Properties of Fire Protection Materials

with special reference to intumescent coatings

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General Structural Fire Engineering Procedure

- Fire behaviour
- Heat Transfer
- Assessment of structural behaviour at elevated temperatures
- Thermal properties
- Mechanical properties
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
A Model of Thermal Conductivity of Porous Materials

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

\[ \beta = \frac{\lambda_g}{\lambda_s}. \]
“Effective” thermal conductivity of hot air

\[ \lambda_g = \lambda_{g,\text{cond}} + \lambda_{g,\text{rad}} \]

\[ \lambda_{g,\text{rad}} = 4GdE\sigma T^3 \]

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

[Graph showing thermal conductivity of Fireline and Wallboard at different temperatures]
Approximately, if $\varepsilon \approx 1$

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

\[
\lambda^* = C_1 + C_2 \lambda_g \quad \rightarrow \quad \lambda^* = \lambda_0^* + C T^3
\]
Some thermal conductivity models of common fire protection materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$, kg/m$^3$</th>
<th>Base value of specific heat, J/kg.K</th>
<th>Thermal conductivity, W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock fibre</td>
<td>155–180</td>
<td>900</td>
<td>$\lambda_{\text{rock fibre}} = 0.022 + 0.1475 \left( \frac{T}{1000} \right)^3$</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>165</td>
<td>840</td>
<td>$\lambda_{\text{mineral wool}} = 0.03 + 0.2438 \left( \frac{T}{1000} \right)^3$</td>
</tr>
<tr>
<td>Calcium silicate</td>
<td>Various</td>
<td>900</td>
<td>$\lambda^* = \lambda_0^* + CT^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\lambda_0^* = \frac{0.23 \rho}{1000}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C = 0.08 \times \frac{(2540 - \rho)}{2540}$</td>
</tr>
<tr>
<td>Vermiculite</td>
<td>Various</td>
<td>900</td>
<td>$\lambda^* = \lambda_0^* + CT^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\lambda_0^* = \frac{0.27 \rho}{1000}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C = 0.18 \times \frac{(1000 - \rho)}{1000}$</td>
</tr>
</tbody>
</table>
Validation: Effects of density: Vermiculite
Comparison of thermal conductivity values: Calcium Silicate
Gypsum Plaster

![Graph showing thermal conductivity of Fireline and Wallboard vs temperatures.](image-url)
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, gypsum, 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

<table>
<thead>
<tr>
<th></th>
<th>Standard fire</th>
<th>Slow fire</th>
<th>Fast fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web</td>
<td>29.5</td>
<td>47.3</td>
<td>46.5</td>
</tr>
<tr>
<td>Flange</td>
<td>25.9</td>
<td>37.3</td>
<td>37.5</td>
</tr>
</tbody>
</table>
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:

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

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

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

\[ \therefore \frac{\partial^2 T}{\partial t^2} \approx 0 \text{ and } \frac{\partial^2 m_2}{\partial t^2} \approx 0 \]

\[ \therefore F \approx 2m_2 \frac{\partial m_2}{\partial t} \frac{\partial T}{\partial t} \text{ when } F \rightarrow F_{\text{max}}, \quad T = T_C \]
Retention of released gas of blowing agent

\[ \beta = \left( \frac{T_{\text{melt}}}{T} \right)^{C_{\text{trap}} m_{s,g} T/m_{s,0} T_0} \]
Cone tests

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

* Sample ID = steel thickness (A: 5 mm, B: 10 mm, C: 20 mm) + coating thickness (04, 08, 12 mm) + heat flux (H: 65 kW/m² L: 50 kW/m²) + 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/m².

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Final thickness (mm)/expansion ratio (E.R.)</th>
<th>Predicted thickness (mm)/E.R.</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A04L1</td>
<td>22/63</td>
<td>17.3/48.6</td>
<td>−22.7</td>
</tr>
<tr>
<td>A04L2</td>
<td>20/54</td>
<td>19.4/51.4</td>
<td>−5</td>
</tr>
<tr>
<td>A08L1</td>
<td>38/42</td>
<td>32.6/35.6</td>
<td>−15.8</td>
</tr>
<tr>
<td>A08L2</td>
<td>36/36</td>
<td>34.1/34</td>
<td>−5.6</td>
</tr>
<tr>
<td>A12L1</td>
<td>48/38</td>
<td>32.9/26.4</td>
<td>−31.2</td>
</tr>
<tr>
<td>A12L2</td>
<td>46/35</td>
<td>36.2/27.7</td>
<td>−21.7</td>
</tr>
<tr>
<td>B04L1</td>
<td>25/50</td>
<td>21.6/42</td>
<td>−16</td>
</tr>
<tr>
<td>B04L2</td>
<td>24/48</td>
<td>21.6/42</td>
<td>−12.5</td>
</tr>
<tr>
<td>B08L1</td>
<td>38/47</td>
<td>29.8/35.3</td>
<td>−9.1</td>
</tr>
<tr>
<td>B08L2</td>
<td>38/46</td>
<td>29.2/34.9</td>
<td>−23.7</td>
</tr>
<tr>
<td>B12L1</td>
<td>41/37</td>
<td>30.3/27.3</td>
<td>−26.8</td>
</tr>
<tr>
<td>B12L2</td>
<td>39/33</td>
<td>32.4/26.7</td>
<td>−17.9</td>
</tr>
<tr>
<td>C04L1</td>
<td>20/37</td>
<td>21.8/40.7</td>
<td>10</td>
</tr>
<tr>
<td>C04L2</td>
<td>19/35</td>
<td>23.1/41.8</td>
<td>21.1</td>
</tr>
<tr>
<td>C08L1</td>
<td>39/35</td>
<td>35.1/31.8</td>
<td>−10.2</td>
</tr>
<tr>
<td>C08L2</td>
<td>38/38</td>
<td>33.5/33</td>
<td>−13.2</td>
</tr>
<tr>
<td>C12L1</td>
<td>40/27</td>
<td>35.0/23.3</td>
<td>−12.5</td>
</tr>
<tr>
<td>C12L2</td>
<td>42/26</td>
<td>38.3/23.8</td>
<td>−9.5</td>
</tr>
</tbody>
</table>
Sensitivity: effects of $C_{\text{trap}}$ value
Sensitivity: effects of bubble size
Global modelling of fire protection performance of intumescent coating under different cone calorimeter heating conditions

Y. Zhang\textsuperscript{a}, Y.C. Wang\textsuperscript{a,*}, C.G. Bailey\textsuperscript{a}, A.P. Taylor\textsuperscript{b}

\textsuperscript{a} School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK
\textsuperscript{b} Lehighs Paints, Bolton, UK
Further results from furnace testing (using exactly the same predictive model and properties as cone tests)
Char

Combining the strengths of UMIST and The Victoria University of Manchester
Examples of comparison: ISO fire

a) ISO Fire
    steel thickness: 6mm

b) ISO Fire
    steel thickness: 10 mm

c) ISO Fire
    Steel Thickness: 20 mm
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Fast Fire

Steel Thickness: 6 mm

Fast Fire
Steel Thickness: 10 mm

Fast Fire
Steel Thickness: 20 mm

Combining the strengths of UMIST and The Victoria University of Manchester
Combining the strengths of UMIST and The Victoria University of Manchester

**Slow Fire**

**Steel Thickness: 6 mm**

- A04SL Test
- A04SL Modelling
- A08SL Test
- A08SL Modelling
- A12SL Test
- A12SL Modelling

**Steel Thickness: 10 mm**

- B04SL Test
- B04SL Modelling
- B08SL Test
- B08SL Modelling
- B12SL Test
- B12SL Modelling

**Steel Thickness: 20 mm**

- C04SL Test
- C04SL Modelling
- C08SL Test
- C08SL Modelling
- C12SL Test
- C12SL Modelling
Overall temperature accuracy

![Graph showing predicted versus measured temperatures with tolerances of ±10% for ISO, Fast, and Slow fire scenarios.](image)
Overall thickness accuracy

Predicted expansion ratio

Measured Expansion Ratio

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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
Combining the strengths of UMIST and The Victoria University of Manchester

Further research: stickability

![Diagram with temperature-time graph showing comparison between average furnace, centre of web post, and centre of web on solid beam.]
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.
Combining the strengths of UMIST and The Victoria University of Manchester