Properties of Fire Protection Materials

with special reference to intumescent coatings

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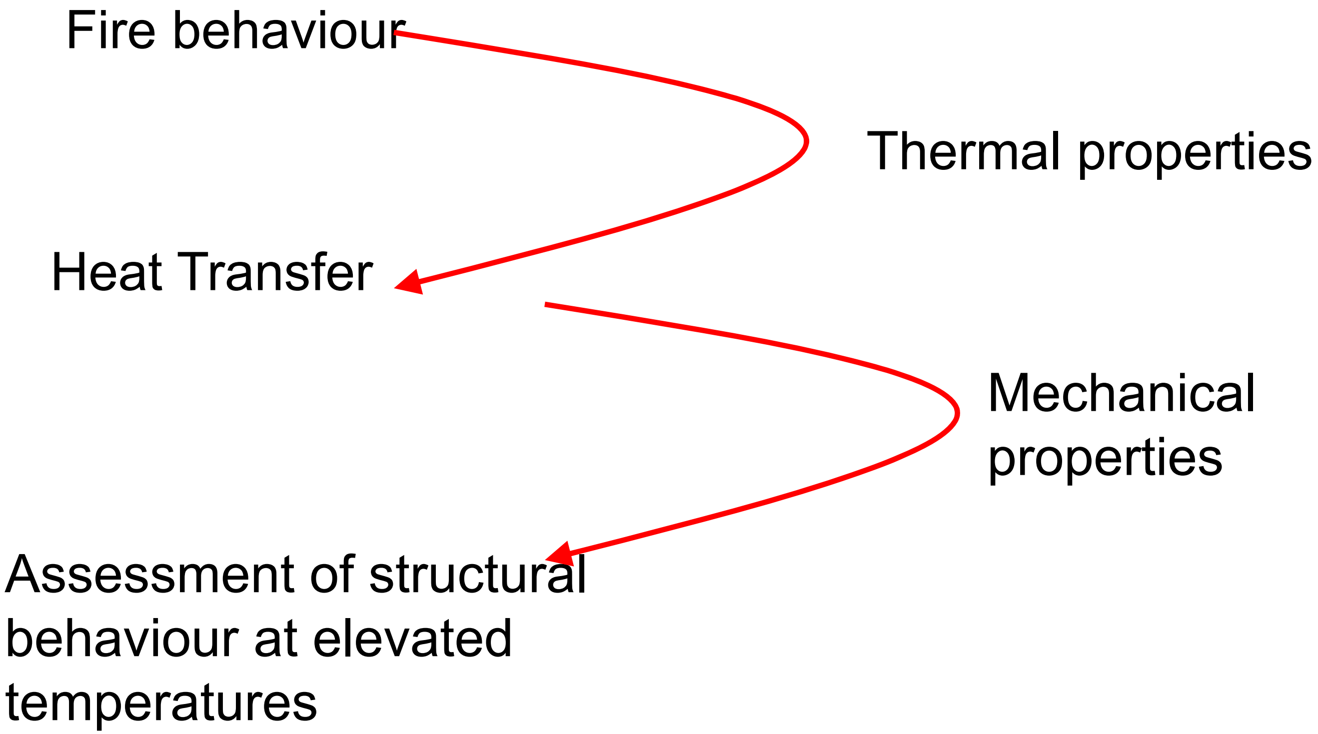
General Structural Fire Engineering Procedure



Fire behaviour

Thermal properties

Heat Transfer

Mechanical properties

Assessment of structural behaviour at elevated temperatures

Contents of Presentation

- Sensitivity of steel temperatures to fire protection material properties
- Current assessment method for fire protection materials
- A theoretical model for thermal conductivity of porous material
- Thermal conductivity of pores at high temperatures
- Thermal conductivity models for a few common fire protection materials

Intumescent coatings

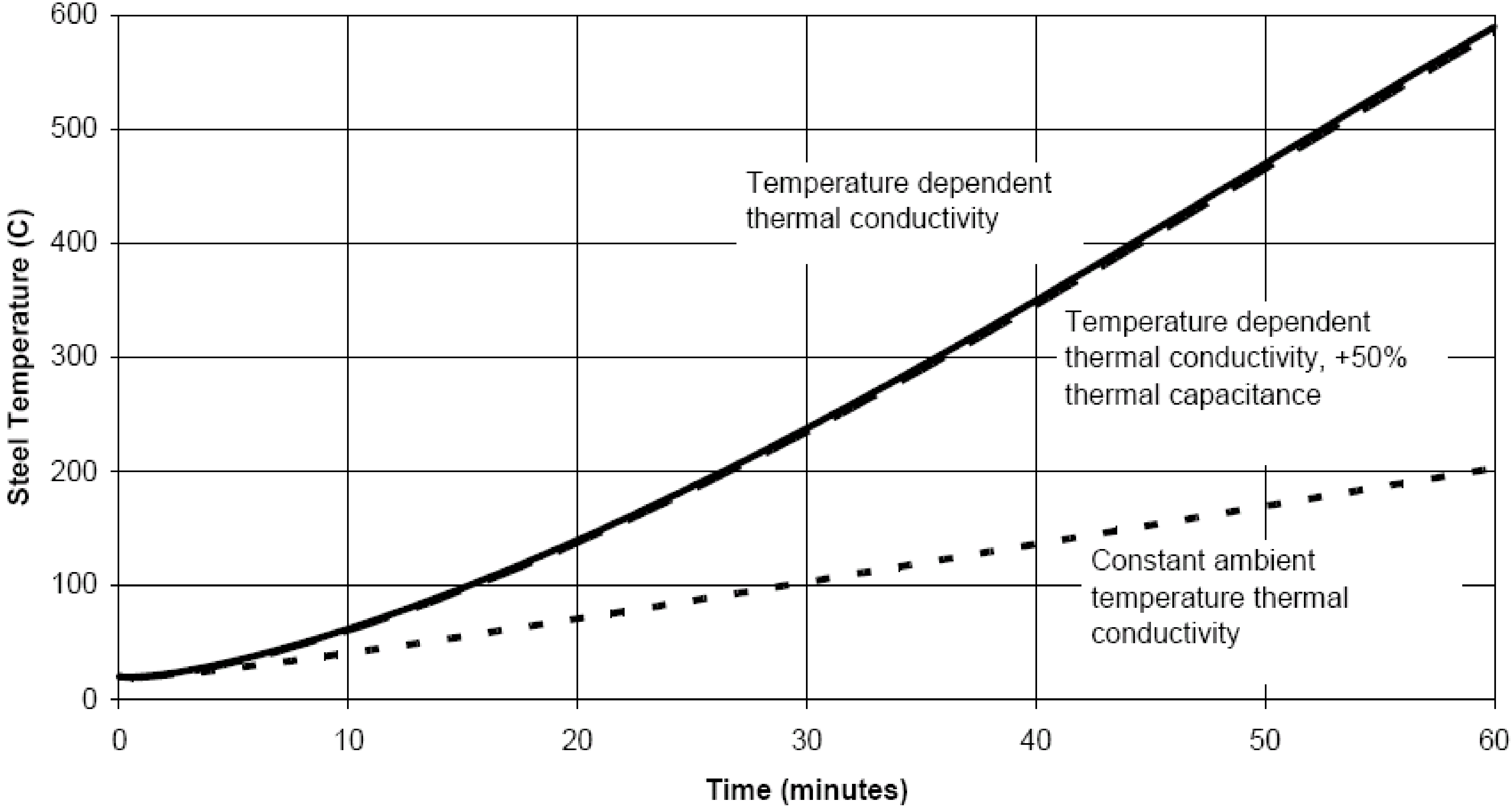
- Variability of “effective” thermal conductivity of intumescent coatings
- Modelling expansion of intumescent coatings
- Some recent research results
- Further research on intumescent coatings

Protected Steel Temperature: EN 1993-1-2

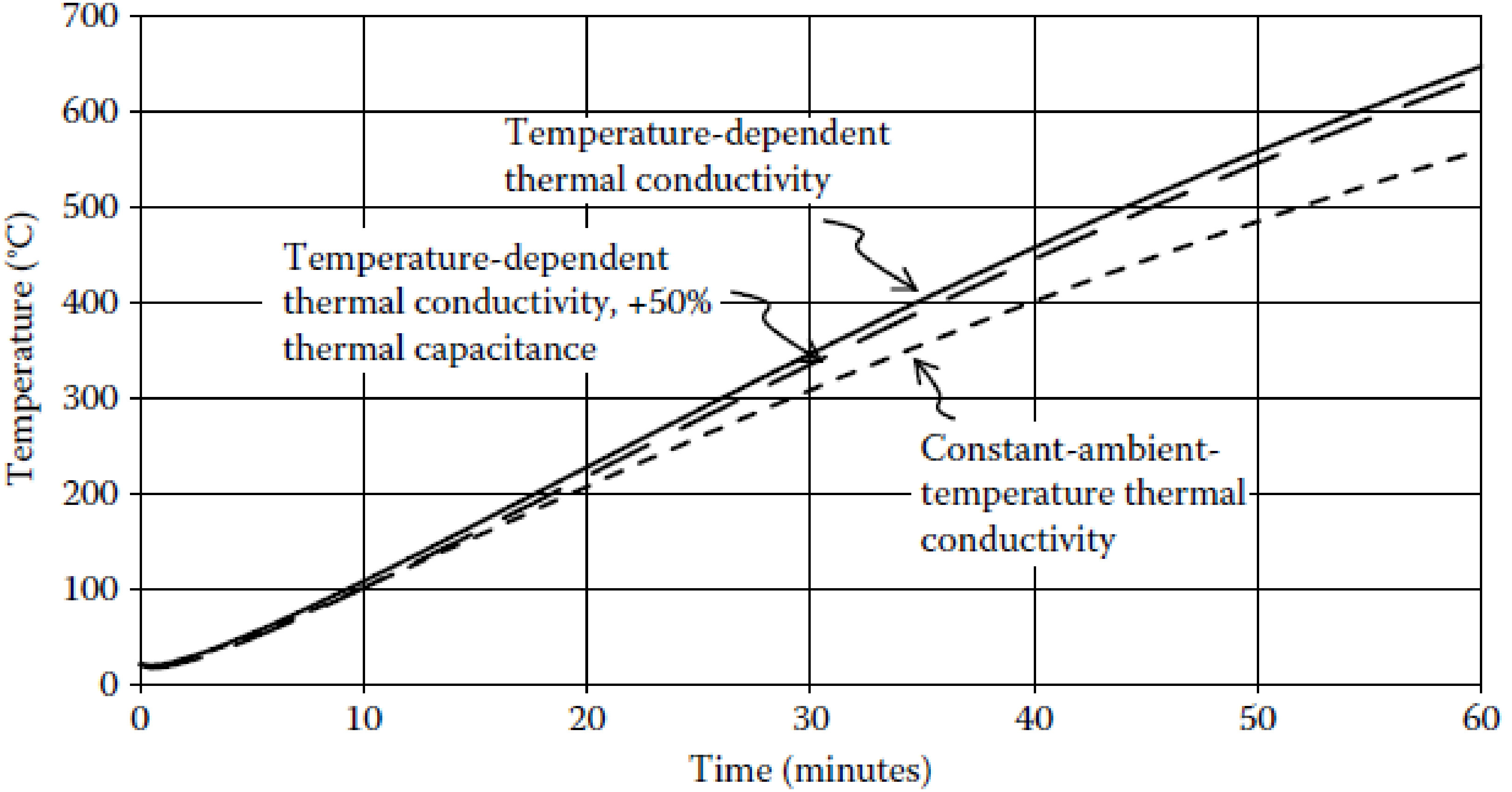
$$\Delta T_s = \frac{\left(T_{fi} - T_s\right) A_p / V}{\left(t_p / k_p\right) C_s \rho_s \left(1 + \frac{1}{3}\phi\right)} \Delta t - \left(e^{\phi / 10} - 1\right) \Delta T_{fi}$$

$$\phi = \frac{C_p \rho_p}{C_s \rho_s} t_p \frac{A_p}{V}$$

Sensitivity of steel temperature to thermal properties of fire protection materials – rock fibre



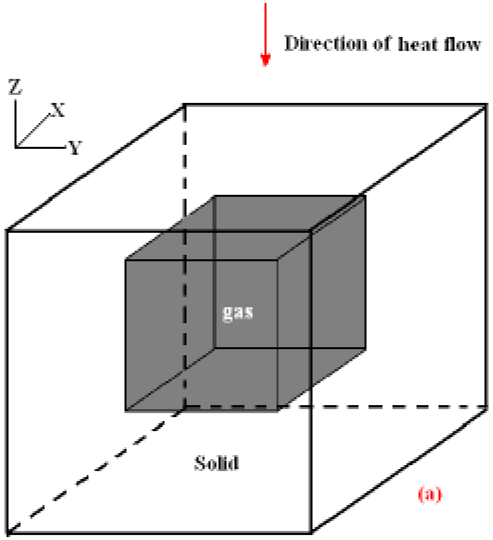
Sensitivity of steel temperature to thermal properties of fire protection materials – vermiculite



Thermal conductivity of fire protection materials: EN 13381-4 assessment method

$$\lambda_p = \left[d_p \times \frac{V}{A_p} \times C_s \rho_s \times (1+\phi/3) \times \frac{1}{(T_{fi} - T_s)\Delta t} \right] \times \left[\Delta T_s + (e^{\phi/10} - 1)\Delta T_{fi} \right]$$

A theoretical model for thermal conductivity of porous materials



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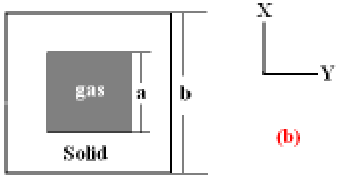

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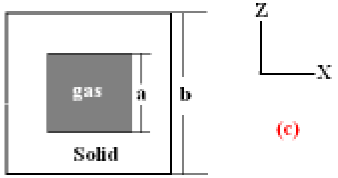

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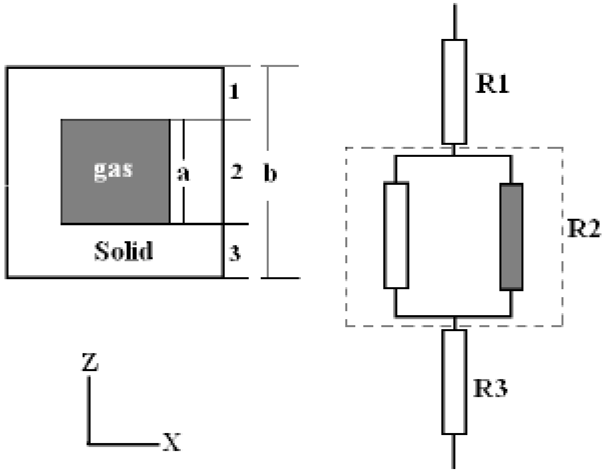


A Model of Thermal Conductivity of Porous Materials

$$\lambda^* = \lambda_s \frac{\lambda_g \varepsilon^{\frac{2}{3}} + (1-\varepsilon^{\frac{2}{3}})\lambda_s}{\lambda_g(\varepsilon^{\frac{2}{3}} - \varepsilon) + (1-\varepsilon^{\frac{2}{3}} + \varepsilon)\lambda_s} = \lambda_s \frac{\beta\varepsilon^{\frac{2}{3}} + (1-\varepsilon^{\frac{2}{3}})}{\beta(\varepsilon^{\frac{2}{3}} - \varepsilon) + (1-\varepsilon^{\frac{2}{3}} + \varepsilon)}$$

$\beta=\lambda_g/\lambda_s$.

"Effective" thermal conductivity of hot air

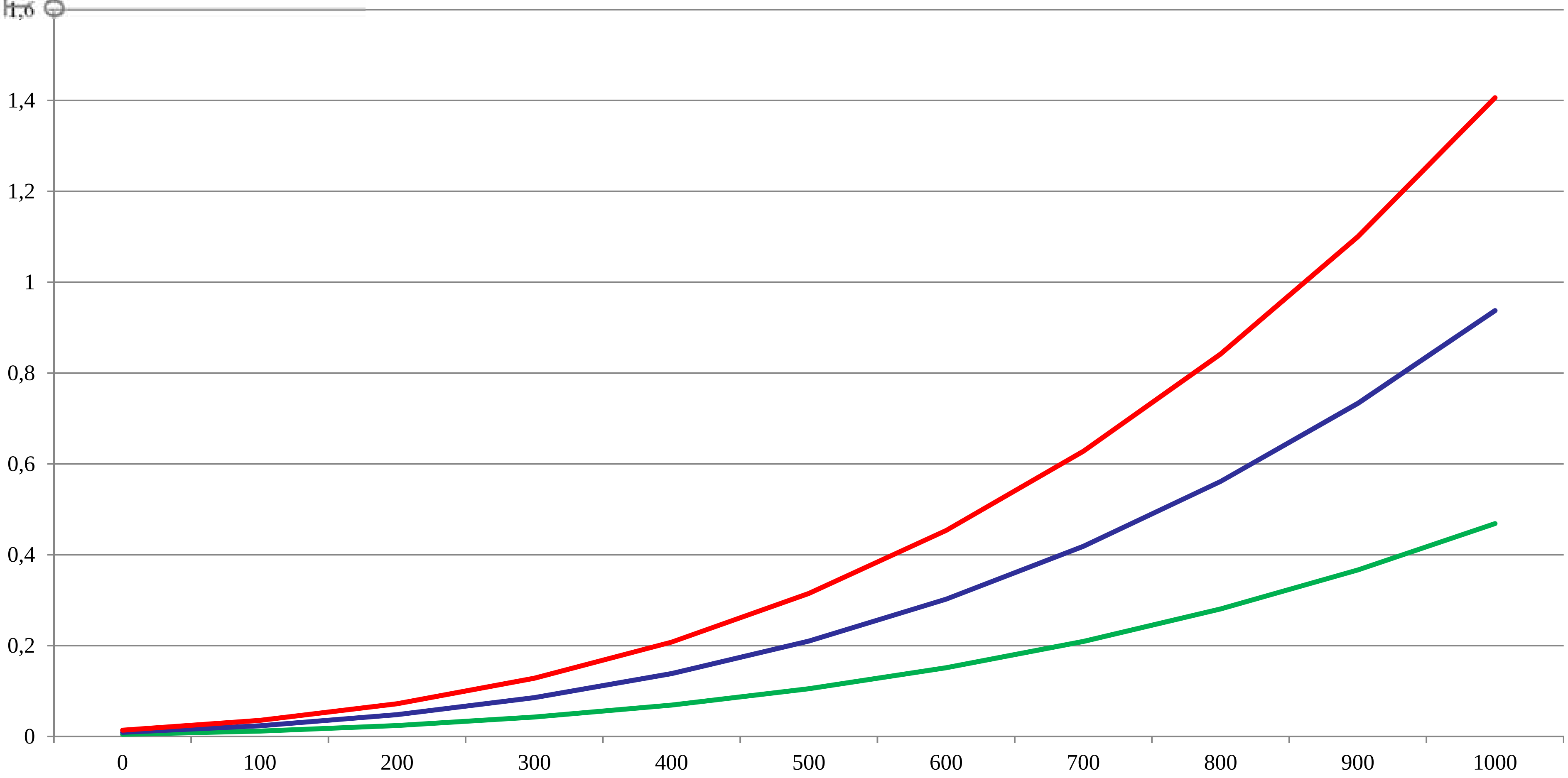
$$\lambda_g = \lambda_{g,cond} + \lambda_{g,rad}$$

$$\lambda_{g,rad} = 4GdE\sigma T^3$$

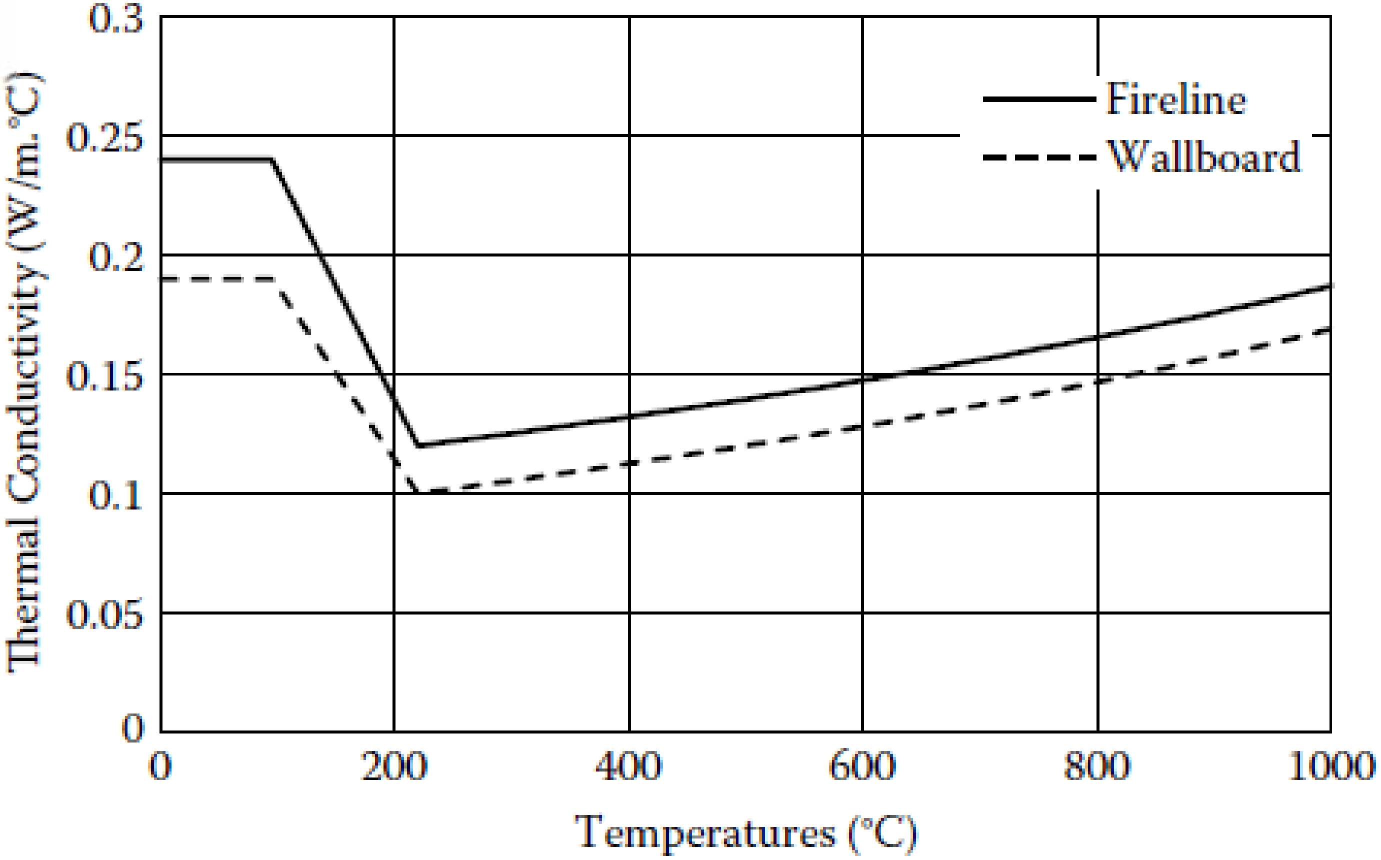
G=2/3 for spherical pore, d=diameter

G=1 for slits perpendicular to heat transfer direction

Radiation contribution to thermal conductivity of air



Gypsum Plaster



Approximately, if ε≈1

$$\lambda^* = \lambda_s \frac{\lambda_g \varepsilon^{\frac{2}{3}} + (1-\varepsilon^{\frac{2}{3}})\lambda_s}{\lambda_g(\varepsilon^{\frac{2}{3}} - \varepsilon) + (1-\varepsilon^{\frac{2}{3}} + \varepsilon)\lambda_s} = \lambda_s \frac{\beta\varepsilon^{\frac{2}{3}} + (1-\varepsilon^{\frac{2}{3}})}{\cancel{\beta(\varepsilon^{\frac{2}{3}} - \varepsilon)} + (1\cancel{-\varepsilon^{\frac{2}{3}} + \varepsilon})}$$

$$\lambda^* = C_1 + C_2\lambda_g \xrightarrow{\qquad\qquad} \lambda^* = \lambda_0^* + CT^3$$

Some thermal conductivity models of common fire protection materials

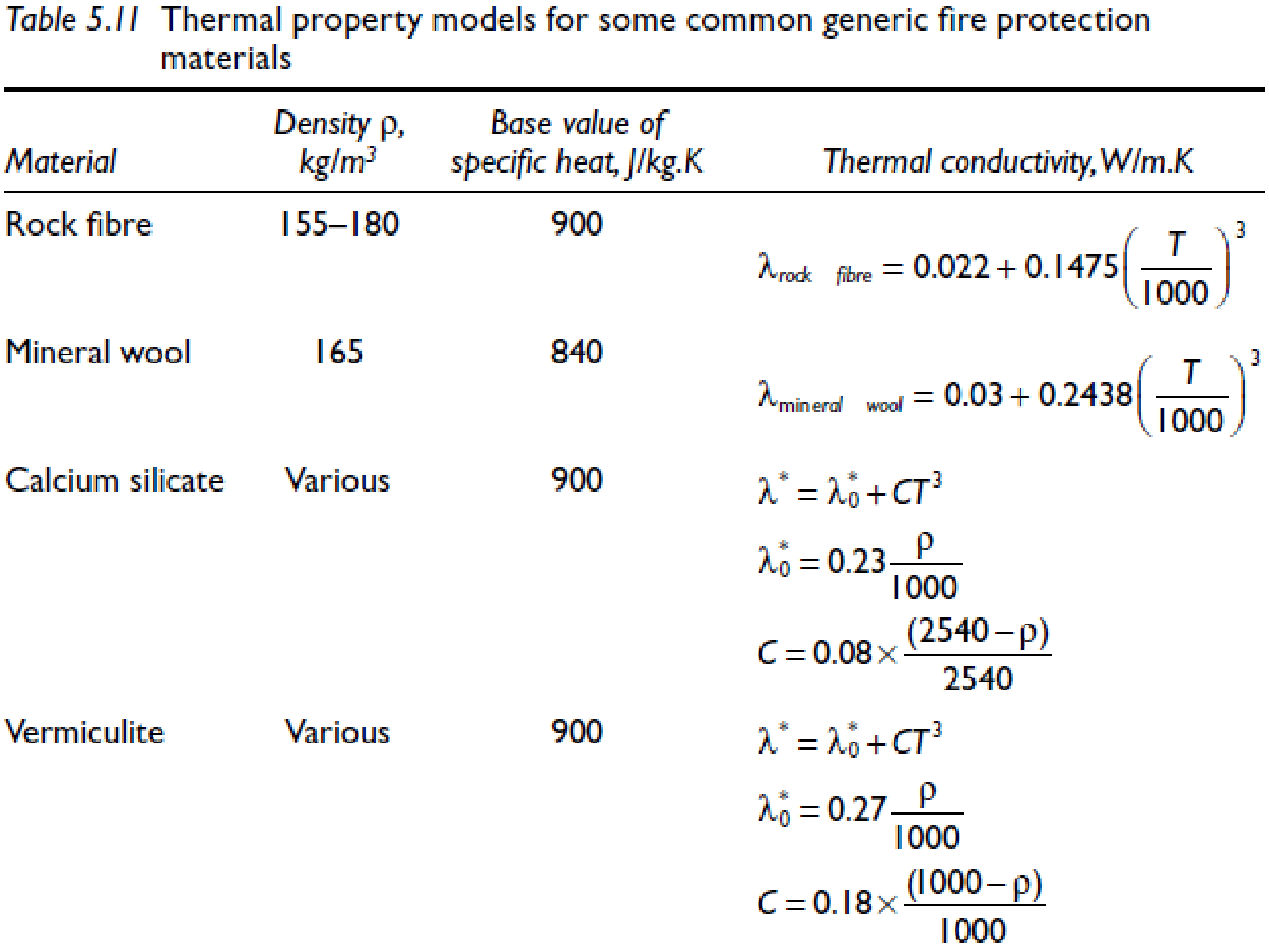
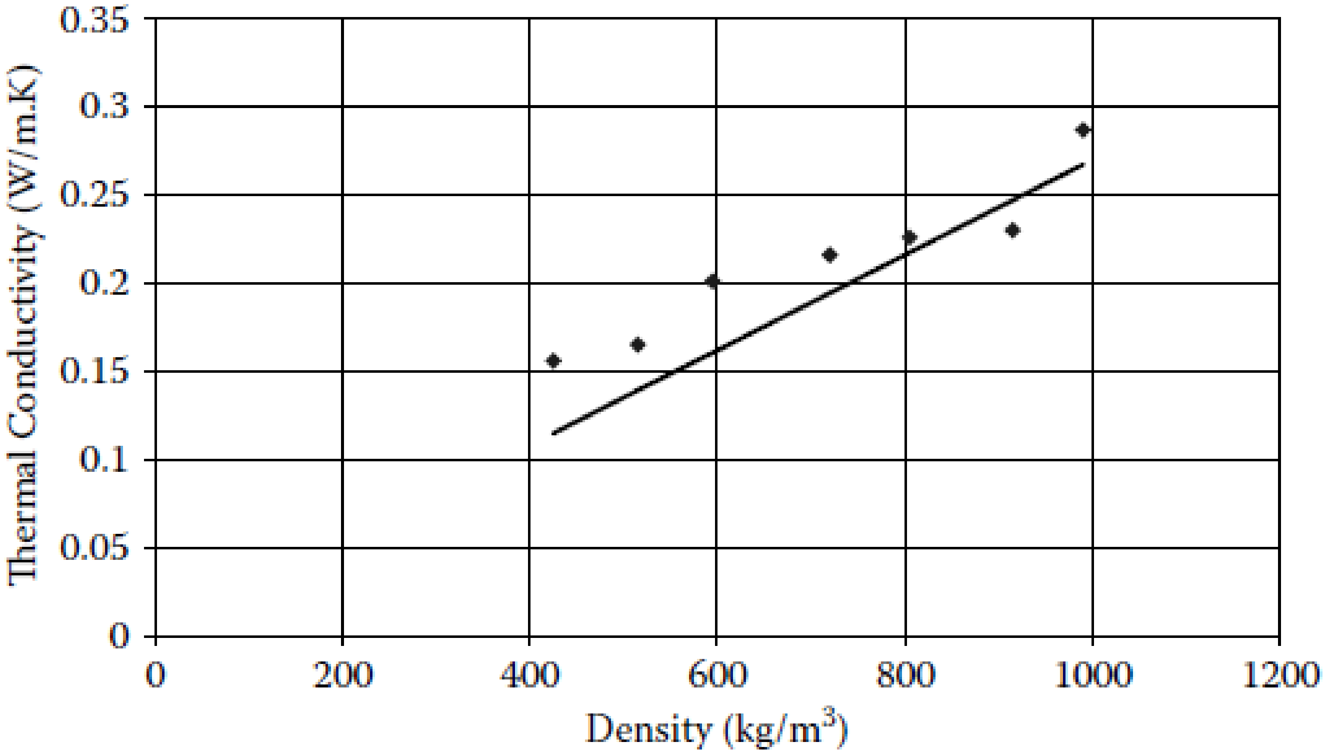


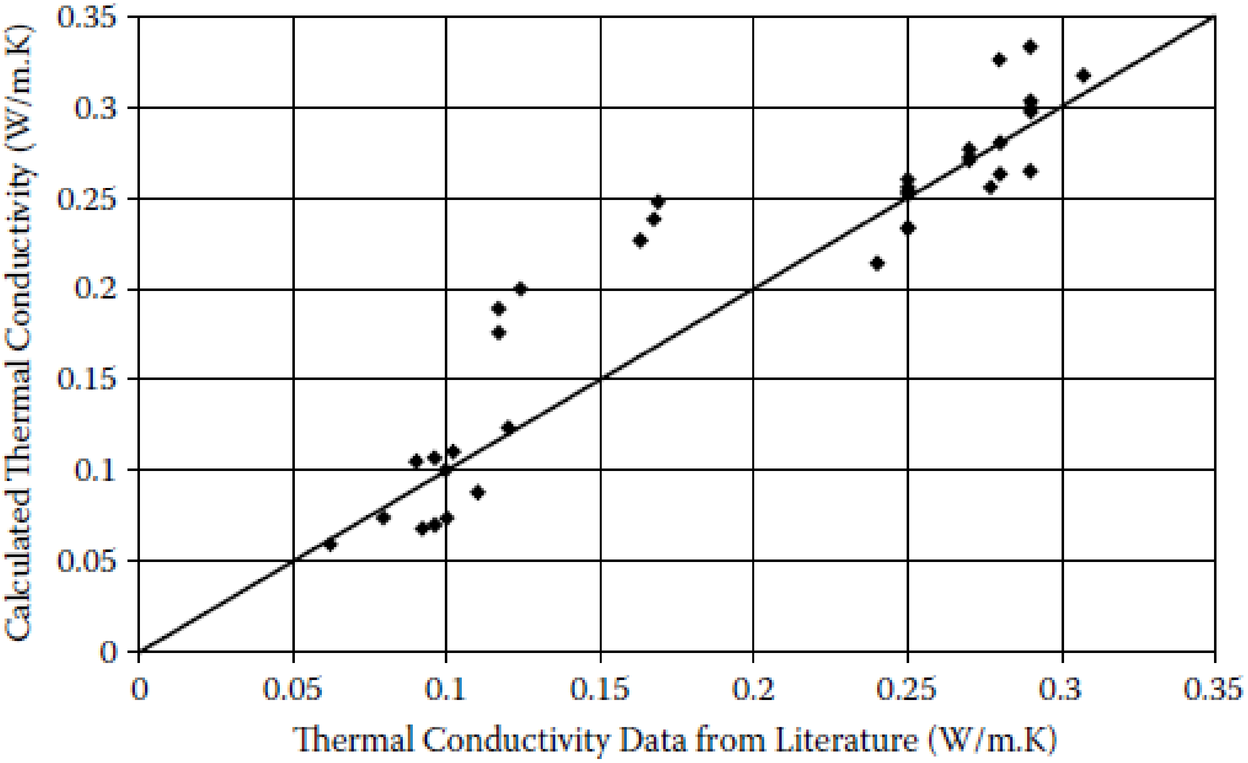
Table 5.11 Thermal property models for some common generic fire protection materials

Material	*Density ρ, kg/m^3*	*Base value of specific heat, J/kg.K*	*Thermal conductivity, W/m.K*
Rock fibre	155–180	900	$\lambda_{rock\ \ fibre} = 0.022 + 0.1475\left(\frac{T}{1000}\right)^3$
Mineral wool	165	840	$\lambda_{mineral\ \ wool} = 0.03 + 0.2438\left(\frac{T}{1000}\right)^3$
Calcium silicate	Various	900	$\lambda^* = \lambda_0^* + CT^3$ $\lambda_0^* = 0.23\frac{\rho}{1000}$ $C = 0.08 \times \frac{(2540-\rho)}{2540}$
Vermiculite	Various	900	$\lambda^* = \lambda_0^* + CT^3$ $\lambda_0^* = 0.27\frac{\rho}{1000}$ $C = 0.18 \times \frac{(1000-\rho)}{1000}$

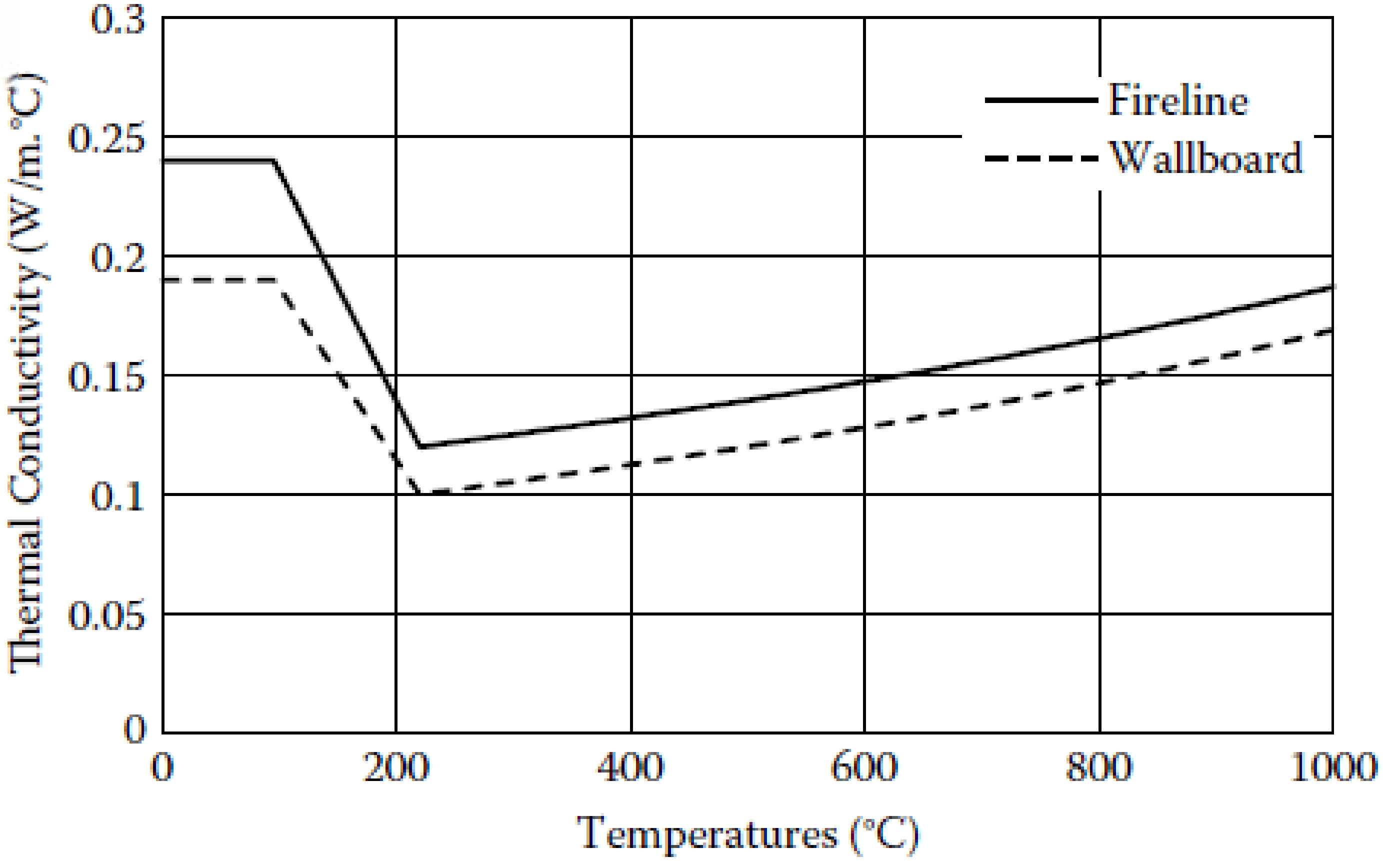
Validation: Effects of density: Vermiculite



Comparison of thermal conductivity values: Calcium Silicate



Gypsum Plaster

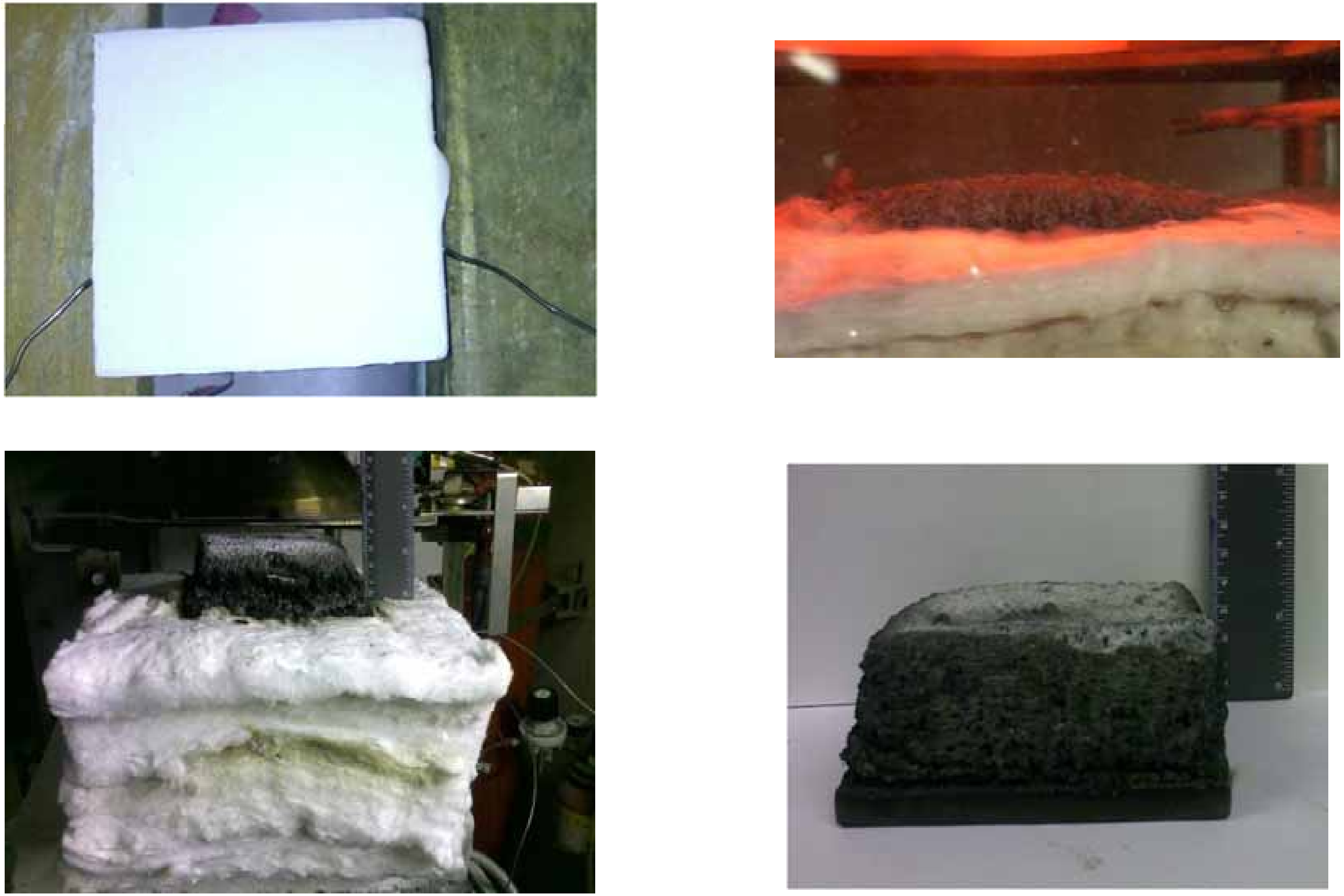


Conclusions

- Important to have reliable data of thermal conductivity.
- The effects of high temperature on thermal conductivity should be included.
- EN 13381-4 method gives thermal conductivity – temperature relationship, but information confidential to manufacturers . Also results lack fundamental insight and based on gross assumption-treating entire fire protection as one layer with average temperature.
- Thermal conductivity of porous materials can be theoretically analysed.
- High temperature radiation within pores should be included.
- High temperature thermal conductivity model proved accurate for a number of fire protection materials: rock fibre, mineral fibre, vermiculite, calcium silicate, gypsu, plaster.

Intumescent coatings

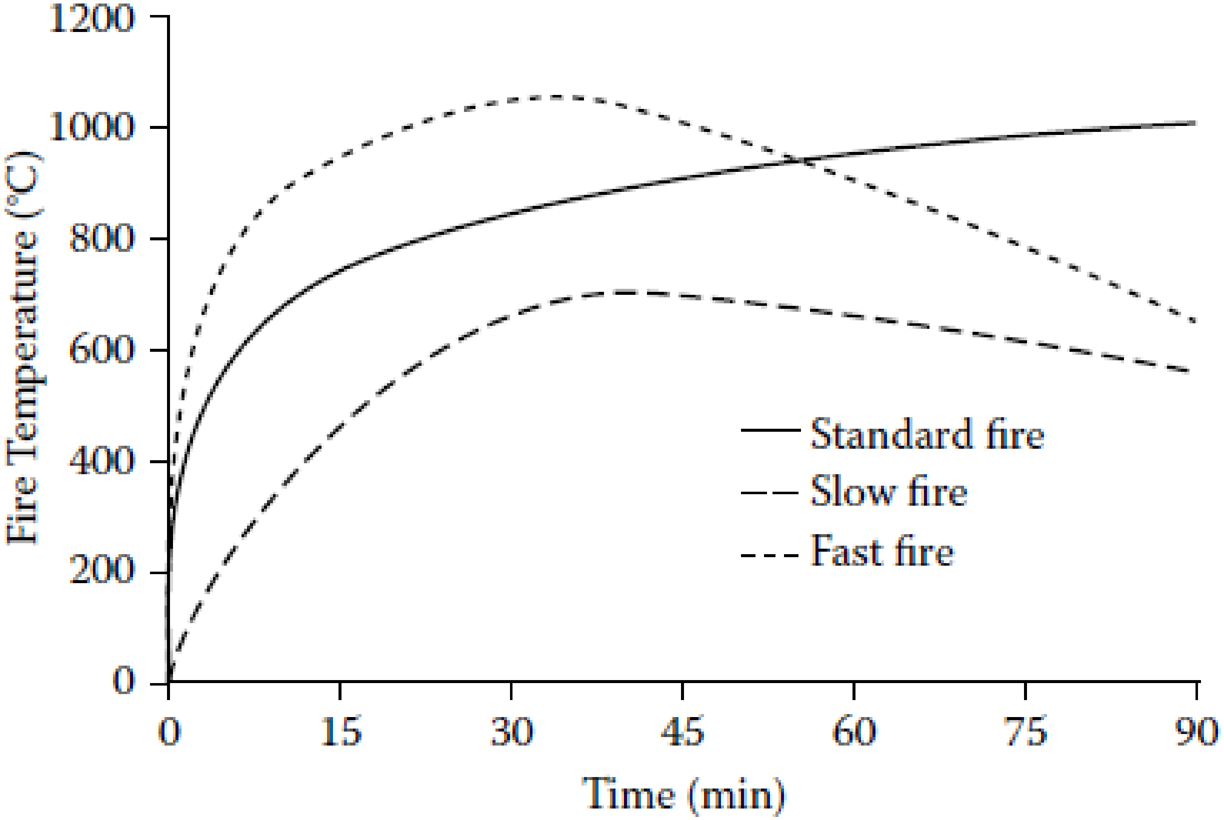
Introduction



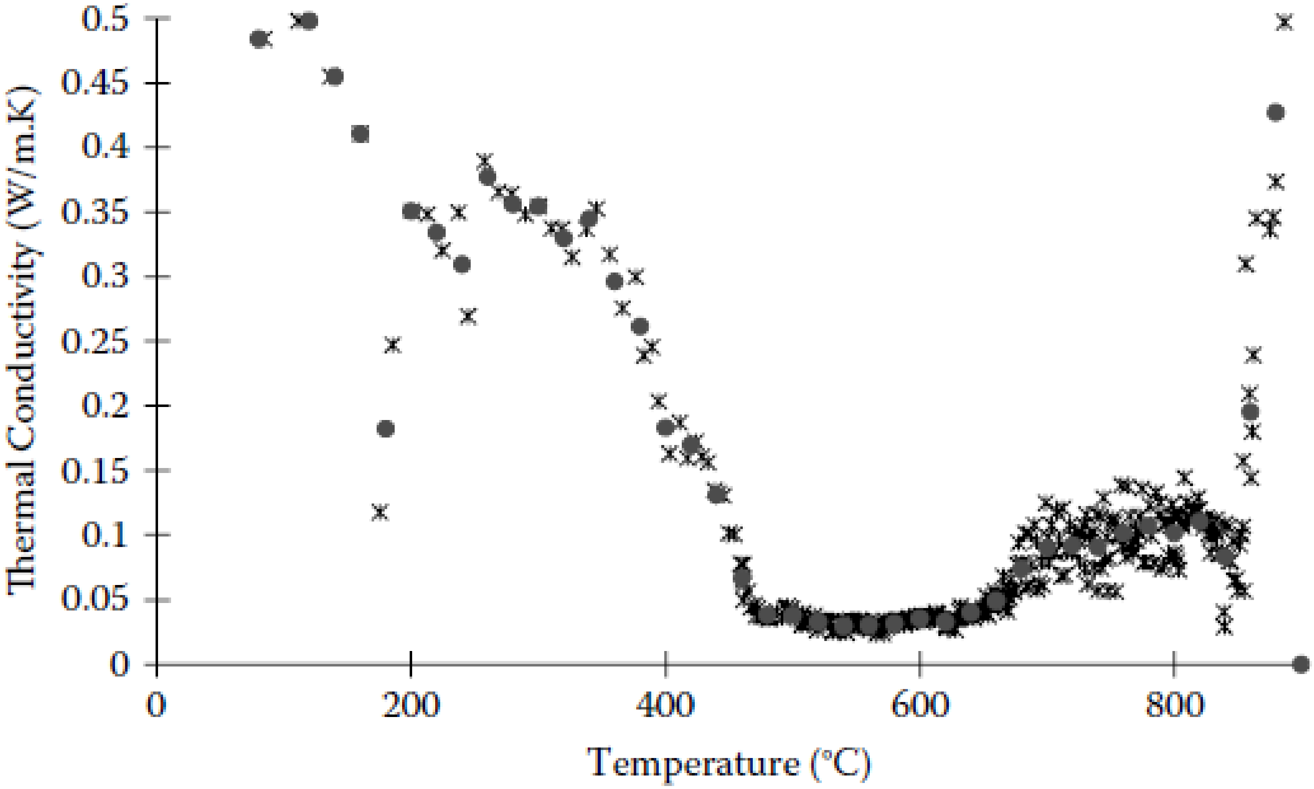
Thermal conductivity of fire protection materials: prEN 13381-8 assessment method

$$\lambda_p = \left[d_p \times \frac{V}{A_p} \times C_s \rho_s \times (1 + \phi / 3) \times \frac{1}{(T_{fi} - T_s)\Delta t} \right] \times \left[\Delta T_s + (e^{\phi/10} - 1)\Delta T_{fi} \right]$$

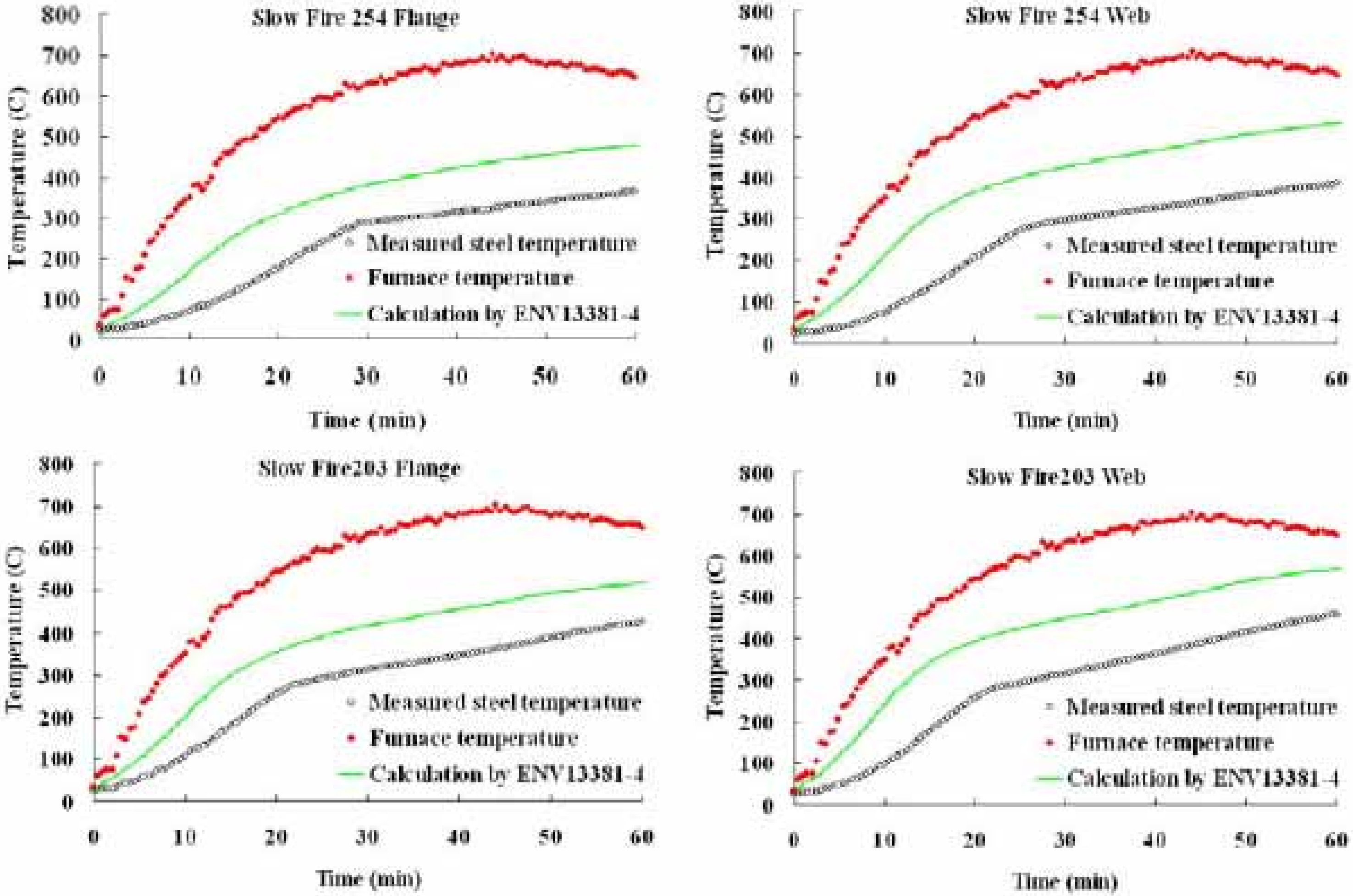
Inaccuracy of assessment method (prEN 13381-8)



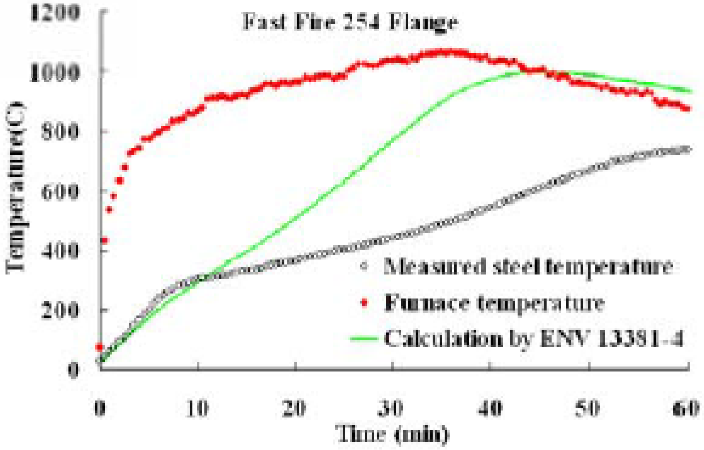
Effective thermal conductivity from standard fire test

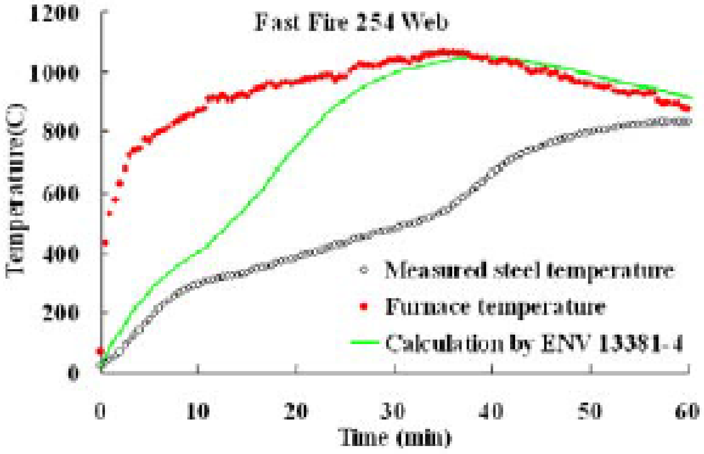


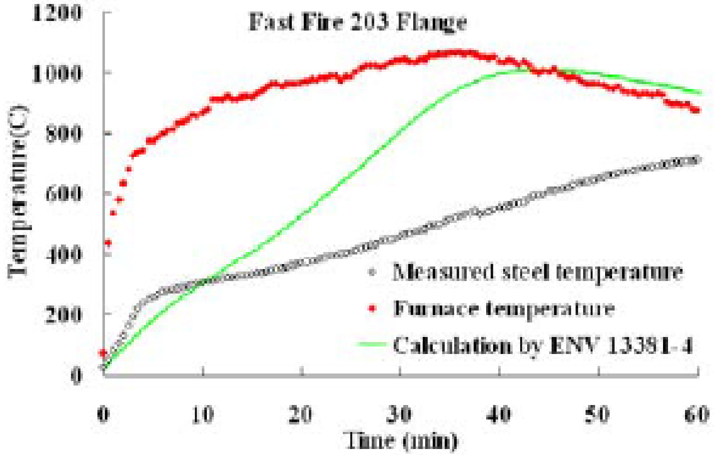
Predicted results for slow parametric fires

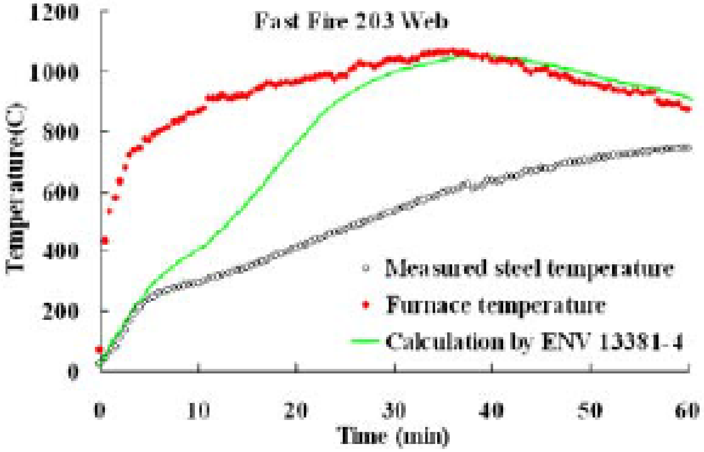


Predicted results for fast parametric fires

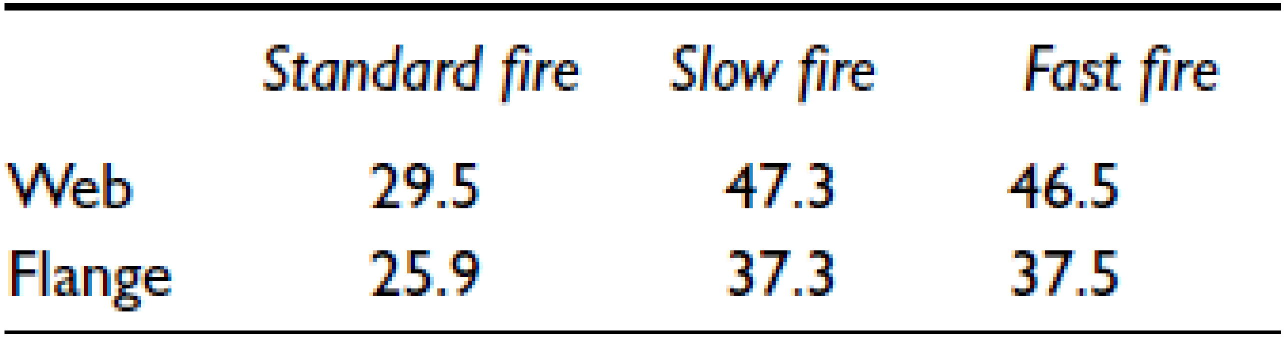






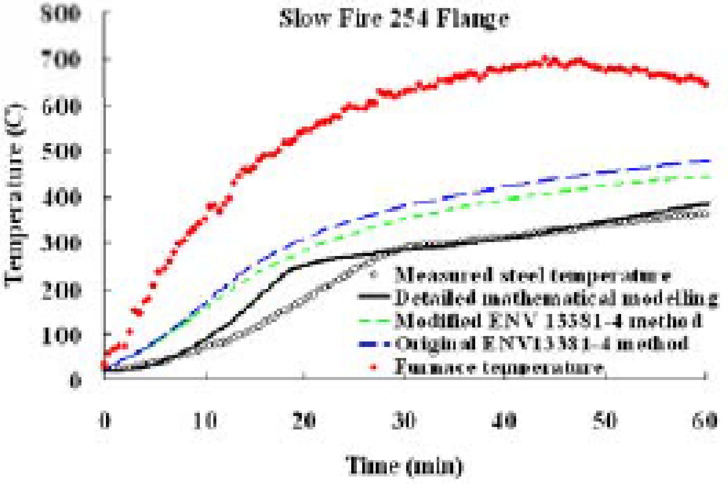


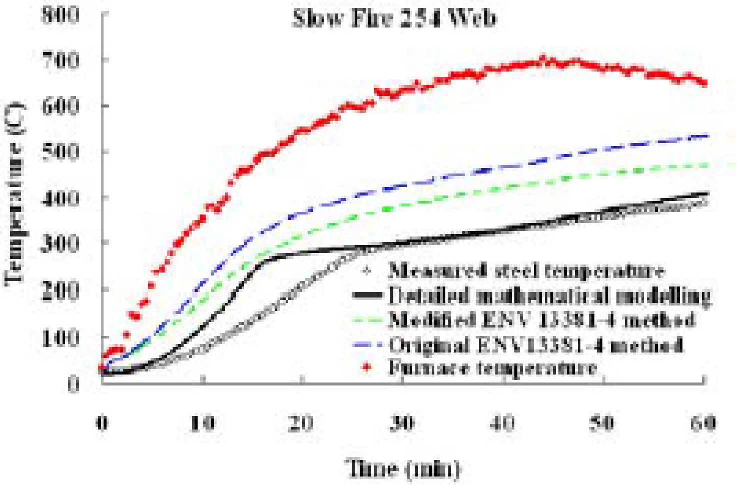
Expansion ratios

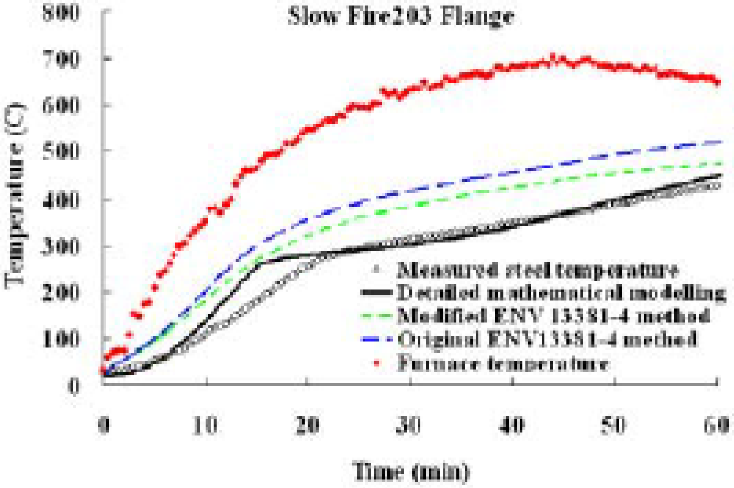


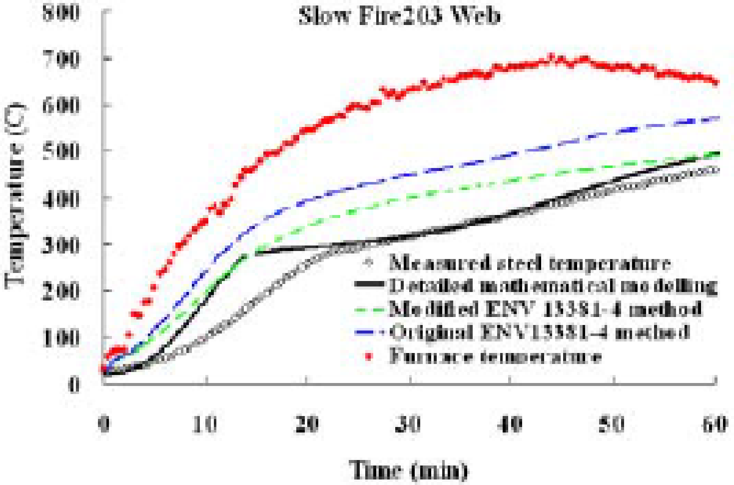
	Standard fire	*Slow fire*	*Fast fire*
Web	29.5	47.3	46.5
Flange	25.9	37.3	37.5

Including the effects of expansion thickness for slow fire

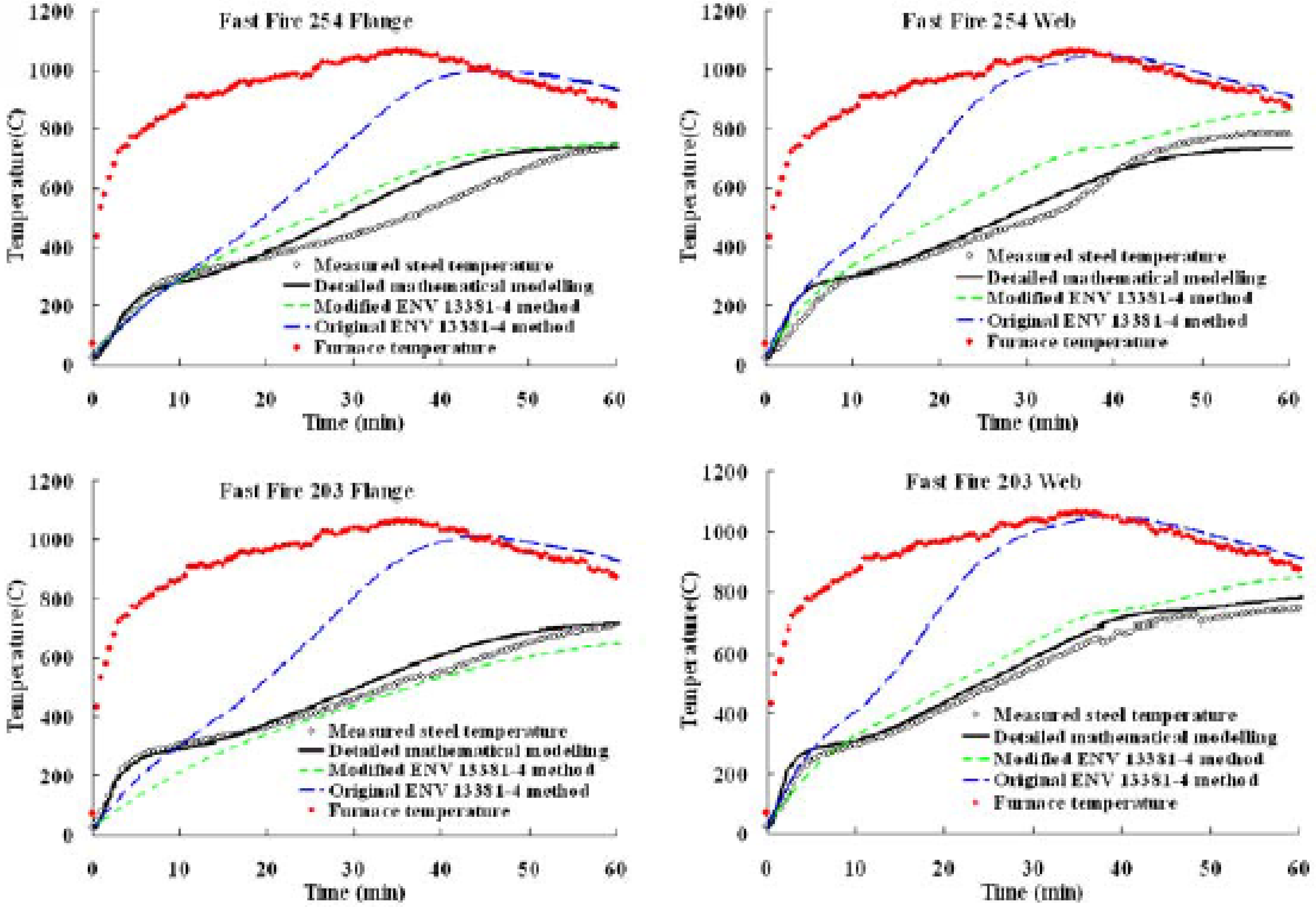




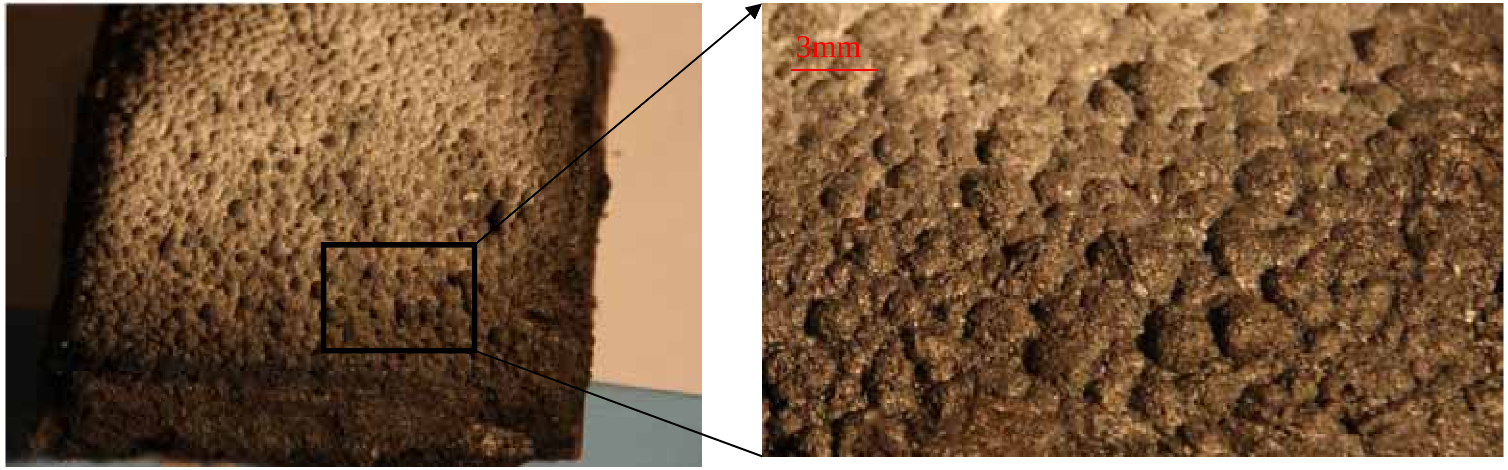




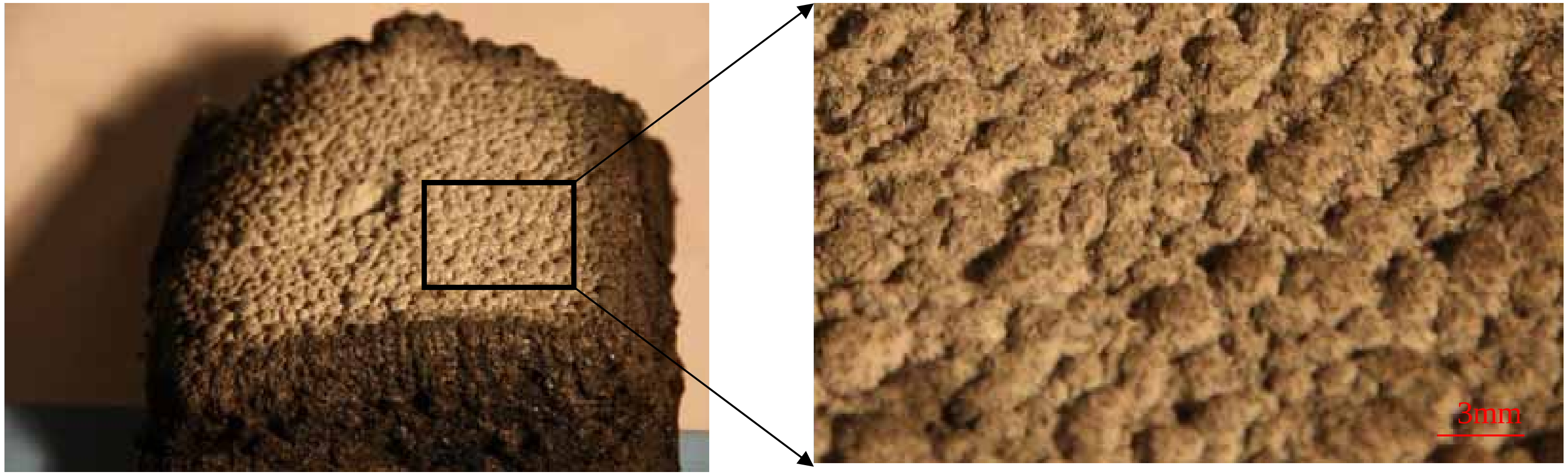
Including the effects of expansion thickness for fast fire



Char Structure



50 kw 0.4 mm D.F.T



65 kw 1.2 mm D.F.T

Modelling expansion

Based on ideal gas law:

$$\frac{\partial x}{\partial t} = \frac{\beta R}{a P_0 W_g}\left(T\frac{\partial m_2}{\partial t} + m_2\frac{\partial T}{\partial t}\right)(T_{melt} < T < T_C)$$

$$F = m_2\frac{\partial^2 x}{\partial t^2}$$

$$F = m_2\frac{\partial^2 T}{\partial t^2} + 2m_2\frac{\partial m_2}{\partial t}\frac{\partial T}{\partial t} + T^2\frac{\partial^2 m_2}{\partial t^2}$$

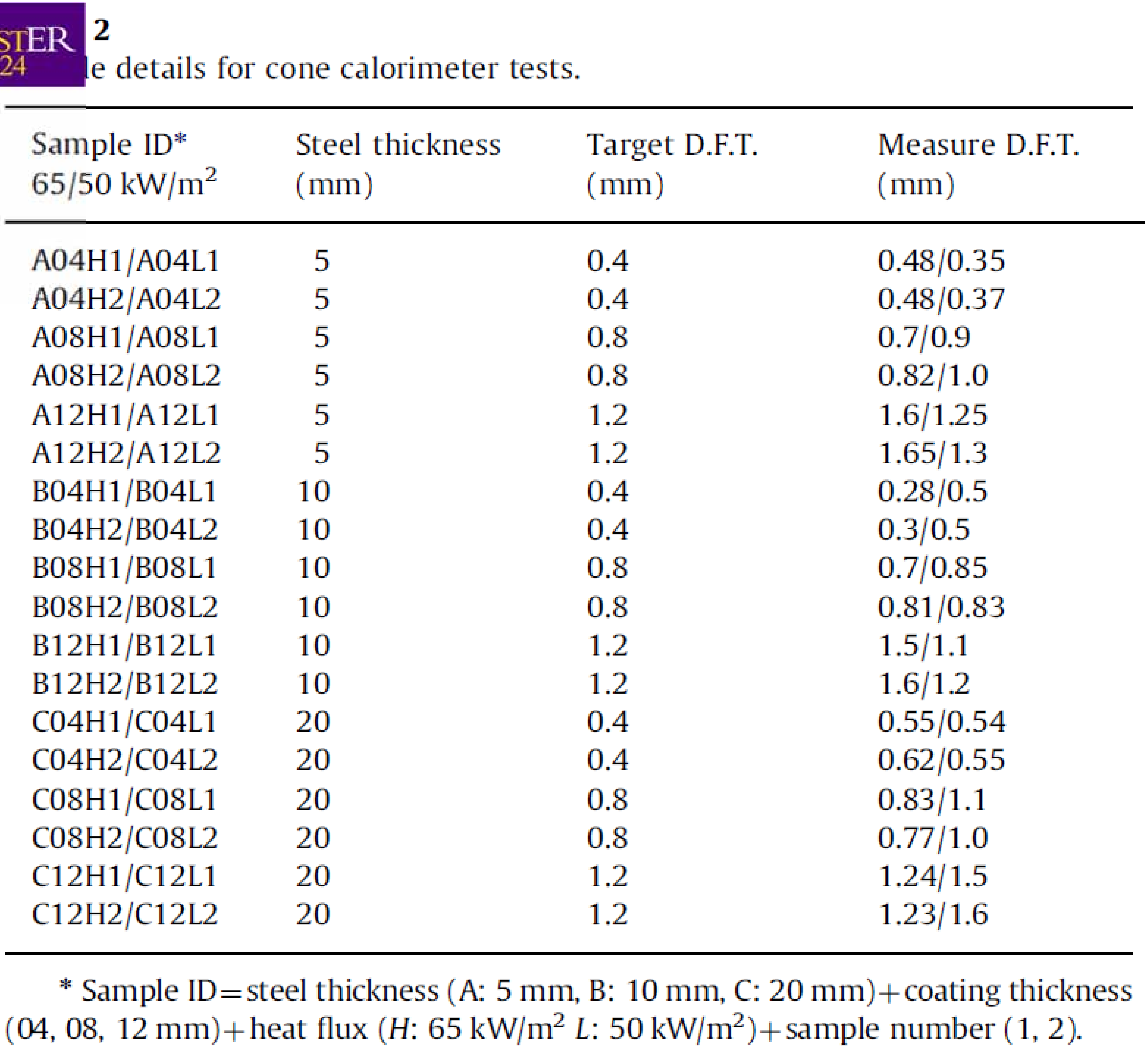
$$\because \frac{\partial^2 T}{\partial t^2} \approx 0 \text{ and } \frac{\partial^2 m_2}{\partial t^2} \approx 0$$

$$\therefore F \approx 2m_2\frac{\partial m_2}{\partial t}\frac{\partial T}{\partial t} \text{ when } F \to F_{\max}, \quad T = T_C$$

Retention of released gas of blowing agent

$$\beta = \left(\frac{T_{melt}}{T}\right)^{C_{trap} m_{s,g} T / m_{s,0} T_0}$$

Cone tests

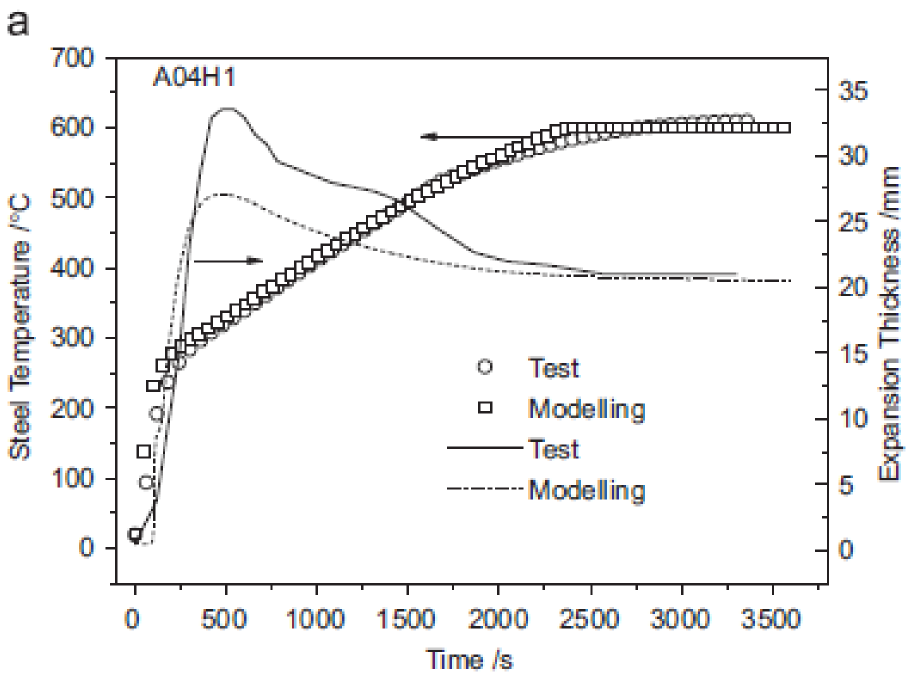


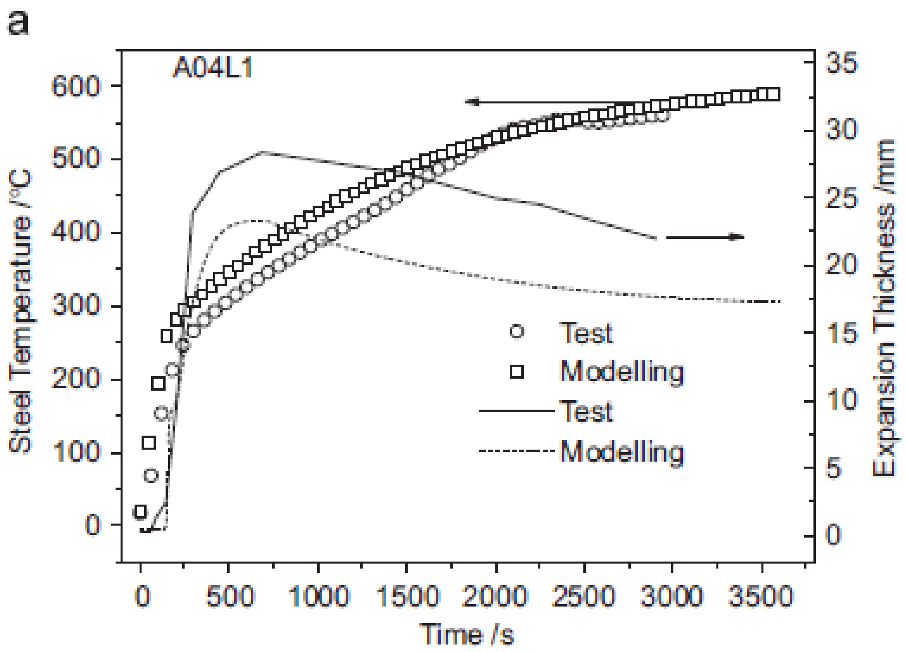
2
le details for cone calorimeter tests.

Sample ID* 65/50 kW/m^2	Steel thickness (mm)	Target D.F.T. (mm)	Measure D.F.T. (mm)
A04H1/A04L1	5	0.4	0.48/0.35
A04H2/A04L2	5	0.4	0.48/0.37
A08H1/A08L1	5	0.8	0.7/0.9
A08H2/A08L2	5	0.8	0.82/1.0
A12H1/A12L1	5	1.2	1.6/1.25
A12H2/A12L2	5	1.2	1.65/1.3
B04H1/B04L1	10	0.4	0.28/0.5
B04H2/B04L2	10	0.4	0.3/0.5
B08H1/B08L1	10	0.8	0.7/0.85
B08H2/B08L2	10	0.8	0.81/0.83
B12H1/B12L1	10	1.2	1.5/1.1
B12H2/B12L2	10	1.2	1.6/1.2
C04H1/C04L1	20	0.4	0.55/0.54
C04H2/C04L2	20	0.4	0.62/0.55
C08H1/C08L1	20	0.8	0.83/1.1
C08H2/C08L2	20	0.8	0.77/1.0
C12H1/C12L1	20	1.2	1.24/1.5
C12H2/C12L2	20	1.2	1.23/1.6

* Sample ID=steel thickness (A: 5 mm, B: 10 mm, C: 20 mm)+coating thickness (04, 08, 12 mm)+heat flux (*H*: 65 kW/m^2 *L*: 50 kW/m^2)+sample number (1, 2).

Comparison between theory and test results





Comparison of final thickness

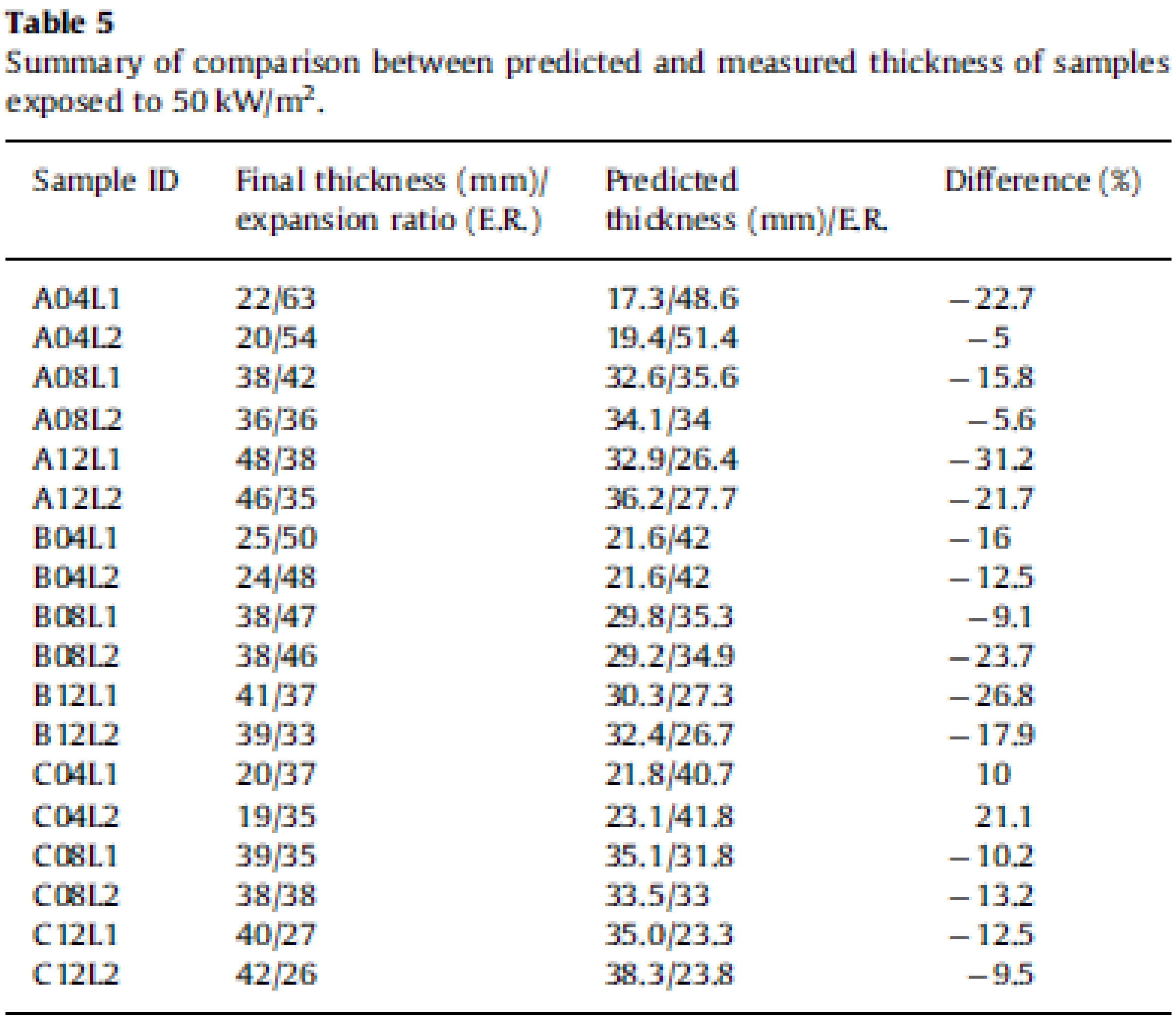
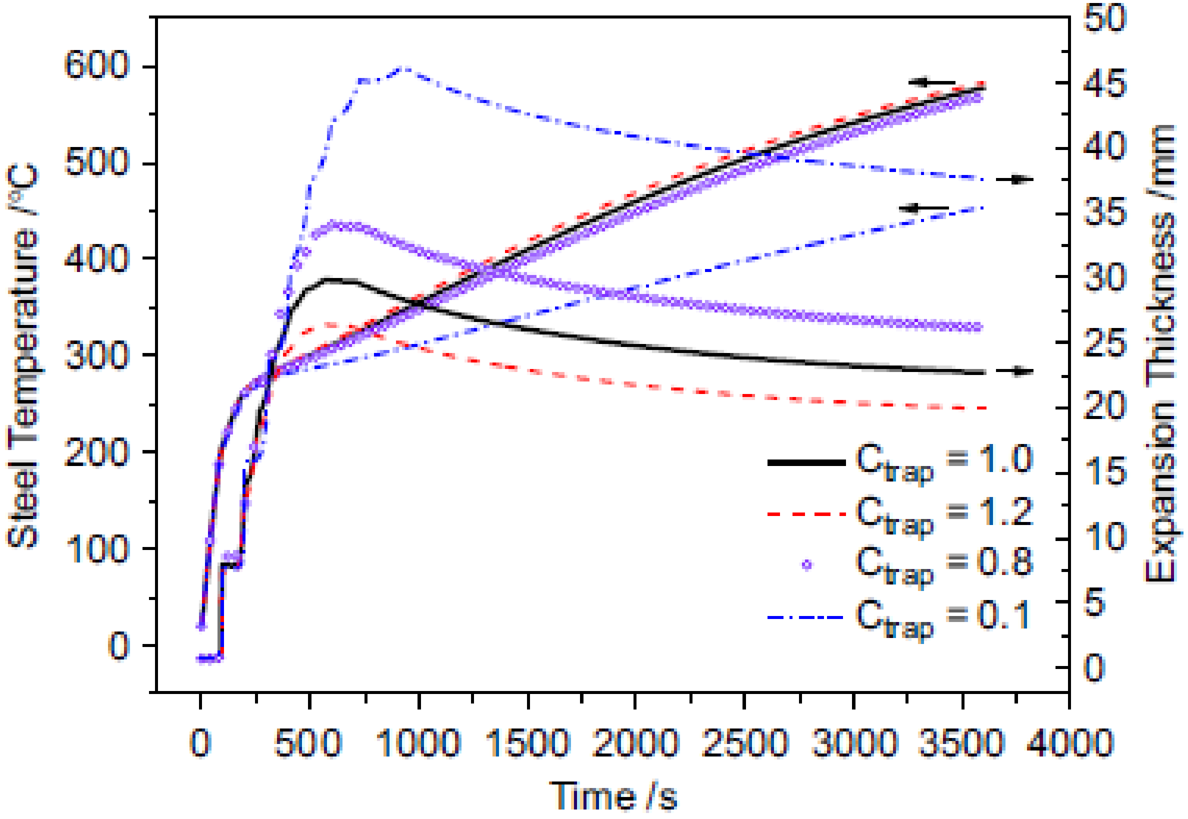


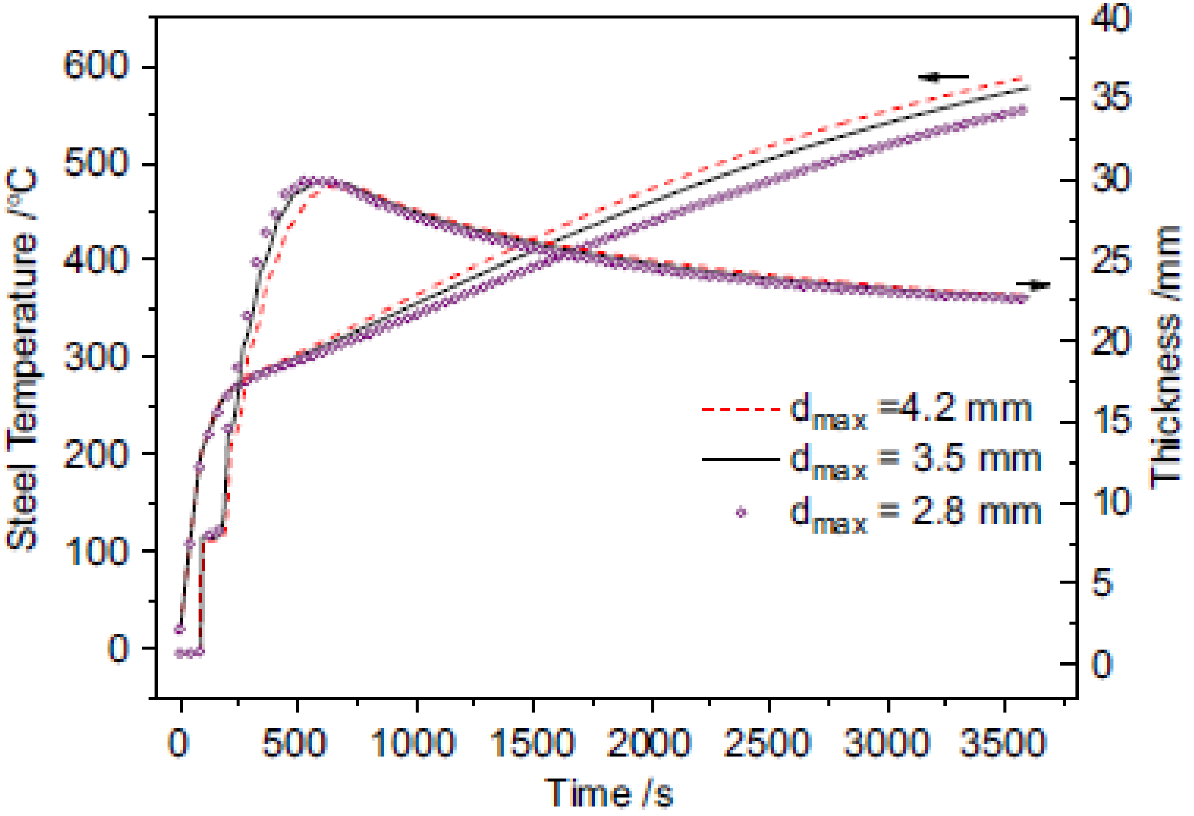
Table 5
Summary of comparison between predicted and measured thickness of samples exposed to 50 kW/m^2.

Sample ID	Final thickness (mm)/ expansion ratio (E.R.)	Predicted thickness (mm)/E.R.	Difference (%)
A04L1	22/63	17.3/48.6	−22.7
A04L2	20/54	19.4/51.4	−5
A08L1	38/42	32.6/35.6	−15.8
A08L2	36/36	34.1/34	−5.6
A12L1	48/38	32.9/26.4	−31.2
A12L2	46/35	36.2/27.7	−21.7
B04L1	25/50	21.6/42	−16
B04L2	24/48	21.6/42	−12.5
B08L1	38/47	29.8/35.3	−9.1
B08L2	38/46	29.2/34.9	−23.7
B12L1	41/37	30.3/27.3	−26.8
B12L2	39/33	32.4/26.7	−17.9
C04L1	20/37	21.8/40.7	10
C04L2	19/35	23.1/41.8	21.1
C08L1	39/35	35.1/31.8	−10.2
C08L2	38/38	33.5/33	−13.2
C12L1	40/27	35.0/23.3	−12.5
C12L2	42/26	38.3/23.8	−9.5

Sensitivity: effects of C_{trap} value



Sensitivity: effects of bubble size



Reference

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Global modelling of fire protection performance of intumescent coating under different cone calorimeter heating conditions

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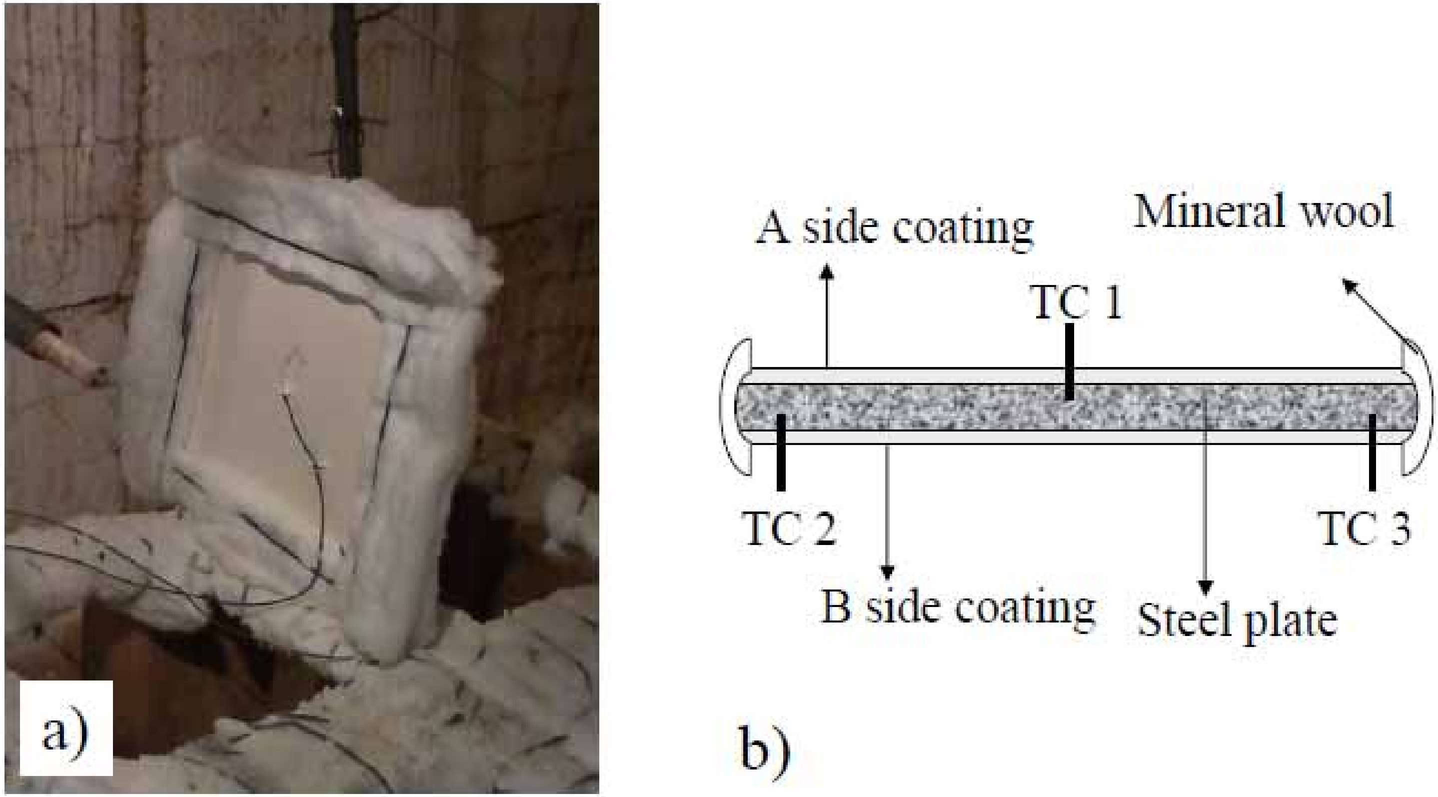
Further results from furnace testing (using exactly the same predictive model and properties as cone tests)



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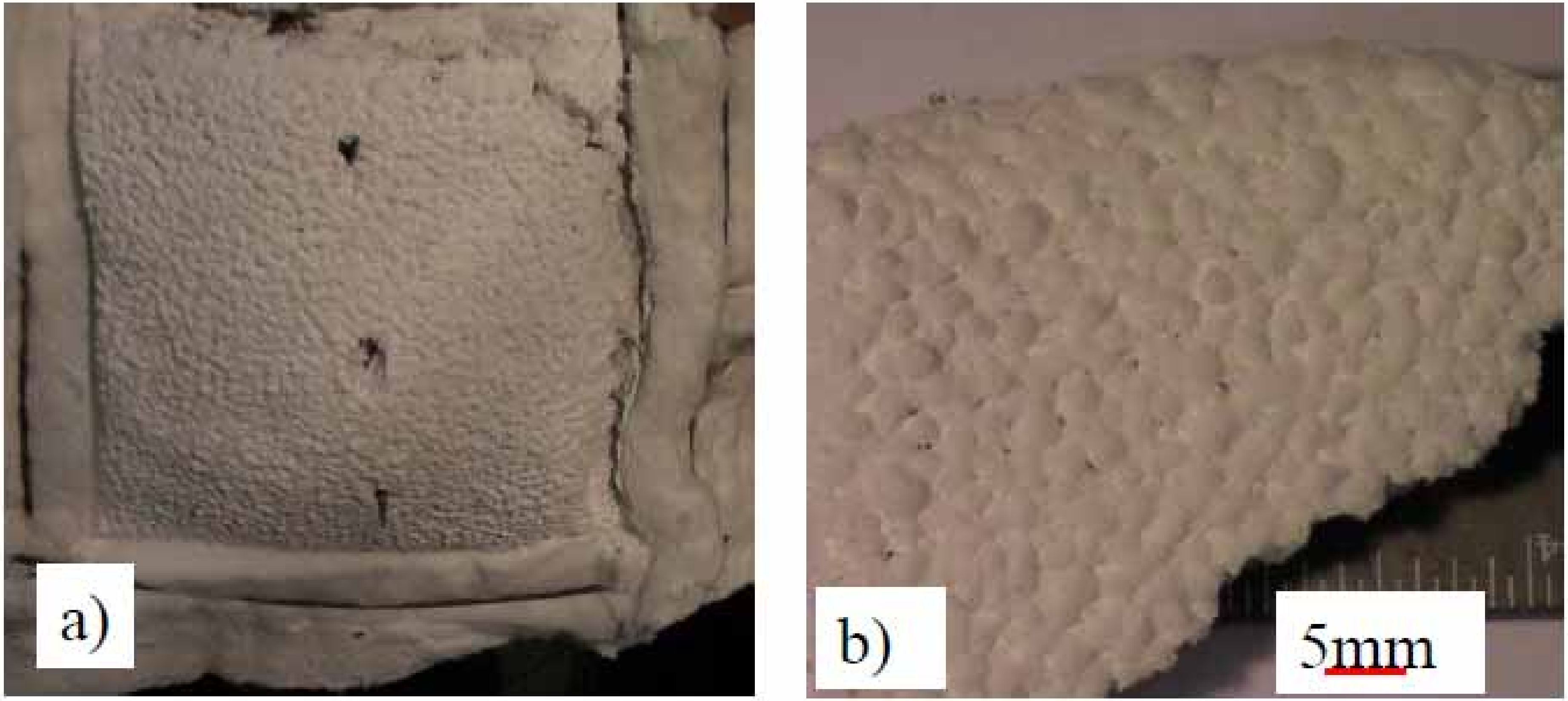
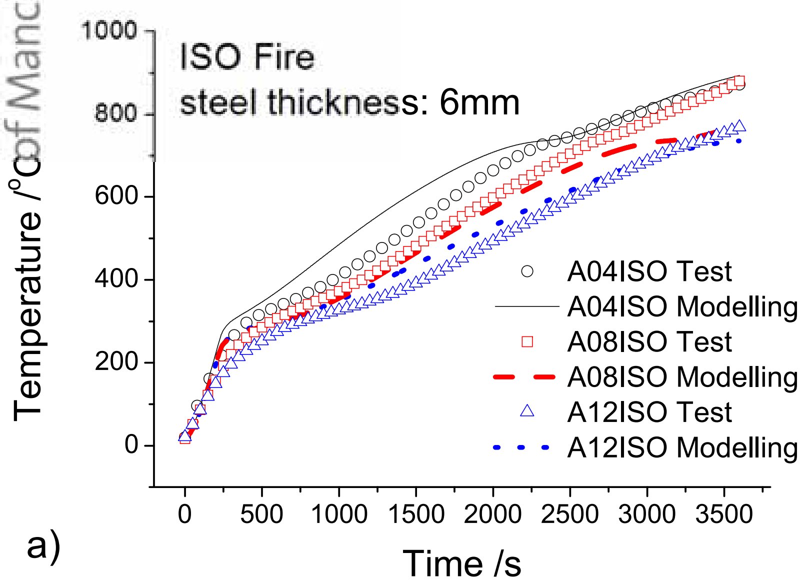


Examples of comparison: ISO fire



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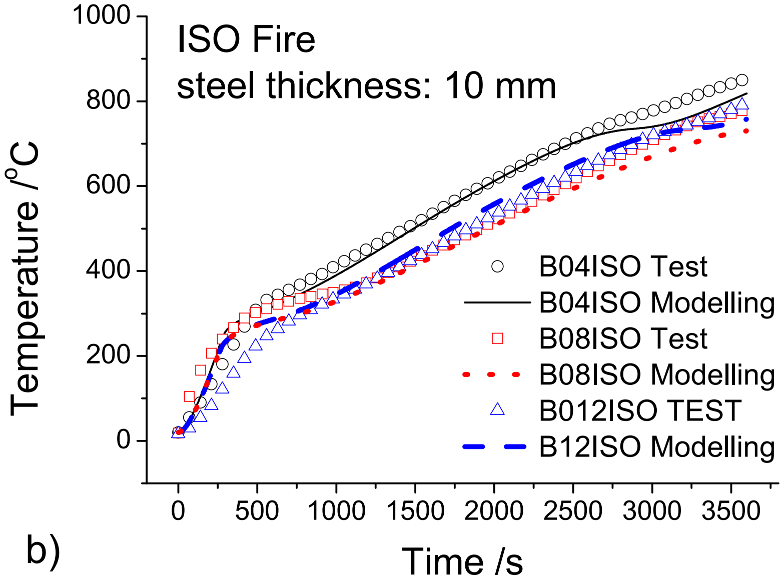

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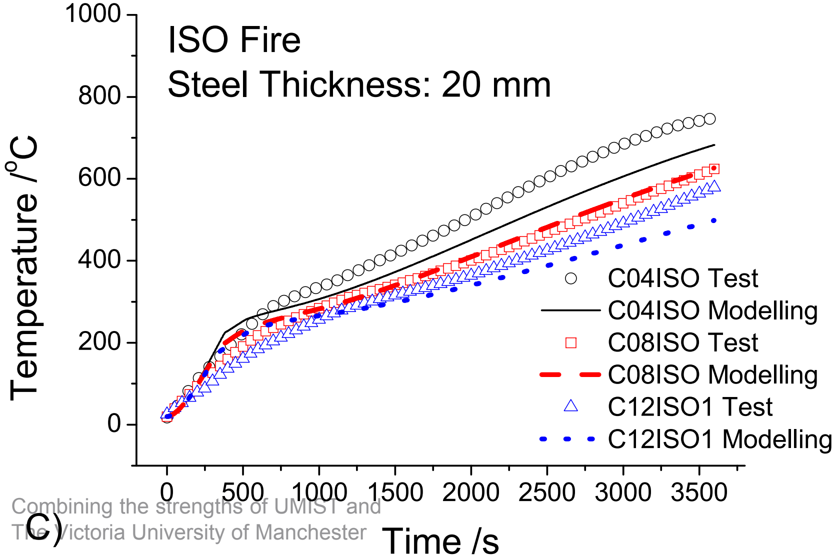
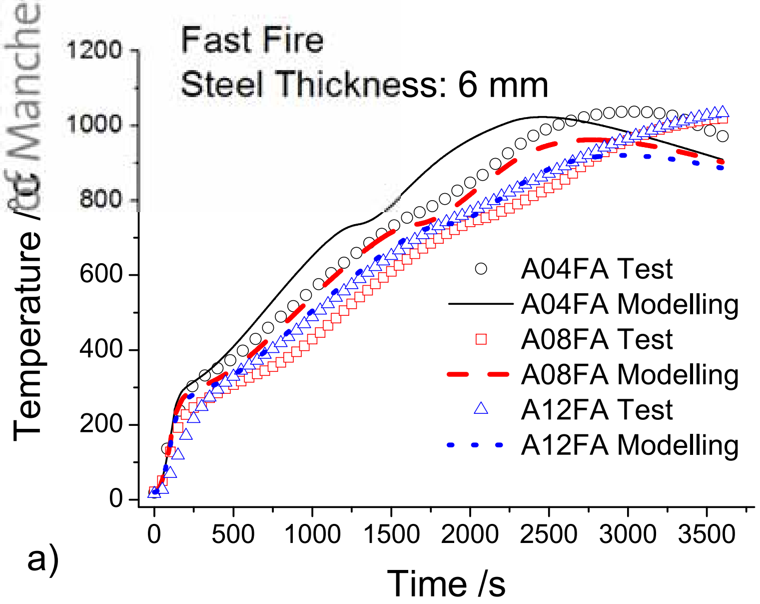


c)

Fast Fire



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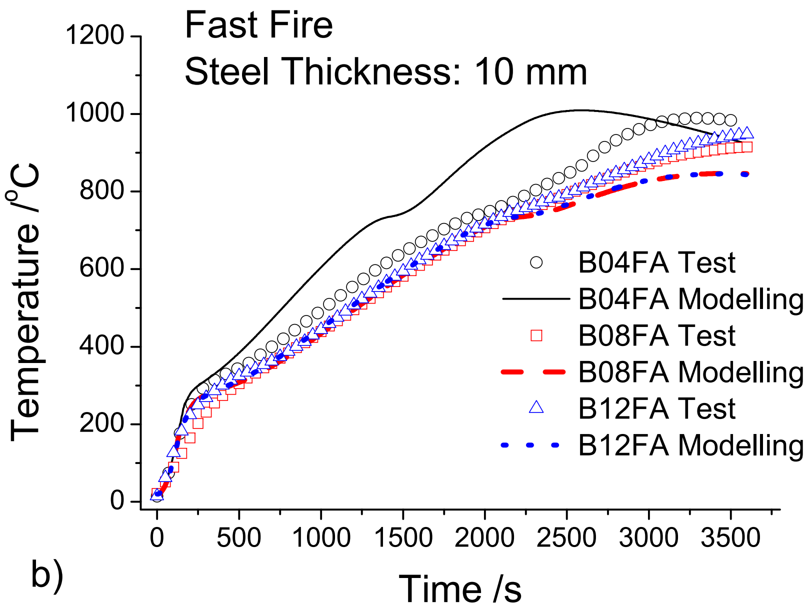

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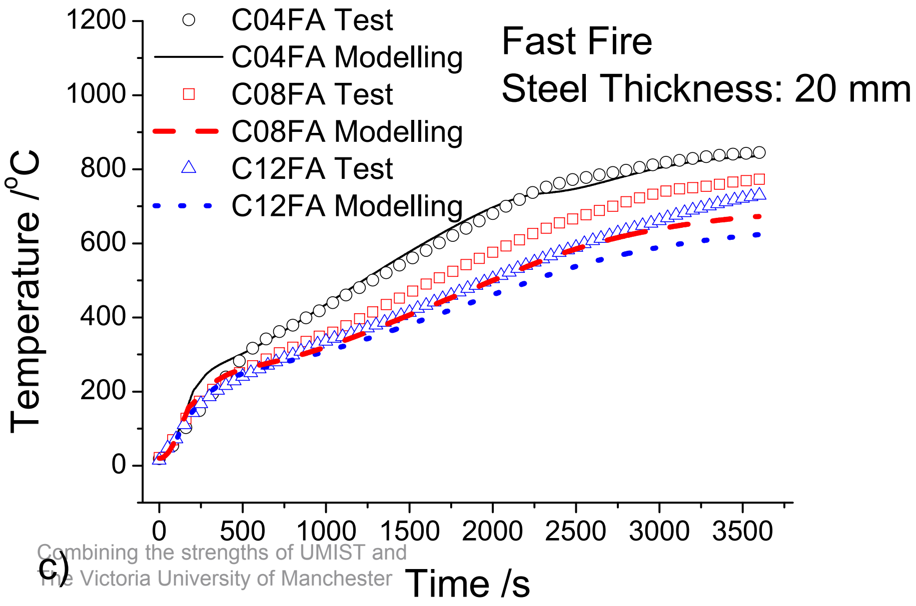
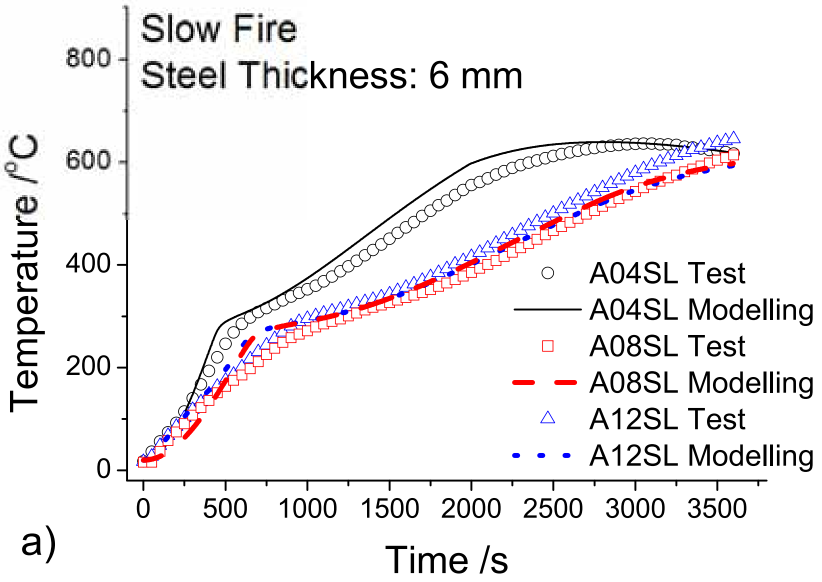


c)

Slow Fire



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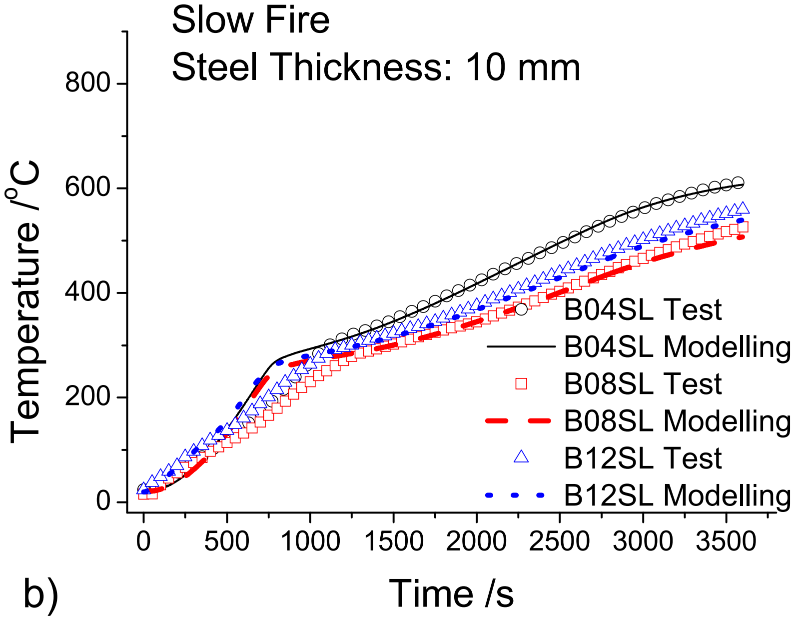

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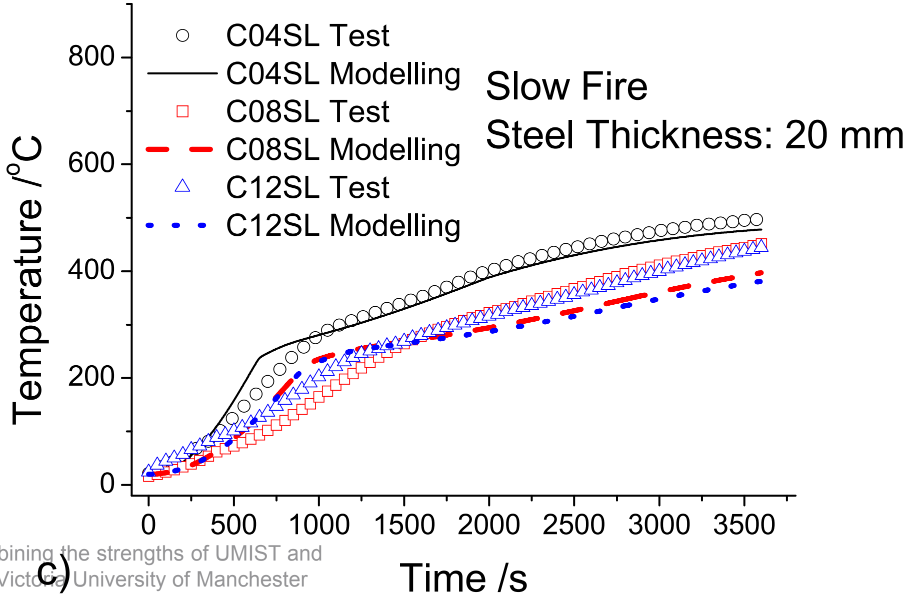
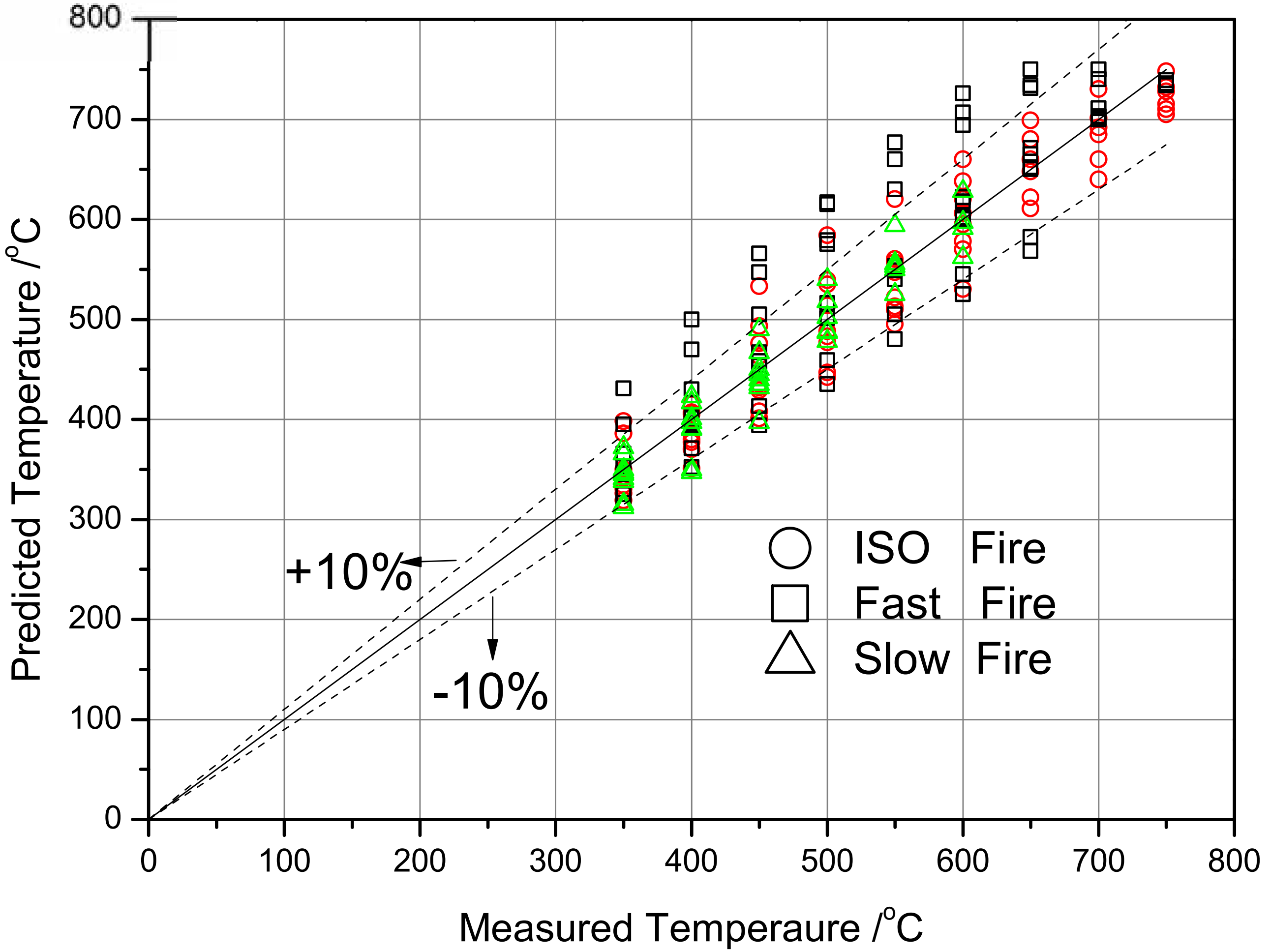
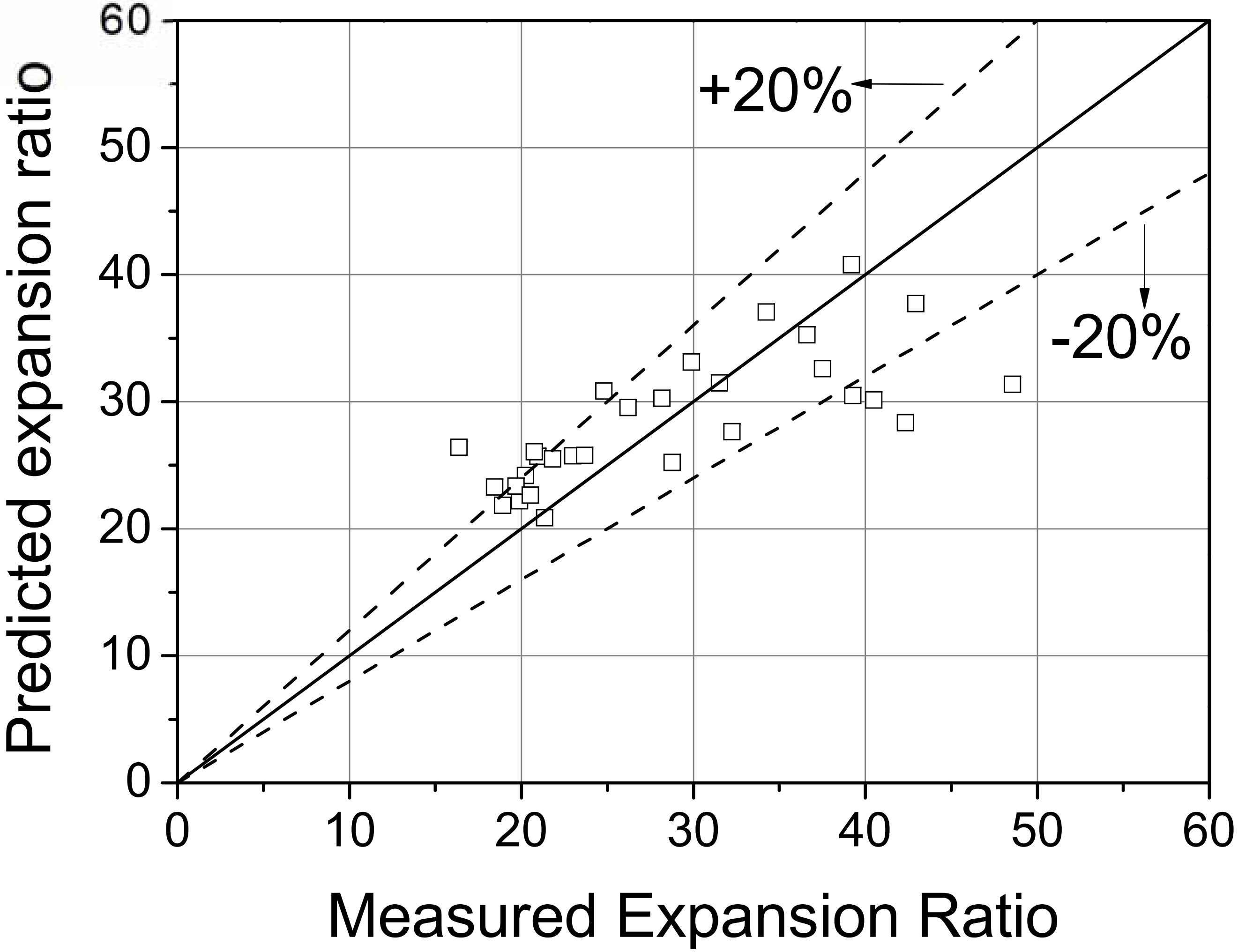


c)

Overall temperature accuracy



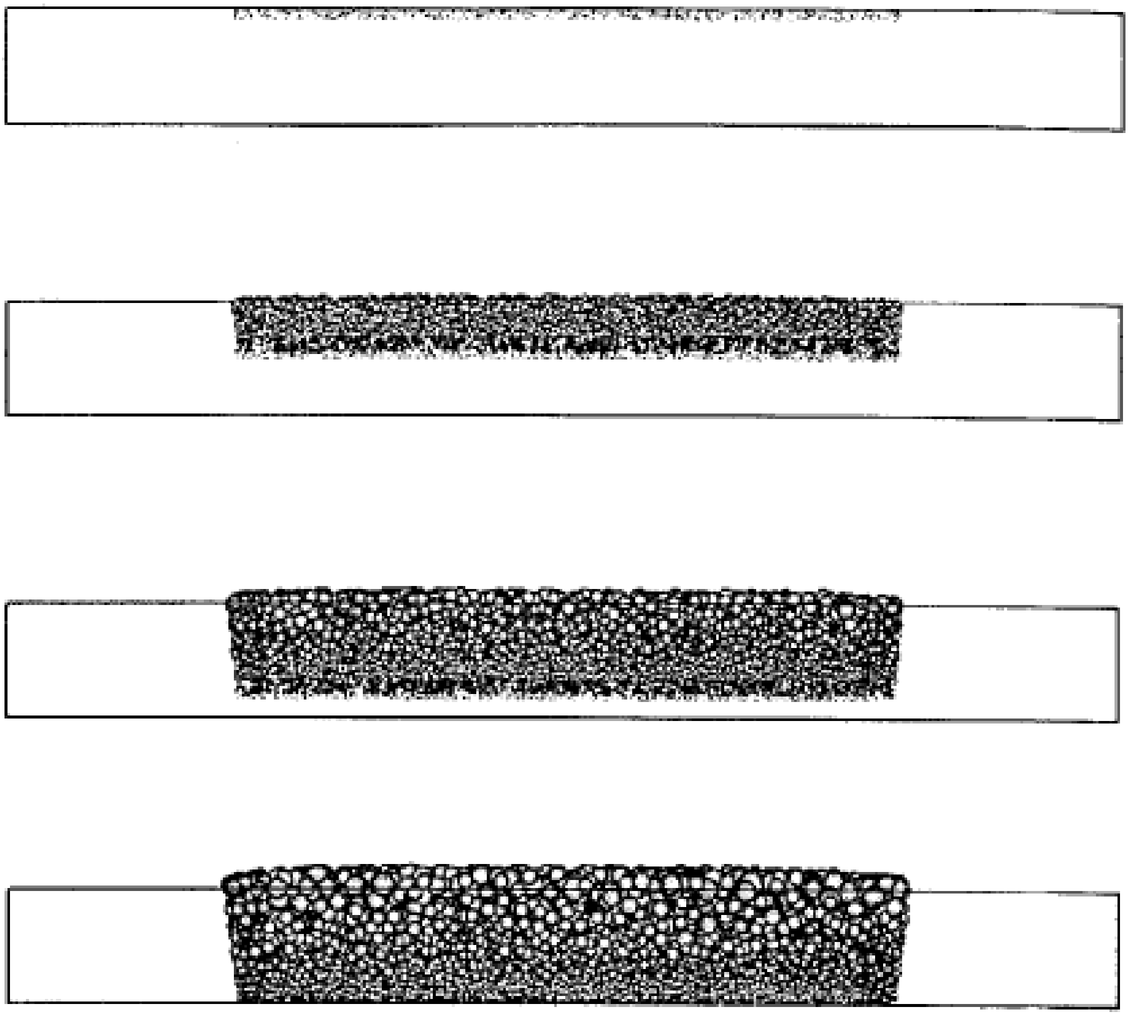
Overall thickness accuracy



Conclusions

- Intumescent coatings are reactive materials. prEN 13381-8 not suitable for different fire conditions.
- Expansion process key to coating behaviour.
- A consistent set of material properties can be used for all different fire conditions, including cone calorimeter tests under different levels of heat flux, and furnace fire with different temperature-time relationships.
- Model can predict expansion process and final expansion thickness within 20%, steel temperature-time relationships with 10%.

Further research: microscopic modelling of expansion



Further research: effects of weathering


(a) AZ-1-00


(b) AZ-1-04

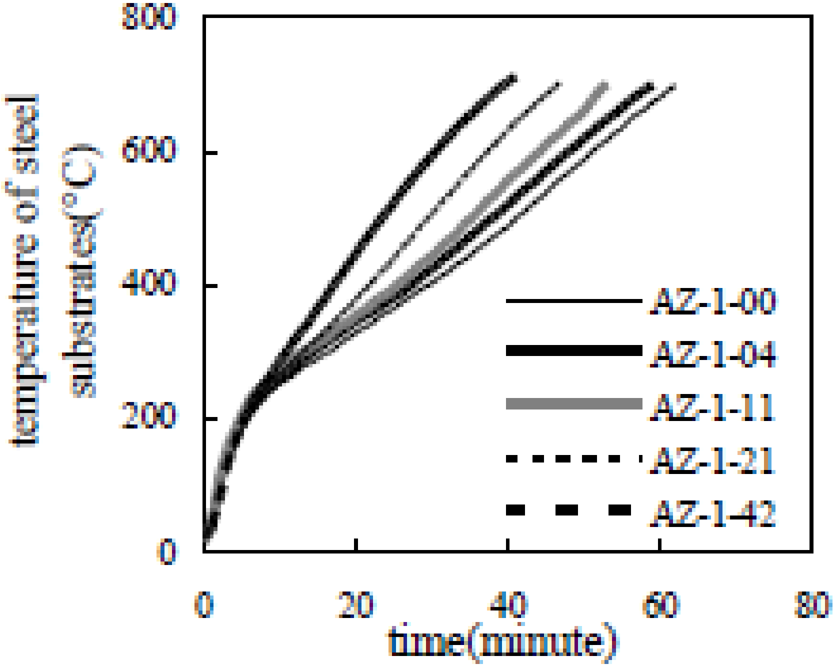

(c) AZ-1-11


(d) AZ-1-21

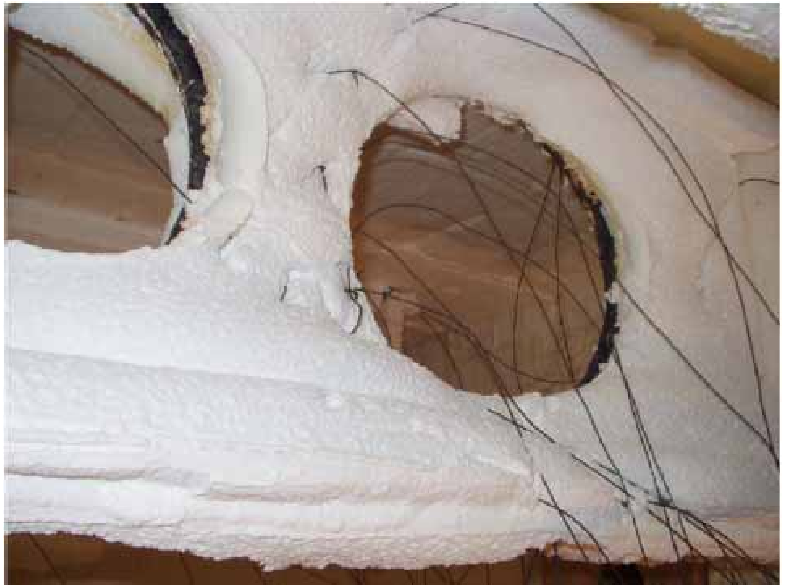

(e) AZ-1-42

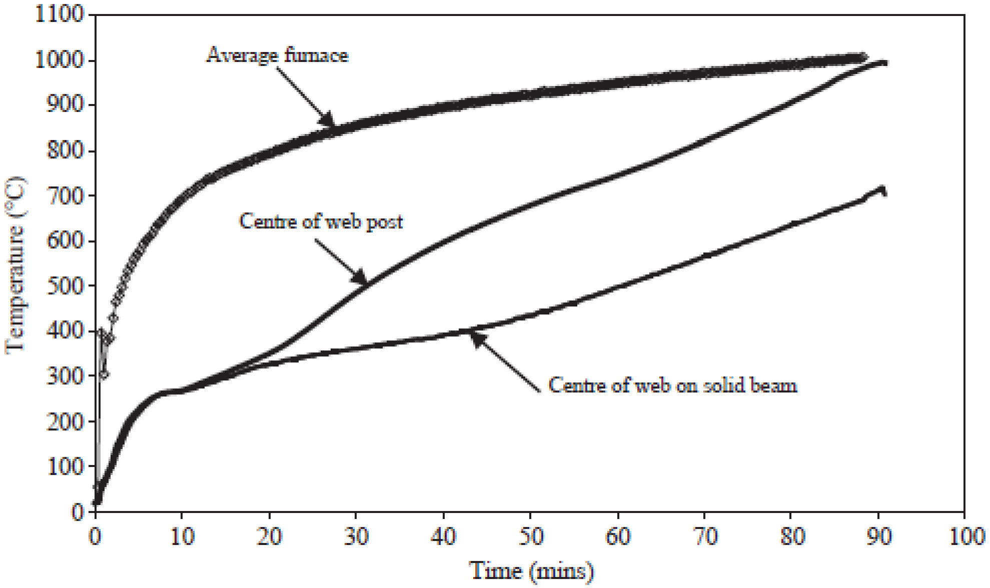

(a) AZ-2-00


(b) AZ-2-42



Further research: stickability





Overall summary

- Properties of fire protection materials are vital information to performance-based fire engineering of structures.
- A relatively neglected area to other aspects of structural fire engineering.
- Some progresses have been made recently. But much more research is required.
- Technical challenges are as deep as the most challenging of predicting structural performance in fire.


Missing
Insulation