Post-peer review (non-publisher's document) of:

C. Maraveas, Y.C. Wang, T. Swailes, Thermal and mechanical properties of 19th century fireproof flooring systems at elevated temperatures, *Construction and Building Materials*, Volume 48, November 2013, Pages 248-264,

ISSN 0950-0618,

<http://dx.doi.org/10.1016/j.conbuildmat.2013.06.084>.

Thermal and Mechanical properties of 19th century fireproof flooring systems at elevated temperatures

Abstract

Two types of fireproof flooring systems commonly encountered in the 19th century are the “jack arch floor” and “the filler joist floor”. A proper evaluation of their fire resistance requires reliable information of the thermal and mechanical properties of their construction materials, namely cast iron, wrought iron, mild steel, “early” concrete and masonry, at elevated temperatures. This paper collates temperature-dependent thermal (i.e. thermal conductivity and specific heat) and mechanical properties (i.e. yield strength, tensile or compressive strength, Young’s elastic modulus and thermal expansion) of the metals as well as the temperature dependent thermal properties of the “insulation” from literature. The collated data are then compared with Eurocode’s mathematical expressions for contemporary materials to assess the applicability of the Eurocode expressions for the 19th century fireproof flooring systems.

Keywords: fireproof flooring; cast iron; wrought iron; mild steel; thermal conductivity; specific heat; mechanical properties; insulation, elevated temperature

1. Introduction

For preservation of historic 19th century buildings, an understanding of their constructional material properties at elevated temperatures is required so that they can be demonstrated to possess sufficient fire resistance in their new uses. The flooring systems of such historical structures consist of wrought iron/cast iron/mild steel embedded within early concrete or masonry.

Wrought iron, cast iron and mild steel (which will be referred to as metals in this paper) are the main load-bearing elements so it is clearly important that their mechanical properties, including thermal expansion, at elevated temperatures be determined with good accuracy. However, it should be borne in mind that the varying and often primitive manufacturing processes compared to the modern steel making process means that there will inevitably be many uncertainties with regard to their chemical compositions and geometrical dimensions. Furthermore, these are specialist structures. A lack of interest from the mainstream construction industry means that there is no detailed and systematic study to provide a comprehensive database of their mechanical properties to allow the effects of different influential parameters to be fully appreciated. The purpose of this research is to conduct an exhaustive search through open literature to obtain their mechanical properties from different sources and to identify the main parameters that have profound effects on them. Comparison with modern steel (whose properties can be obtained from relevant expressions given in the Eurocode) will be made.

Their thermal properties consist of thermal conductivity and thermal capacitance (the product of density and specific heat). The thermal conductivity of these materials will be similar to that of normal carbon steel and is expected to have a high value. Such a high thermal conductivity allows the so-called lumped mass assumption to be made so that the material can be assumed to have uniform temperature distribution when exposed to fire. It is expected that this assumption will hold true regardless of the thermal conductivity value used.

On the other hand, the thermal properties of the “insulating” materials will play a critical role in affecting the fire resistance of the 19th century building structures through influencing the temperatures of the load-bearing elements. This paper will also report the results collated from literature regarding the variation of thermal conductivity and specific heat of the “insulating” materials. Comparison with the properties of contemporary materials will also be made.

2. Fireproof Flooring systems of the 19th Century Buildings

The concept of fireproof flooring is linked with encasing the fire-susceptible structural element (metal) within fire-resistant materials (concrete or masonry). In 19th century construction, two types of fireproof flooring systems are typically encountered. In the first type, the “jack arch floor”, asymmetrical cast iron beams were encased in “early concrete” underlain by masonry (Figure 1, left). The bottom flange would not be encased and would serve as support for the overlaying masonry. The second type, called “filler joist”, involved pouring the “early concrete” slab in such a way that the beams were completely embedded

(Figure 1, right). In the “filler joist” construction, however, the beams were made out of wrought iron or mild steel and rarely out of cast iron. In certain cases, the soffit of the cast floor was level with the lower flange of the beam which was, therefore, unprotected. The term “early concrete” mentioned above refers to concrete made with various types of materials (crushed tile, brick, etc.), different from the ones used in contemporary production.

Figure 1: “Arch jack” floor (left) and “filler joist” construction (right) [1].

3. Material Properties of Metals at elevated temperatures

3.1 Structural Cast Iron

3.1.1 Thermal properties at elevated temperatures

Research on cast iron dates back to the beginning of the 20th century. Table 1 lists the sources of information.

Table 1: Experimental data referring to the thermal properties of cast iron

Source	Properties provided	Specific materials
Angus [2]	Thermal conductivity Specific heat	High Carbon iron, Blackheart malleable, Whiteheart malleable, pure iron White iron, Grey iron, pure iron, high and low phosphorus iron
Holmgren [3]	Thermal conductivity	Cast irons with different graphite morphology (flake, nodular, compacted irons)
Donaldson [4]	Thermal conductivity	Various cast irons, including Blackheart malleable and Whiteheart malleable

3.1.2 Literature results and proposed models

Figure 2 plots the specific heat and thermal conductivity values at different temperatures.

Also, the respective values of steel according to EN 1993-1-2 [5] are plotted in this figure.

a)

b)

Figure 2: Variations of specific heat (plot a) and thermal conductivity (plot b) of cast iron with temperature.

Despite some scatter, the variation of specific heat with temperature is quite similar for cast iron and steel; both materials experience a transformation phase at approximately 725°C, which results in the sharp rise in specific heat observed around that temperature region.

For thermal conductivity, the results in Figure 2 show considerable scatter. This variation has been explained by Holmgren and Svensson [6] and Holmgren et al [7], who state that the thermal conductivity of cast iron is sensitive to a number of parameters including carbon content, solidification rate and microstructure. Nevertheless, the average thermal conductivity value of cast iron is similar to that of steel per EN 1993-1-2 [5], as shown in Figure 2(b).

3.1.3 Mechanical properties at elevated temperatures

At ambient temperature, cast-iron is brittle with limited elongation before fracture. Its elongation improves at temperatures higher than 500°C. Because of a lack of a clear yield plateau, the “yield stress” of cast iron is usually a specific proof stress, such as the stress corresponding to 0.1% permanent strain (0.1% proof stress) of the material. Table 2 lists existing investigations.

Table 2: Experimental data referring to the mechanical properties of cast iron

Source	Type of material	Data collected	Comments
Angus [2]	Grey Iron	0.1% proof stress- “yield stress”	Unalloyed / Alloyed acicular
	Pearlitic, low/high carbon grey iron, heat resting, high silicon iron	Coefficient of thermal Expansion	
	Grey Iron	Tensile strength	Unalloyed / Alloyed acicular
Palmer [8]	Cast iron (flake graphite irons)	Tensile strength	Three Irons Iron 1: unalloyed flake graphite iron, Iron 2: high carbon iron Iron 3: nickel chromium molybdenum iron
	Cast iron (flake graphite irons)	Elongation	

Figure 3(a) and 3(b) plot the yield stress (proof stress) reduction factor – temperature and ultimate tensile stress reduction factor – temperature relationships. In Figure 3(a), the EN

1993-1-2 [5] reduction factors for proportional stress and yield stress are also included whilst in Figure 3(b), only the EN 1993-1-2 [5] yield stress reduction factors are included. It should be noted that the experimental results are limited to temperatures below 580°C. It appears that the EN 1993-1-2 [5] yield stress reduction factors may be used for the ultimate tensile stress of cast iron and the EN 1993-1-2 [5] proportional stress reduction factors are suitable for the yield stress of cast iron.

Figure 3(d) plots limited data of elongation with temperature. This value increases with temperature, reflecting increased ductility at increasing temperatures. As a safe approximation, elongation may be assumed to be constant at 0.5% up to 400°C, linearly increase to 1.5% at 600°C and then maintained at this value for higher temperatures.

Structural cast iron is a material that displays different tensile/compressive behavior, with the compressive strength at ambient temperature being 3 to 4 times [2] higher than the tensile value. However, in historical “fireproofing” flooring systems, the upper flange of the iron beam, which is in compression, is not expected to experience high temperature rise as it is heavily insulated by the overlying masonry or early concrete. Therefore, there is a complete absence of “hot” compressive strength of the material. As a rough estimate, the reduction factors for the tensile strength of cast iron may be used for the compressive strength. For cast iron columns, more reliable data for the compressive strength of cast iron will be required.

3.1.4 Coefficient of thermal expansion at elevated temperatures

Figure 3(c) collates the thermal expansion data. The EN 1993-1-2 [5] proposal for steel is also included in the figure. Although the thermal expansion coefficient of cast iron varies in different sources, the EN 1993-1-2 [5] proposal appears to be capable of representing the average of the collated test data. Unless the fire resistance of the cast iron structure is sensitive to its coefficient of thermal expansion (which usually is not), it is proposed to adopt the EN 1993-1-2 [5] values for steel.

a)

b)

c)

d)

Figure 3: Variation of yield stress (plot a), tensile strength (plot b), coefficient of thermal expansion (plot c) and elongation (plot d) of cast iron with temperature.

As a summary, the EN 1993-1-2 [5] values for thermal conductivity, specific heat and thermal expansion coefficient for carbon steel can be used for those of cast iron. The EN 1993-1-2 [5] proportional stress reduction factors at elevated temperatures for carbon steel can be used for the yield stress reduction factors of cast iron. The EN 1993-1-2 [5] yield stress reduction factors at elevated temperatures for carbon steel can be used for the ultimate tensile stress reduction factors of cast iron.

3.2 Wrought Iron

Wrought iron was widely used in the construction industry of the 19th century, despite considerable variability in its strength. Moy et al [9], after compiling a large database (more than 400) of experimental results from various sources, reported ambient temperature tensile strengths ranging from 277 to 410 N/mm², while the measured compressive strengths varied from 485 to 553 N/mm². The experimental data by Jeffrey et al [10] suggest that this variability is influenced by the chemical composition of the material. In this paper, only the tensile behaviour under elevated temperatures will be investigated, because of the relatively minor effect of compression behaviour on “fireproof” flooring systems, as explained in section 3.1.3.

3.2.1 Mechanical properties at elevated temperatures

Table 3 lists the sources of data.

Table 3: Experimental data referring to the thermo-mechanical properties of cast iron

Source	Material type	Data collected	Comments
Donaldson [4]	Wrought Iron	Thermal conductivity	
Carrington [11]	Wrought Iron	“Yield stress”, Tensile strength, Young’s Modulus, Elongation	“Yield stress” defined as stress where sudden discontinuity was observed in stress strain diagram (>

			0.5% elongation). Elongation measured at fracture
Epps and Jones [12]	Wrought Iron	“Yield stress”, Tensile strength, Young’s Modulus, Elongation	“Yield stress”: defined as the elastic limit
Carpenter [13]	Wrought Iron	“Yield stress”, Tensile strength, Young’s Modulus, Elongation	
Roelker [14]	Wrought Iron	Tensile strength	“Fibrous” wrought iron tests included

Figures 4(a)-(c) present the reduction factor – temperature relationships for the yield stress (>0.5% proof stress), ultimate tensile stress and Young’s modulus. For comparison, these figures also show the EN 1993-1-2 [5] proportional stress, yield stress (including the effects of strain hardening) and Young’s modulus reduction factors. The main observations are:

- The EN 1993-1-2 reduction factors for the proportional limit of carbon steel are close to the average values of wrought iron.
- For the ultimate tensile stress, the EN 1993-1-2 reduction factors for the yield stress of carbon steel are upper bound to the wrought iron values while the EN 1993-1-2 reduction factors for the proportional limit of carbon steel give a good safe estimate.

- The EN 1993-1-2 reduction factors for the Young's modulus of carbon steel can be used for those of wrought iron.

In Figure 4(d), wrought iron maximum elongation data are plotted against temperature. These show a loss at temperature around 150°C. Beyond that region, elongation remains majorly unaffected by temperature rise. In EN 1993-1-2 [5], for modern steel, the maximum elongation corresponding to the yield stress is 15% and the fracture strain is 20%. The latter value is close to the average of the collected data and can be used as a rough approximation of the fracture strain.

3.2.2 Thermal properties at elevated temperatures

Figure 4(e) shows the limited data of thermal conductivity [4]. No information could be found in literature giving the specific heat of wrought iron. However, it is proposed that the EN 1993-1-2 [5] values for steel be used based on the similarity in chemical compositions of these two materials.

a)

b)

c)

d)

e)

Figure 4: Variation of yield stress (plot a) tensile strength (plot b), Young's elastic modulus (plot c), elongation (plot d) and thermal conductivity (plot e) of wrought iron with temperature.

3.3 Old Mild Steel

3.3.1 General

The beams in the “filler joist” system were generally made from mild steel. Table 4 lists the sources of data in literature.

Table 4: Experimental data referring to the thermo-mechanical properties of mild steel

Source	Material type	Data collected	Comments
Donaldson [4]	Mild Steel	Thermal conductivity	
Carrington [11]	Mild Steel	Yield stress, Tensile strength, Young's Modulus, Elongation	Elongation measured at fracture
Kirby [15]	Mild Steel	Yield stress	measured different proof stresses, ranging from 0.2% to 5%
Bach [16]	Mild Steel	Yield stress, Tensile strength, Elongation	Three different mild steels tested
Lea and Crowther [17]	Mild Steel	Yield stress, Tensile strength, Young's Modulus	
Rang [18]	Mild Steel	Tensile strength, Young's Modulus	

3.3.2 Mechanical properties at elevated temperatures

Figure 5 plots the different properties (yield stress, tensile stress, Young's modulus and maximum elongation) and compares their temperature dependent variations with the EN

1993-1-2 [5] models for modern carbon steel. Figure 5(d) shows that old mild steel has excellent elongation (corresponding to fracture strain). As with cast iron, the EN 1993-1-2 proportional reduction factors for carbon steel can be used for the yield stress reduction factors of old mild steel and the EN 1993-1-2 yield stress reduction factors can be used for the ultimate tensile stress reduction factors of old mild steel. The EN 1993-1-2 reduction factors for the Young's modulus of carbon steel can be used for old mild steel.

As mentioned in the previous section, the fracture strain for modern steel, per EN 1993-1-2 [5], is 20%. For the old mild steel, the elongation may reach 50% at elevated temperatures. Therefore, the EN 1993-1-2 [5] stress-strain model for modern steel at elevated temperatures may be safely, but very conservatively, used for the old mild steel.

a)

b)

c)

d)

e)

Figure 5: Variation of yield stress (plot a), tensile strength (plot b), Young's elastic modulus (plot c), elongation (plot d) and thermal conductivity (plot e) of mild steel with temperature.

3.3.3 Thermal properties at elevated temperatures

Experimental results on the thermal properties of mild steel are extremely limited. Only one source [4] refers to the variation of thermal conductivity with temperature (Figure 5(e)).

Despite the complete absence of data referring to specific heat, the EN 1993-1-2 [5]

mathematical expression for modern steel may be used due to the similar chemical compositions of these two materials.

4. Thermal properties of insulating materials at elevated temperatures

4.1 Early Concrete

4.1.1 Background

“Early” concrete was made out of materials which are not used in modern concrete production. According to Hurst [19], before and during most of the nineteenth century, the terms “concrete” and “cement” were defined with less certainty than today. Especially for the studied fireproof flooring systems, it is stated in Hurst [19] that the aggregate was coke, breeze, cinders, broken brick, burnt clay, limestone or even rubbish (debris from the demolition of old structures, namely a mixture of broken bricks, plaster and mortar), while “cement” could be lime, Roman or Portland cement. Beckmann et al [20] described the use of clinker aggregate concrete in fireproof flooring systems. Crushed clinker (containing coal or coke) or cinders were used as aggregate while the cement was lime, in earlier applications, and Portland cement later. Furthermore, it is stated in the literature that the concrete used for “filler joist” floors was made with aggregates from broken brick, cinders etc [21], or lime and ashes [22]. Similar information is provided in another source [23], suggesting that early concrete was constructed by a great variety of materials and constitutes a material which is different from modern Portland concrete.

4.1.2 Thermal properties at elevated temperatures

A number of authors investigated the effects of temperature on the thermal properties of early concrete. Schneider [24] studied the thermal conductivity and specific heat of limestone (moist or dried) aggregate and lightweight concrete at elevated temperatures. Harmathy and Allen [25] conducted a relevant study on the thermal conductivity of several concrete mixes, including siliceous and calcareous aggregate concrete, slag concrete, shale concrete, clay concrete and pumice concrete and classified them as “normal weight concrete mixes” and “lightweight concrete mixes” based on their unit weight. In their reports, they presented boundaries for the variation of thermal conductivity with temperature and made a distinction between the normal weight and lightweight mixes. The thermal conductivity of concretes containing crushed brick, pumice and slag as aggregate, at room temperature, was presented by Loudon [26].

The above data are shown in Figure 6, in conjunction with relevant values for common concrete given Eurocode 2 [27]. Observations of the relevant plots suggest that the variation of thermal conductivity with temperature depends on the density of the material. In the normal weight mixes, the thermal conductivity reduces until 700°C, where it stabilizes, in most cases, around 1.10~ 1.20 W/m*°C. On the contrary, the thermal conductivity of lightweight mixes is generally unaffected by temperature, as reported by Schneider (1998) [24]. A reasonable explanation for this discrepancy was given by the same author [24], who commented that: “The thermal conductivity of concrete depends on the conductivities of its constituents. The major factors are the moisture content, the type of aggregate and the mix proportions”.

Indeed, lightweight materials tend to have increased porosities/voids and, therefore, reduced thermal conductivities. The boundary curves proposed by Eurocode 2 [27] could be used to capture the variation of thermal conductivity with temperature for early concrete. The specific heat of the material displays an increase (similar to the one proposed by Eurocode 2 [27]) between temperatures of 150°C to 400°C. Beyond that temperature, the data show that specific heat remains constant. As a result of the above observations, the relevant equation in Eurocode 2 [27] can be selected to describe its variation with temperature.

a)

b)

Figure 6: Variation of thermal conductivity (plot a) and specific heat (plot b) of early concrete with temperature.

Table 5 lists existing investigations regarding early concrete.

Table 5: Collected data for early concrete.

Source	Aggregate type	Data collected	Comments
Schneider [24]	limestone (moist or dried), lightweight	thermal conductivity and specific heat	
Harmathy and Allen [25]	siliceous and calcareous	thermal conductivity	authors give boundaries for

	aggregate, slag, shale, clay and pumice		normalweight and lightweight mixes
Loudon [26]	crushed brick, pumice and slag	thermal conductivity	

4.2 Masonry Units (Burnt Clay)

4.2.1 Thermal conductivity at elevated temperatures

The thermal conductivity of clay bricks at room temperature depends on bulk density. Relevant measurements [28] confirm this. More specifically, Dondi et al [28] reported values around $0.2 \text{ W/m}^\circ\text{C}$ for lightweight bricks (bulk density approximately 1100 kg/m^3), while the thermal conductivity of heavyweight bricks (bulk density approximately 2000 kg/m^3) exceeded $0.7 \text{ W/m}^\circ\text{C}$ in certain cases. For this reason, a distinction between the two brick types should be made when studying the variation of their thermal conductivity with temperature. A relevant plot, presenting experimental data from various sources ([29], [30]) is given in Figure 7. The data refer to lightweight ($\rho=700\text{-}1000 \text{ kg/m}^3$) as well as heavyweight ($\rho=1900\text{-}2200 \text{ kg/m}^3$) masonry units and verify the dependence of thermal conductivity on density. Minor deviation from the values at ambient conditions is observed before 400°C (with the exception of one data set). Afterwards, the data display an increase at a slow rate, which can be attributed to the radiation effect of the pores. The water evaporation phase does not appear for burnt clay bricks, as it has already occurred during production burning, which prevents the expected decrease in thermal conductivity around

200°C from occurring. In lightweight units, the data show negligible scatter. This is not the case for heavyweight units, in which thermal conductivity values vary from 0.7 W/m*°C to 1.5 W/m*°C.

Density is clearly an important factor in affecting the thermal conductivity values of masonry units. Because of the large variations shown in Figure 7(a), the effects of density should be reflected in deriving expressions for the thermal conductivity of masonry units.

The upper and lower bounds given in Eurocode 2 [27] for modern concrete are generally not consistent with the gathered experimental data. Some correlation can be seen among these curves for the heavyweight units in the range of 20°C to 600°C. They cannot, however, describe the results for the lightweight units which have much lower thermal conductivity values.

4.2.2 Specific heat at elevated temperatures

Harmathy [29] and Hu et al [30] also presented experimental results regarding the specific heat of clay masonry units (Figure 7). The results presented by the two authors are contradictory for the temperature region of 300°C-600°C. Harmathy [29] reports negligible variation for that region, while the data by Hu et al [30] suggest that specific heat increases by more than 50%. The sharp increase around 100°C due to water evaporation is not observed in the examined data sets because of their negligible moisture content. This is confirmed by experimental results on clay bricks with different moisture contents (including zero moisture) reported by Harmathy [31].

The expression for modern concrete proposed by Eurocode 2 [27] (0% moisture content) is included in the same graph for comparison. It corresponds to approximately the average variation in the specific heat of masonry units with temperature, regardless of density.

a)

b)

Figure 7: Variation of thermal conductivity (plot a), specific heat (plot b) of masonry units with temperature.

A synopsis of the gathered data is given in Table 6.

Table 6: Data on elevated temperature properties of bricks.

Source	Brick type	Density (kg/m ³)	Data collected
Harmathy [29]	clay brick	2180	thermal conductivity, specific heat
	clay brick	1935	
	insulating fire brick	757	
	insulating fire brick	735	
Hu et al [30]	standard clay brick	700-980	thermal conductivity, specific heat
	fire brick	-	thermal conductivity, specific heat

4.3 Mortars

4.3.1 Thermal conductivity at elevated temperatures

The thermal conductivity of mortars at room temperature generally ranges between 1.1 – 0.7 W/m*K, but values as low as 0.5 W/m*K for Portland cement paste with lower density (high water-to-cement ratio) have been reported [29]. The experimental results (Figure 8) regarding its variation with temperature are limited to cement pastes [29], which do not exhibit reduction until 400°C. A steady decline is observed afterwards, with values having decreased by 25% at 800°C. This decrease is most probably related to the evaporation of the water, which seems to occur around 400°C. The sharp peak observed in the variation of specific heat around that temperature strengthens this argument. Beyond 800°C, thermal

conductivity remains generally constant and does not increase as one would expect for other materials (i.e. bricks). This fact can be attributed to the generally small values of porosity (usually 0.15% to 0.30%) for mortars. The data also suggest that the w/c ratio reduces thermal conductivity at ambient and elevated temperatures, because the thermal conductivity of water is less than that of cement).

The lower bound curve proposed in Eurocode 2 [27] for concrete can be used as safe approximation for modeling the variation of thermal conductivity of mortars with temperature. Observation of Figure 8a supports this argument.

4.3.2 Specific heat at elevated temperatures

A few researchers have studied the effects of temperature on specific heat. Experimental results regarding cementitious composites and cement mortar generally show a steady increase in specific heat up to 1200 J/kg*K at 600°C, followed by a reduction afterwards [32]. On the other hand, the specific heat of Portland cement [29] shows a sharp peak (with values higher 5000 J/kg*K) around the temperature region of 450°C - 500°C. These data (Figure 8) suggest that water evaporation, which is usually observed around 100°C, does not occur until the temperature range of 500°C - 600°C. The chemical bond between water and cement particles, which requires more energy absorption for water evaporation to occur, might be a reasonable explanation for this delay.

The expression for concrete, as proposed in Eurocode 2 [27], matches the data for mortars well and can be used to describe their specific heat at elevated temperatures. This is not the

case for Portland cement, as it underestimates the values of the collected data and fails to capture the sharp increase around 450°C. It could, however, be used as lower bound.

a)

b)

c)

Figure 8: Variation of thermal conductivity (plot a), specific heat (plot b) of Portland cement and specific heat (plot c) of mortars with temperature.

A synopsis of the gathered data is given in Table 7.

Table 7: Data on elevated temperature properties of mortars and Portland cement.

Source	Admixture	Data collected	Comments
Harmathy [29]	Portland Cement w/c = 0.25, w/c = 0.33, w/c =0.50	thermal conductivity, specific heat	
Poděbradská et al [32]	cementitious composites and cement mortar	specific heat	

5. Conclusions

The data collected from the literature, which are presented in this article, suggest that the mechanical and thermal properties of these materials at elevated temperatures vary considerably and explicit values (e.g. from statistical analysis) to describe them may not be easily determined. However, based on the collected data and comparisons with current design codes, the following can be concluded:

- a) The expressions proposed by the Eurocodes are suitable for describing the thermal properties of the studied metals at elevated temperature.
- b) With regard to the metals, the Eurocode's expressions for the proportional limit of steel can be used to model their yield stress. Their ultimate tensile strength variation can be accurately described according to the Eurocode's expressions for the yield stress of steel.

- c) The thermal properties of “early concrete” can be accurately modeled according to the properties of concrete given in the Eurocodes for modern concrete.
- d) Lightweight masonry units display different thermal conductivity variations from modern concrete (as given in the Eurocodes) when subjected to fire. Some correlation exists, however, for units with heavier densities and temperatures below 600°C. The Eurocode’s formula for the specific heat of concrete is appropriate for modeling those of the lightweight masonry units.
- e) With the exception of the specific heat of Portland cement, whose variation with temperature is under-predicted, the thermal properties of mortars at elevated temperatures can be satisfactorily described by those of concrete in the Eurocodes.

6. References

- [1] Bailey CG. The behavior of asymmetric slim floor steel beams in fire. J Constr Steel Res 1999;50:235-57.
- [2] Angus TH. Cast Iron: Physical and Engineering Properties. 2nd ed. London-Boston: Butterworths; 1976.
- [3] Holmgren D. Review of thermal conductivity of cast iron. Int J Cast Met Res 2005;18(6): 331-45.
- [4] Donaldson JW. The thermal conductivity of wrought iron, steel, malleable cast iron and cast iron. Journal of the Iron and Steel Institute 1933;128:255-74.

- [5] European Committee for Standardization. Eurocode 3 - Design of steel structures - Part 1-2: General rules - Structural fire design. Brussels: The Committee; 2005.
- [6] Holmgren D, Svensson IL. Thermal conductivity – structure relationships in grey cast iron. *Int J Cast Met Res* 2005;18(6):321-30.
- [7] Holmgren D, Dioszegi A, Svensson IL. Effects of carbon content and solidification rate on thermal conductivity of grey cast iron. *China Foundry* 2007;4(3):210-4.
- [8] Palmer KB. High temperature properties of cast irons. In: *Conference on Engineering Performance of Iron Castings*; 1970; British Cast Iron Research Association; 1970. p. 217-49.
- [9] Moy SSJ, Clarke HWJ, Bright SR. The engineering properties of Victorian structural wrought iron. *Mater* 2009;162(1):1-10.
- [10] Jeffry R, Seager J, Woodhead JH. The mechanical properties of commercial wrought iron. Sheffield (UK): Ministry of Power (UK), Safety in Mines Research Establishment; 1959 Feb. Research Report No: 154. Contract No.: U.D.C.620:17:669.18.
- [11] Carrington H. The strength properties of wrought iron mild steel and nickel steel at high temperatures. *Eng* 1924;117(3029):69-71.
- [12] Epps FA, Jones EO. The influence of High Temperature Upon the elastic and Tensile Properties of Wrought Iron. *Metallurgical and Chemical Engineering* 1917;17:67-71.
- [13] Carpenter RC. Effect of temperature on strength of wrought iron and steel. *Transactions of the American Society of Mechanical Engineers* 1895;17:198-211.
- [14] Roelker CR. Experiments on the strength of wrought iron and steel at high temperatures. *J Franklin Inst* 1881;112(4):241-54.

- [15] Kirby BR. The application of BS5950: Part 8 on fire limit state design to the performance of “old” structural mild steels. *Fire Saf J* 1993;20:353-76.
- [16] Bach C. Strength of Mild and Cast Steel at High Temperatures. *Engineering*.1906 Mar: 401-4.
- [17] Lea FC, Crowther OH. The Change of the Modulus of Elasticity and of other Properties of Metals with Temperature. *Engineering*.1914 Oct: 487-9.
- [18] Rang EJ. Some properties of mild steel, with special reference to its behaviour at high temperatures. *ICE Selected Engineering Papers* 1926;1(42):3-14.
- [19] Hurst BL. Concrete and the structural use of cements in England before 1890. In: Sutherland J, Humm D, Chrimes M, editors. *Historic Concrete: The Background to Appraisal*, London: Thomas Telford Publishing; 2001, p. 45-65.
- [20] Beckmann P, Bowles R. *Structural aspects of building conservation*. 2nd ed. Oxford: Elsevier Butterworth-Hehemann; 2004.
- [21] Swailes T, Marsh J. *Structural Appraisal of Iron Framed Textile Mills: ICE Design and Practice Guide*. London: Thomas Telford Publishing; 1998.
- [22] Swailes, T. 19th century “fireproof” buildings, their strength and robustness. *The Structural Engineer* 2003;81(19):27-34.
- [23] Swailes, T. *Scottish iron structures-Historic Scotland Guide for Practitioners 5*. Edinburgh: Historic Scotland; 2006.
- [24] Schneider U. Concrete at high temperatures - A general review. *Fire Saf J* 1988;13:55-68.
- [25] Harmathy TZ, Allen LW. Thermal properties of selected masonry unit concretes. *Journal of the American Concrete Institute* 1973;70(2): 132-42.

- [26] Loudon AG. The thermal properties of lightweight concretes. The International Journal of Lightweight Concrete 1979;1(2):71-85.
- [27] European Committee for Standardization. Eurocode 2 - Design of concrete structures - Part 1-2: General rules - Structural fire design. Brussels: The Committee; 2004.
- [28] Dondi M, Mazzanti F, Principi P, Raimondo M, Zanarini G. Thermal Conductivity of Clay Bricks. J Mater Civ Eng 2004;16(1):8-14.
- [29] Harmathy TZ. Properties of building materials at elevated temperatures. Ottawa: National Research Council of Canada, Division of Building Research; 1983 Mar. Report No.: 1080. Contract No.: 277331626.
- [30] Hu XF, Lie TT, Polomark GM, MacLaurin JW. Thermal Properties of Building Materials at Elevated Temperatures. Ottawa: National Research Council of Canada, Institute for Research in Construction; 1993 Mar. Internal Report No.: 643. Contract No.: 277331626.
- [31] Harmathy TZ. Effect of Moisture on the Fire Endurance of Building Elements. Ottawa: National Research Council of Canada, Division of Building Research; 1965 Aug. Research Paper No.: 270. Contract No.: 277331626.
- [32] Poděbradská J, Pavlík J, Toman J, Černý R. Specific heat capacity of cementitious composites in high-temperature range. In: Proceedings of the Thermophysics 2003 meeting of the Thermophysical Society Working Group of the Slovak Physical Society; 2003; Bratislava, Slovakia. Slovak Academy of Sciences; 2003. p. 18-23.