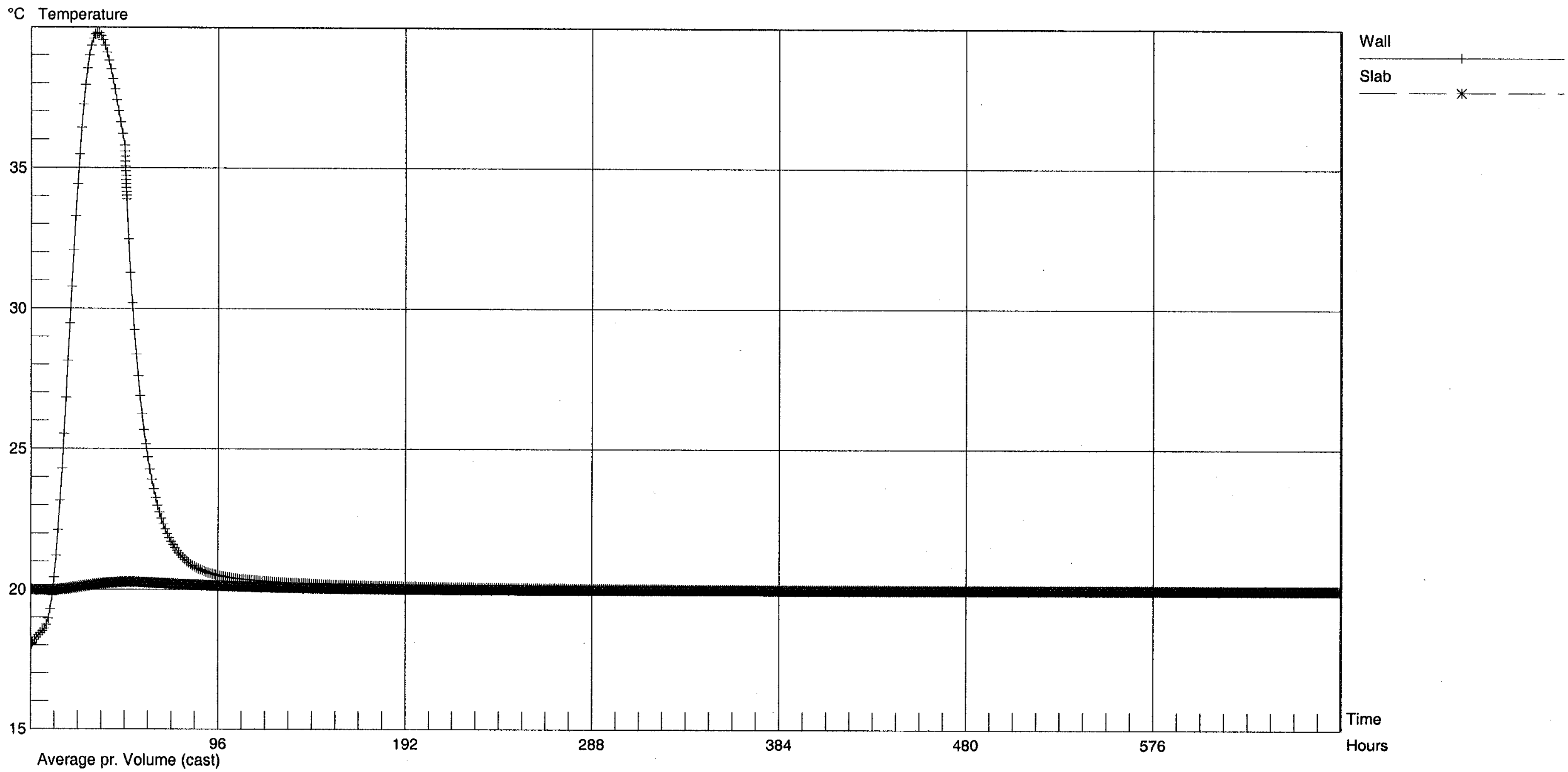

4C-Temp & Stress 2.10, Danish Technological Institute, Building Technology

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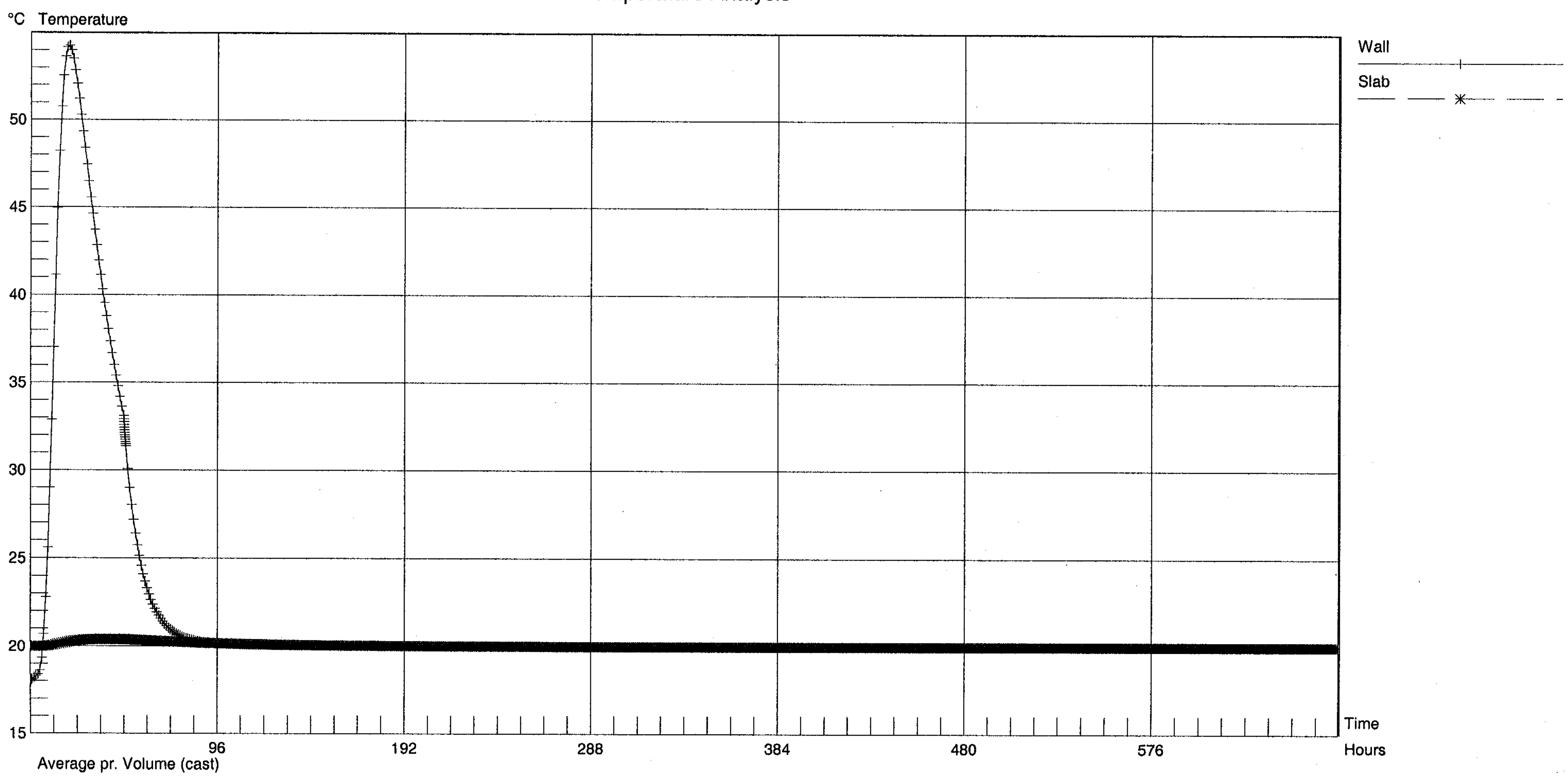

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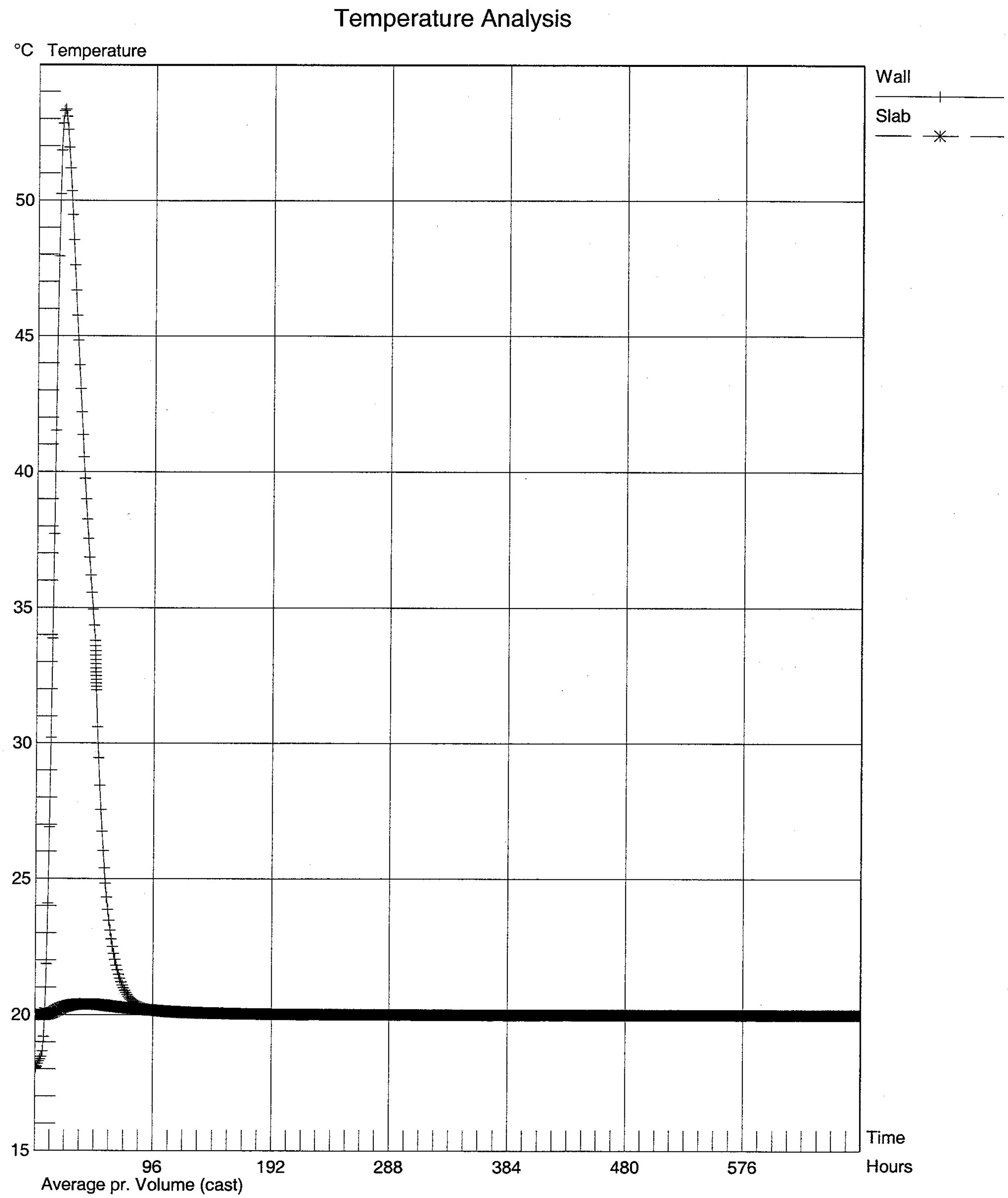

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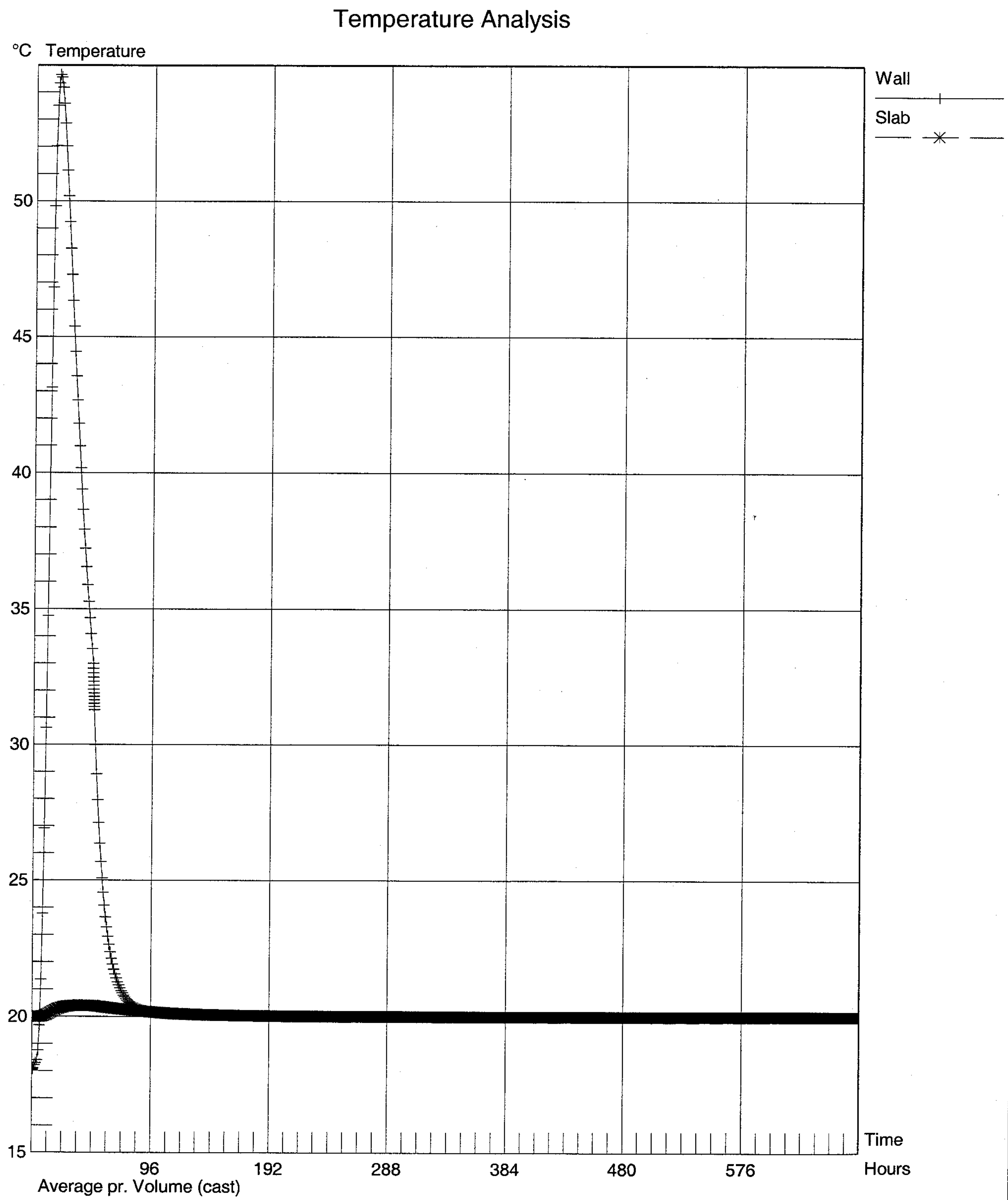

COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Results

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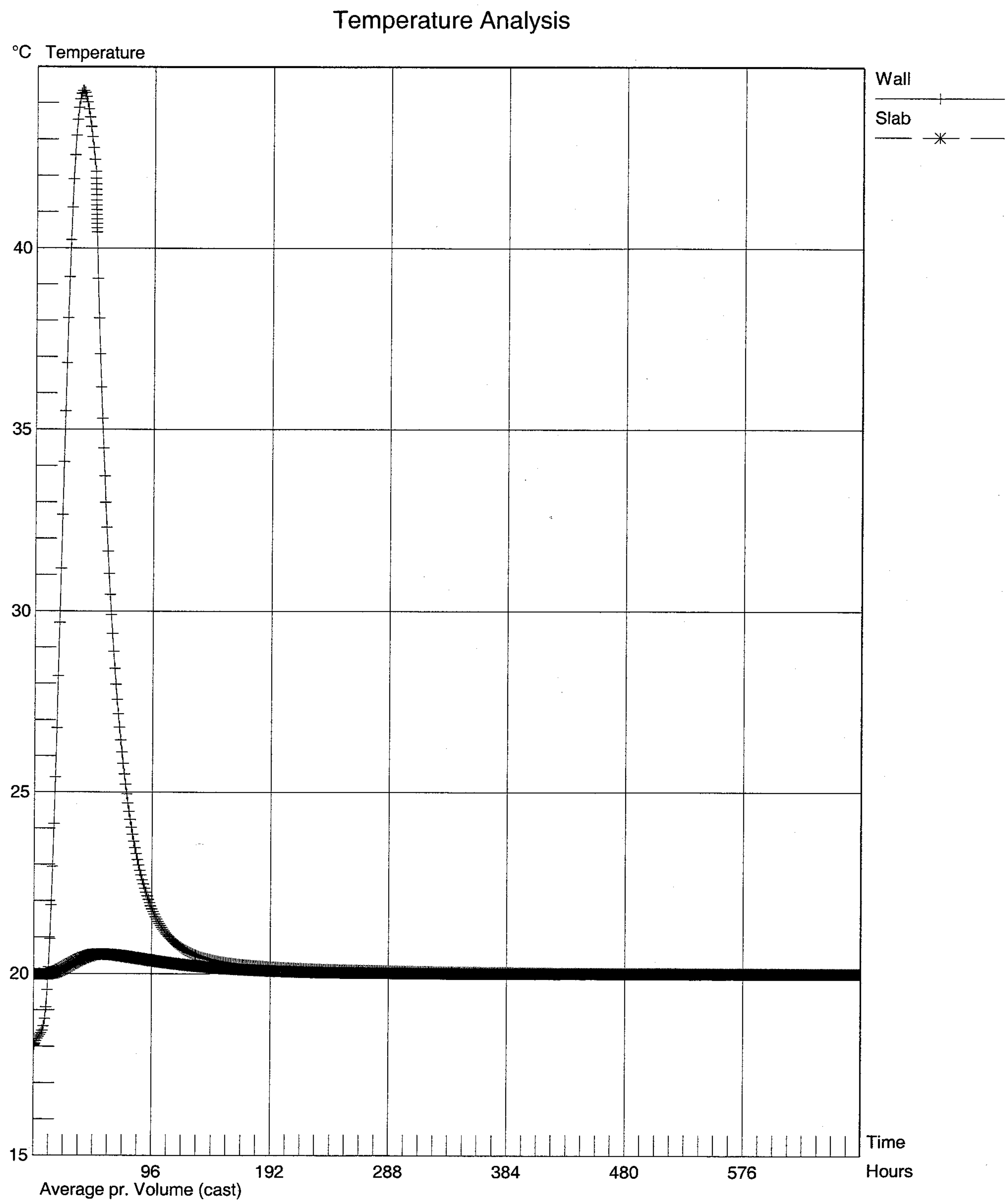
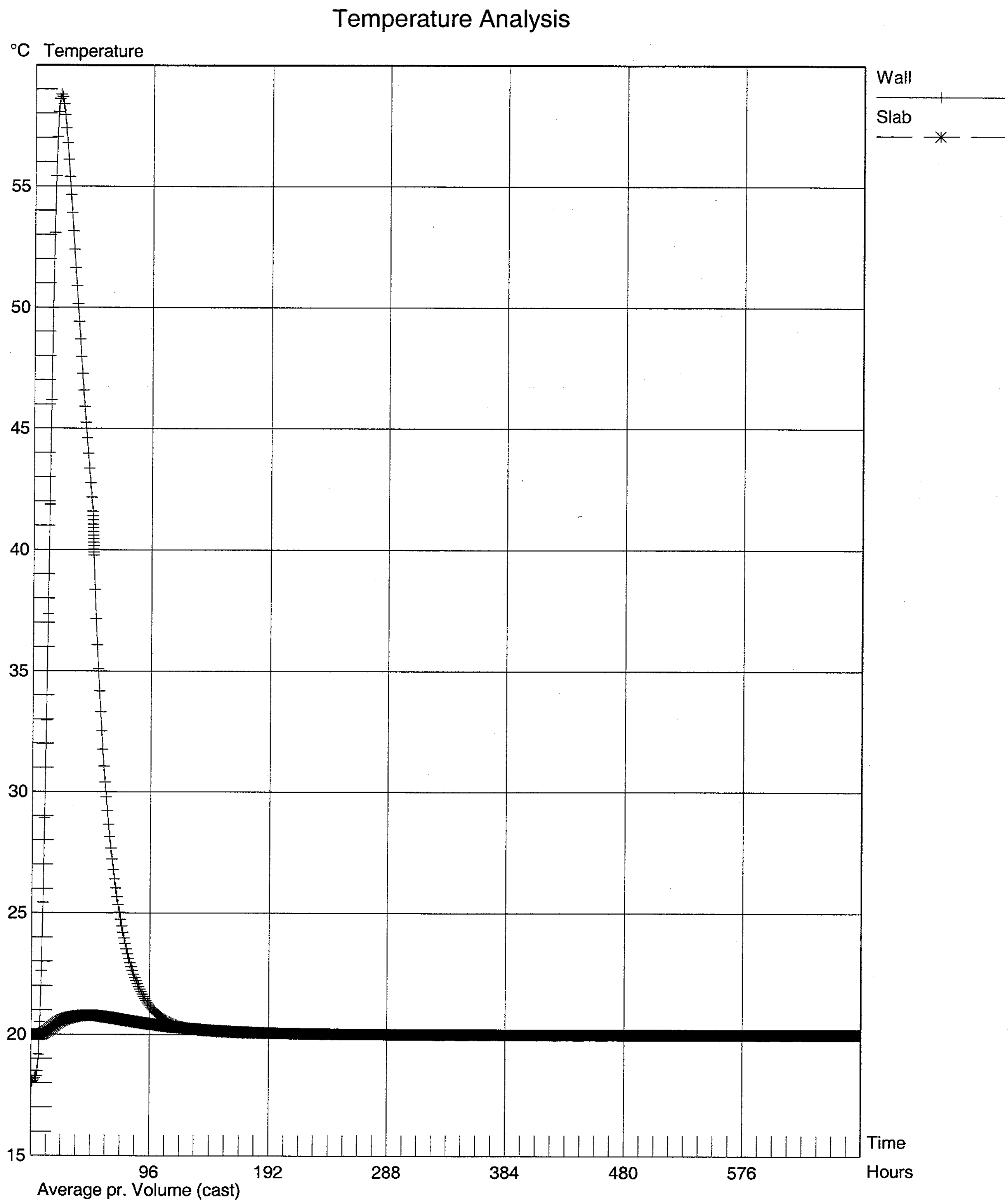


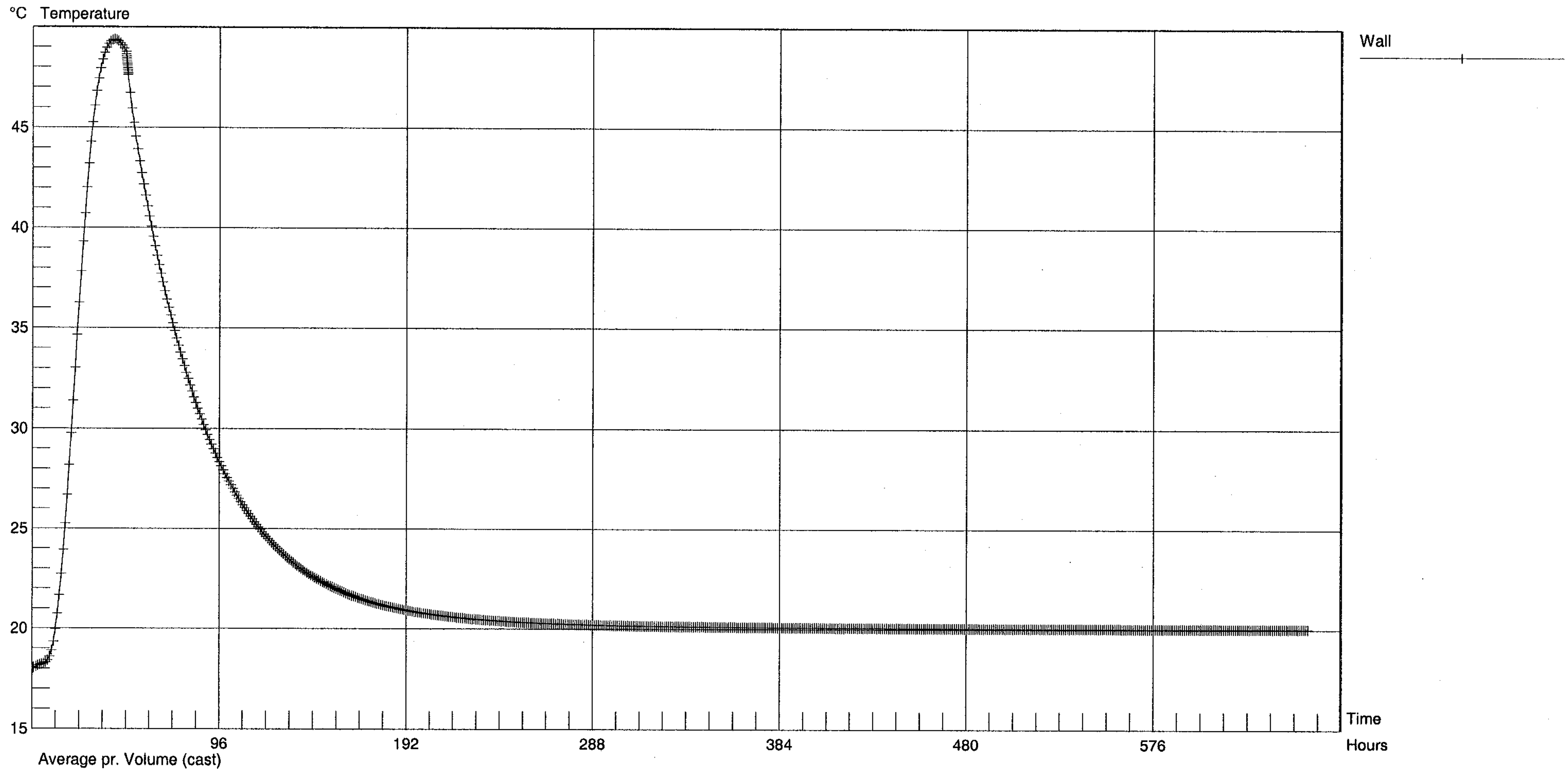
COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Results

Client:	Ref. nr.:	Project: b1_600	Date: 16-12-2003
Name:	Initials :	Id. nr. : XX-AA0193	Time: 12:47



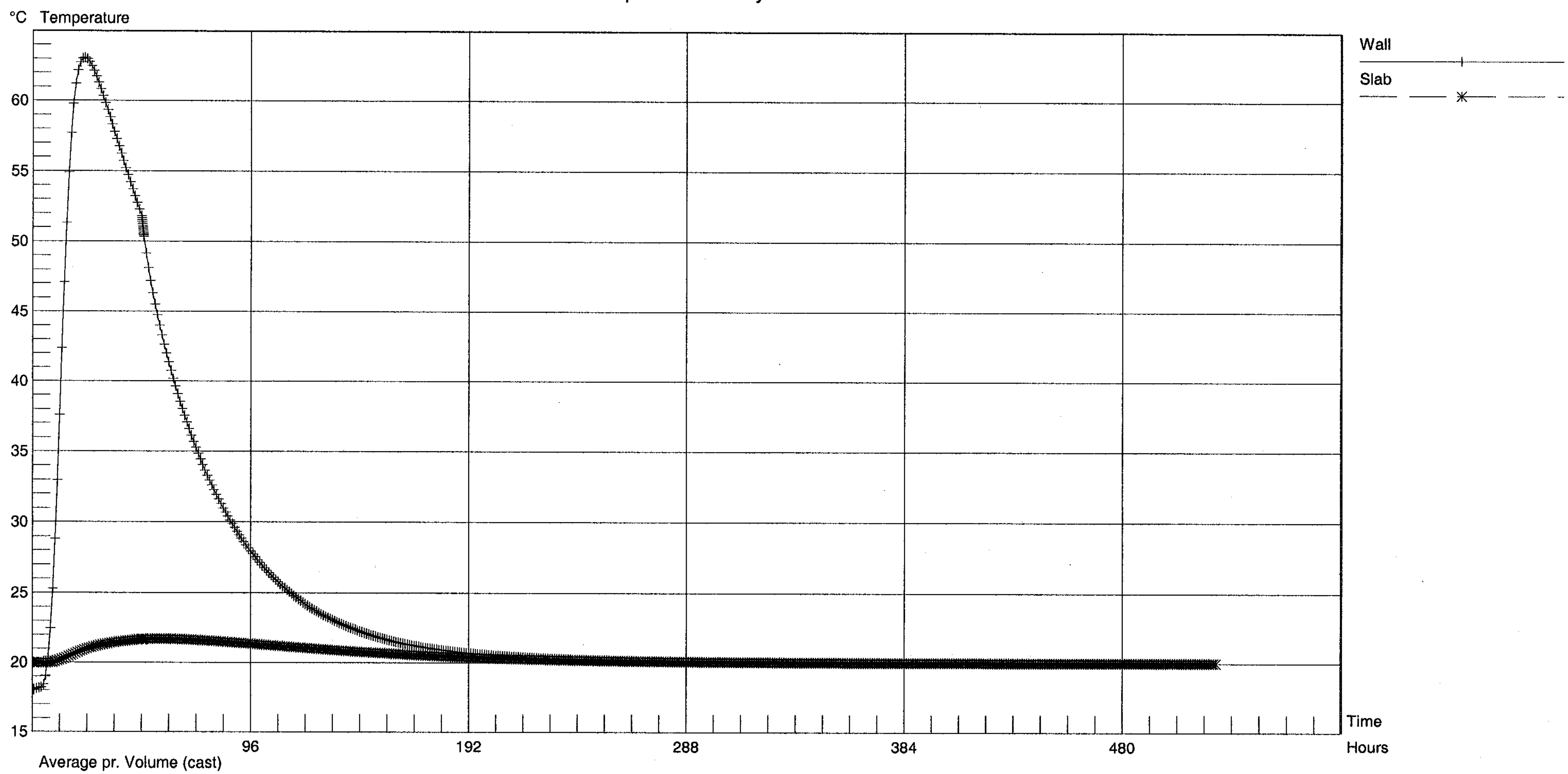
COWI A/S CONSULTING ENGINEERS		4C-Temp & Stress Calculation Results	
Client: Name:	Ref. nr.: Initials :	Project: a_1000 Id. nr. : XX-AA0198	Date: 13-08-2003 Time: 13:01

Temperature Analysis



COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Results		
Client: Name:	Ref. nr.: Initials :	Project: b1_1000 Id. nr. : XX-AA0230	Date: 13-08-2003 Time: 13:01

Temperature Analysis

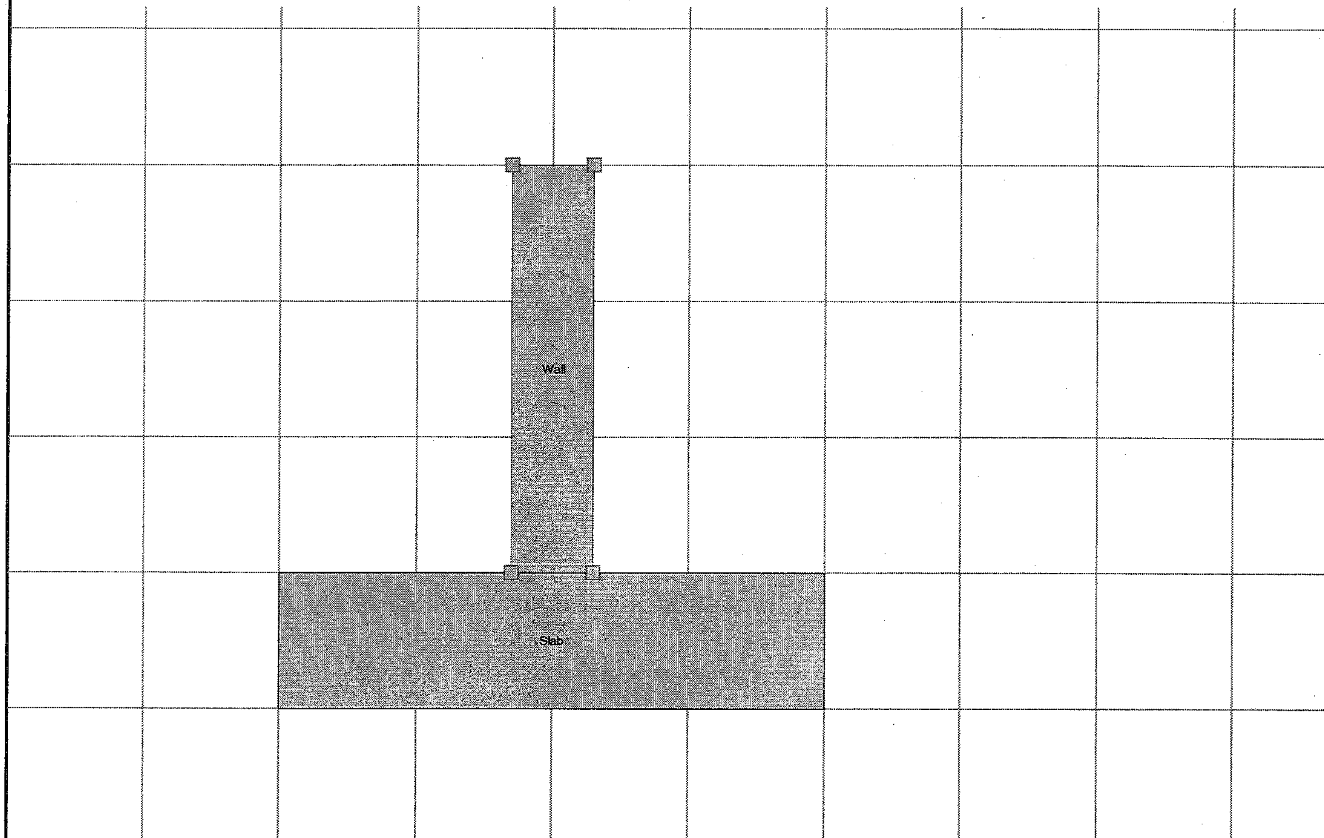


COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Basis

Client:	Ref. nr.:	Project: a_600	Date: 16-12-2003
Name:	Initials :	Id. nr. : XX-AA0192	Time: 12:54

Volumes

Scaling mode: cm
Rulers: [100:100]



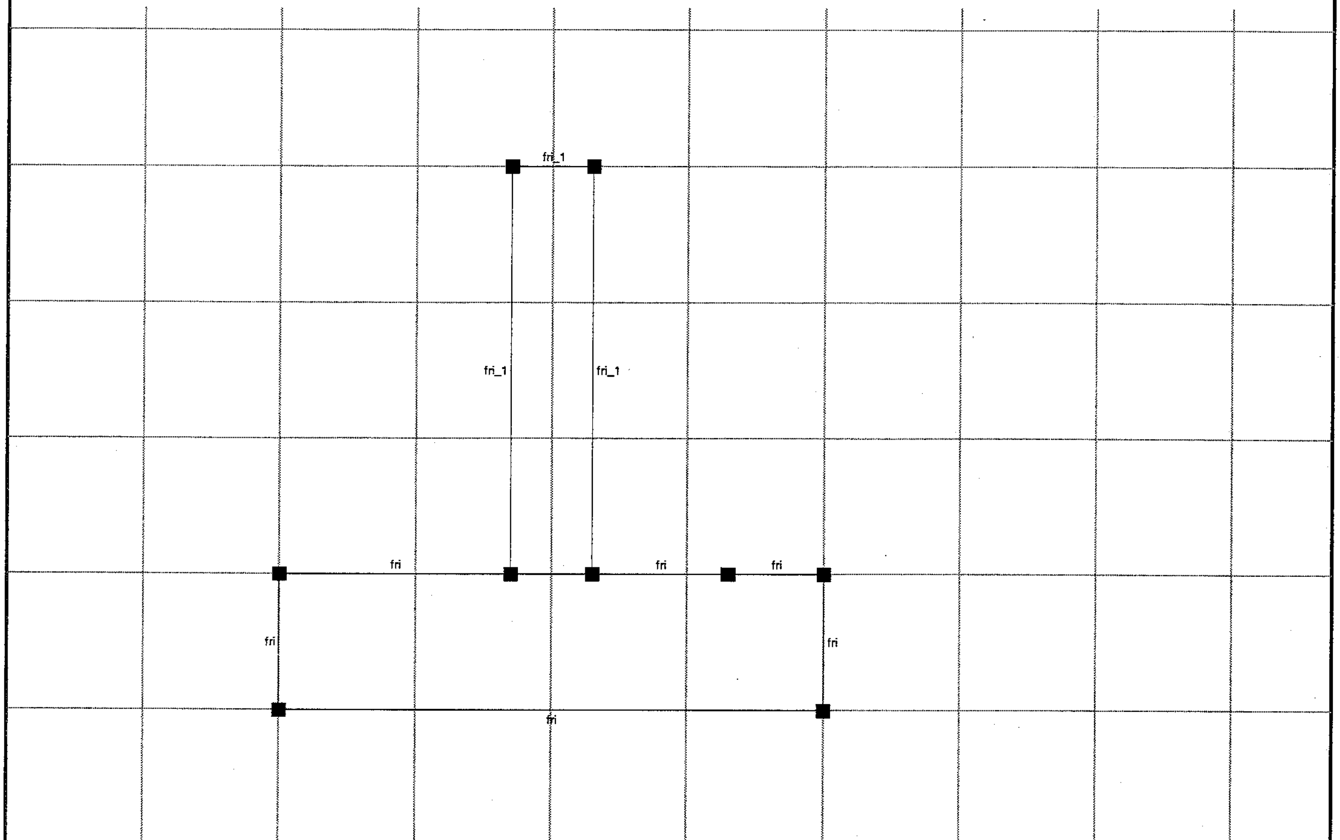
Volume	Size [cm]	Material type [-]	Material name [-]	Thickness [m]	Start time [h]	Temp. [°C]
Wall	60 by 300	Concrete	Ref_A	1.	0.	18.
Slab	400 by 100	Concrete	Ref_A_old	1.	0.	20.

COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Basis

Client:	Ref. nr.:	Project: a_600	Date: 16-12-2003
Name:	Initials :	Id. nr. : XX-AA0192	Time: 12:56

Faces

Scaling mode: cm
Rulers: [100:100]



Boundary condition

Boundary condition name	Function type	Function name
fri	Temperature	Temp_20
	Coef. of transm.	Tr_20
fri_1	Temperature	Temp_20
	Coef. of transm.	Tr_20_1

COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Basis

Client:	Ref. nr.:	Project: a_600	Date: 16-12-2003
Name:	Initials :	Id. nr. : XX-AA0192	Time: 12:54

Functions

Name	Type	Description	Unit	Function table Time [h] / Value
Temp_20	Temperature	Linear curve	[°C]	0. / 20. - 5000. / 20.
Tr_20	Transm. coef.	Piecewise	[kJ/m²/h/°C]	0. / 90. - 48. / 90. - 1000. / 90.
Tr_20_1	Transm. coef.	Piecewise	[kJ/m²/h/°C]	0. / 20. - 48. / 90. - 1000. / 90.

COWI A/S CONSULTING ENGINEERS	4C-Temp & Stress Calculation Basis

Client:	Ref. nr.:	Project: a_600	Date: 16-12-2003
Name:	Initials :	Id. nr.: XX-AA0192	Time: 12:55

Calculation parameters

Thermal analysis	Transient	Circles	
Stress analysis	Based on thermal results	No. of faces	12
Dimensions			
2½-Dimensional	Strain in z-direction	Self weight	
	No rotation around x-axis	Direction X	-
	Rotation around y-axis	Direction Y	-
Time specifications		Mesh, node generation	
Total process time	672.	Percentage of the largest extend	
Time step, desired	1.	Min. distance to border	0.01
Time step, factor	0.5	Density, internal nodes	5.00
		Density, border nodes	5.00
Nonlinear calculations		Density, around c-pipes	5.00
Convergence criteria	1.000e-03	Radius around c-pipes	20.00