This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206.
(https://doi.org/10.1016/j.conbuildmat.2019.04.182)

Properties and Material Models for Common Construction Materials at Elevated Temperatures

M.Z. Naser, PhD, PE
Glenn Department of Civil Engineering, Clemson University, Clemson, SC, 29634, USA
E-mail: mznaser@clemson.edu, m@mznaser.com, Website: www.mznaser.com

ABSTRACT

Construction building materials experience physio-chemical and phase changes when subjected to elevated temperatures. These changes are often defined through temperature-dependent material models. A cross examination of adopted models reveals that such models markedly varies across open literature and fire guides (i.e. ASCE, Eurocodes etc.). This, not only complicates the process of fire analysis and design, but can also hinders ongoing standardization initiatives. In support of these initiatives, this paper leverages symbolic regression through artificial neural networks (ANN) and genetic programming (GP) to arrive at representative temperature-dependent thermal and mechanical material models for common building materials, namely: normal strength concrete, masonry, structural steel, stainless steel, cold-formed steel and wood. The proposed material models have the potential to regulate and modernize structural design under extreme loading conditions, i.e. fire. The result of this investigation demonstrates the value of utilizing artificial intelligence (AI) into comprehending the complex nature of temperature-induced effects on building materials; together with deriving associated temperature-dependent models.

Keywords: Material models; Construction materials; Fire resistance; Artificial intelligence.

1.0 INTRODUCTION

Civil constructions are to be designed to satisfy codal requirements. One such requirement is to withstand extreme events (i.e. fire/thermal loading). The ability of a structure to withstand fire and associated fire-induced forces is highly reliant on, 1) the type of material the main structural members/components are composed of, and 2) how properties of such materials are influenced by elevated temperatures [1]. This ability is often measured through experimental fire testing or, for the most part, through fire resistance evaluation. In such evaluation, thermal and mechanical characteristics of construction materials are of interest as fire resistance assessment requires carrying out a two-step analysis; thermal and structural. In the first step, rise in temperature and associated temperature propagation in a load bearing member are obtained by examining how density, thermal conductivity, and specific heat properties fluctuate with increasing temperatures. Once sectional temperatures are obtained, these are then loaded into the second step of analysis. In this step, the adverse effect of increasing temperature upon mechanical properties of construction materials; primarily comprising of strength, and modulus, is considered in evaluating the assessing behavior of a fire-exposed member [1, 2].

Thus, carrying out a proper fire resistance analysis requires thorough knowledge of thermal and mechanical properties at ambient and fire conditions. While evaluating aforementioned material properties at ambient conditions can be achieved with ease mainly due to the availability of testing standards and instrumentations, assessing properties of building materials at high temperatures is shown to be a tedious task [3]. This can be primarily ascribed to the current lack of expertise and/or standardized (i.e. agreed upon) guidance, shortage and limited access of testing equipment, and most of all complexities arising from simulating fire conditions (i.e. survivability of sensors as well as ensuring proper measurements under elevated temperatures) [4]. As a result, fewer studies managed to successfully conduct material property tests under high temperatures as compared to that at ambient conditions [5].

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

The outcome of these studies presented the adverse effects of fire on material properties through temperature-dependent material models which were either prepared into simplified expressions, or informative charts [6, 7]. Despite the fact that most of these research studies were carried out in 1960-90's, the outcome of such studies continues to form the basis for currently adopted temperature-dependent material models [6, 7]. A close examination of these models exposes discrepancies arising from different testing methods and equipment, specimen configuration etc. used in high temperature tests [5, 8]. Another factor that adds further complexities is the existence of distinct variations in the make-up (composition) of construction materials tested in the 1960-90s and those available today as a result of the natural progression in materials science, differences in origin/amount/type of additives, as well as from modern production/milling procedures.

A review of literature also shows that this community has accepted two material models to be used in fire resistance assessment. For the most part, these models are adopted in North America (i.e. American Society of Civil Engineers (ASCE) design guide [6]), and Europe (Eurocodes [7, 9-11]). Despite the fact that these two models have been widely used, recent works have shown that variation in fire resistance predictions can be in the range of 25% when using temperature-dependent models adopted by ASCE or Eurocodes [5, 12]. This often complicates structural evaluation at elevated temperatures; particularly in the analysis/design for compound load effects (viz. torsion, or buckling etc.), selecting appropriate fire protection material/type/thickness, or even in carrying out design/engineering (consulting) services.

Such variation arises due to a number of reasons. For a start, these codal-adopted models imply that the micro-structure of construction materials is independent of its fabrication process,

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

or composition/origin. Further, these models were developed using vintage devices, which are inferior to the modern and state-of-the-art equipment, and thus provided scientists with restricted testing set-ups, and possibly mediocre measurements [5, 12]. Furthermore, these material models continue to be not updated since their development; dating back to 20-30 years. Finally, while Eurocode 3 suggests the use of certain models to represent behavior of contemporary construction materials (i.e. stainless steel and cold-formed steel), ASCE design guide does not provide direction nor insights into how to account for temperature-dependent effects in materials; leaving designers with limited guidance, hence complicating the process of fire resistance evaluation.

From this work's perspective, it is infeasible to regularly conduct temperature-dependent tests on materials – given the variety in compositions, origins and mixes. Thus, a dilemma arises highlighting the need for a uniform and modern model for construction materials at elevated temperatures. With the hope of overcoming this challenge, and in support of current inertia aimed at promoting standardization for fire resistance assessment, this study aims at utilizing Artificial Intelligence (AI) to develop modern and updated temperature-dependent models for commonly used construction materials – and this could be the first step towards realizing uniform (universal/standardized) constitutive material models. As such, this work presents a novel approach to develop temperature-dependent thermal and mechanical material models for some of the commonly used building materials, namely: normal strength concrete, masonry, structural steel, stainless steel, cold-formed steel and wood. This study starts by presenting high temperature properties of common construction materials and then showcases a proper procedure to developing an AI model capable of deriving temperature-dependent material models. To ensure precision and wide acceptance, the developed AI model integrates material models adopted by notable fire codes,

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

standards and design guides, together with models collected from past and recent published studies/reports.

2.0 TEMPERATURE-DEPENDENT PROPERTIES OF COMMON CONSTRUCTION MATERIALS – AN OVERVIEW

Response of structures once exposed to elevated temperatures is largely a function of properties of building materials. Under such effects, thermal and mechanical* properties fluctuate with temperature mirroring the series of phase changes that occur. As such, this section delivers a brief overview on the various temperature-dependent properties for normal strength concrete, masonry, structural steel, stainless steel, cold-formed steel and wood. For brevity, this paper only covers those properties of interest to fire engineers including thermal conductivity, specific heat, density, strength and modulus. It is worth noting that the variation in other properties such as permeability, charring etc. can be found elsewhere and the readers are encouraged to visit such resources [3, 13, 14].

2.1 Thermal properties

Thermal properties govern both the rise and distribution of temperature within a component or a structural member. These properties comprise of thermal conductivity (k), specific heat (C_ρ), and density (ρ), and for the most part, their behavior is governed by material composition and characteristics of rising temperatures (rate/intensity etc.) [15]. To start with, the thermal conductivity (k) is the property that indicates the rate at which a given material transmits heat. This property is sensitive to the crystalline structure [3].

*There also exist two additional types of properties, i.e. deformation properties and special properties. For brevity, deformational and material specific properties are not be discussed herein.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

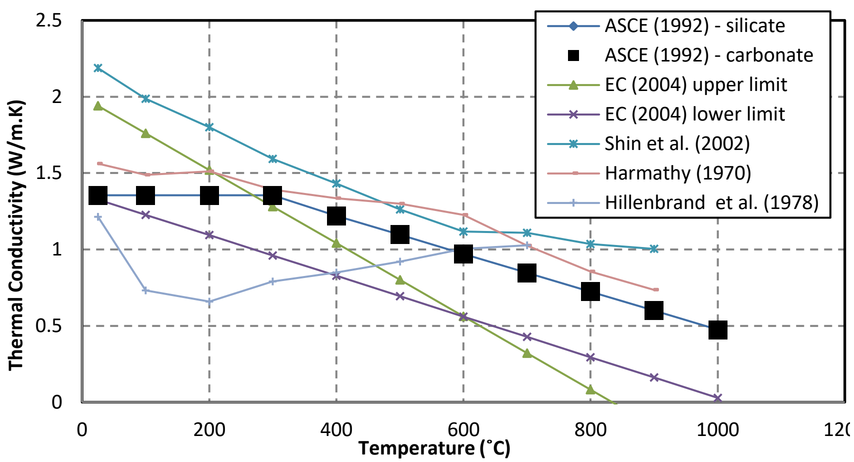
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

The thermal conductivity of concrete derivatives is noted to be highly influenced by moisture content and type of aggregate. On average, the room temperature thermal conductivity of concrete and masonry is comparatively low and ranges between 1.4-3.6 W/m.K and 0.9-1.1 W/m.K, respectively. It is commonly accepted that the thermal conductivity of these materials decreases with temperature rise due a number of factors including loss of moisture, increased permeability and porosity [14]. At high temperatures, those exceeding 800°C, the thermal conductivity stabilizes at about one half its value at ambient conditions. It is worth noting that there is a general tendency for concretes made of siliceous aggregates to have higher conductivity than those made of carbonate aggregates (see Fig. 1a) [16].

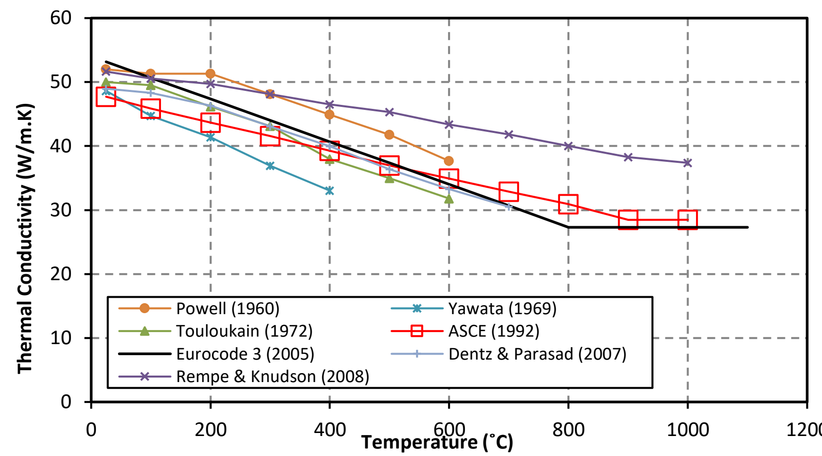
Figures 1b and 1c show that all types of steels have high thermal conductivity as compared to concrete, masonry or wood. This conductivity varies between 46–65 W/m.K for carbon steel to 12-16 W/m.K for stainless steel [16, 17]. While this property decreases at elevated temperature in carbon steel due to a drop in free path of molecules, the conductivity of stainless steel slightly increases over rising temperatures but remains lower than that in carbon steel up to 1000°C [18]. The conductivity of wood is even lower than above construction materials and is in the range of 0.08-0.2 W/m.K at room temperature [19]. A unique feature in wood is that its thermal conductivity slightly drops between 200-320°C and then increases due to the higher conductivity of dry layers (see Fig. 1d).

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

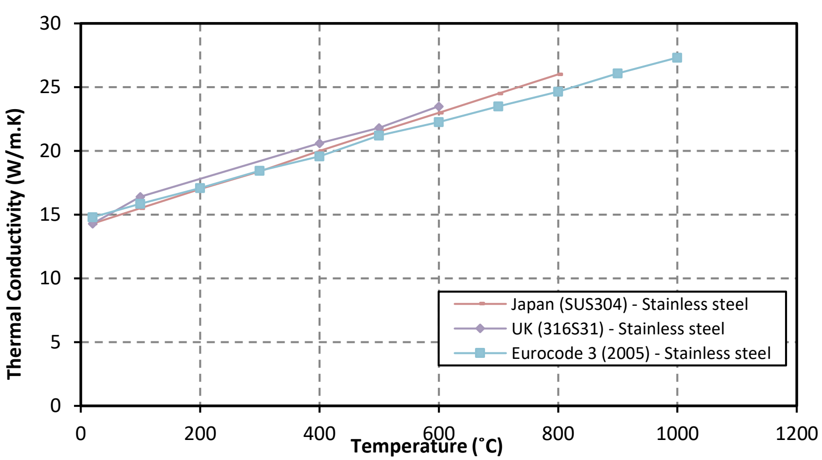
Please cite this paper as:
Naser M.Z. (2019). “Properties and Material Models for Common Construction Materials at Elevated Temperatures.” Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



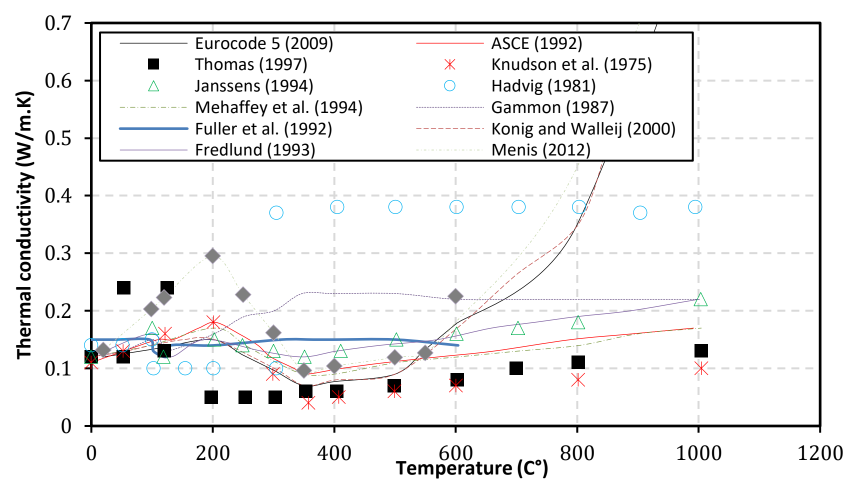
(a) Normal strength concrete



(b) Structural/cold-formed steel



(c) Stainless steel



(d) Wood

Fig. 1 Variation of thermal conductivity for common construction materials with temperature [6, 9, 11, 16, 20-34]

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

The second thermal property is the specific heat, C_ρ. Specific heat defines the magnitude of thermal energy to raise a unit mass of material a single unit temperature. This property is sensitive to the occurrence of physio-chemical changes that may take place under fire conditions. This property for concrete and masonry at ambient temperature can vary within the wide range of 840J/kg.K and 1800J/kg.K (i.e. normal weight aggregate being on the upper side of this range). This variation is mainly influenced by production process, mix proportions etc. [16]. This specific heat remains virtually unchanged throughout exposure to elevated temperature in the range of 25-800°C, expect for temperatures corresponding to 100°C, 400-500°C and 600-700°C reflecting a rise in in energy utilized towards vaporization of free water, breakage of $Ca(OH)_2$ into (CaO) and (H_2O), and transformation of some types of aggregates beyond 600°C, respectively (see Fig. 2a and 2b). In general, concrete made of carbonate aggregate has high specific heat at 600–800°C range due to the occurrence of an endothermic reaction resulting from dolomite decomposition [15]. It should be noted that little amount of research was reported on thermal properties of masonry [3, 16].

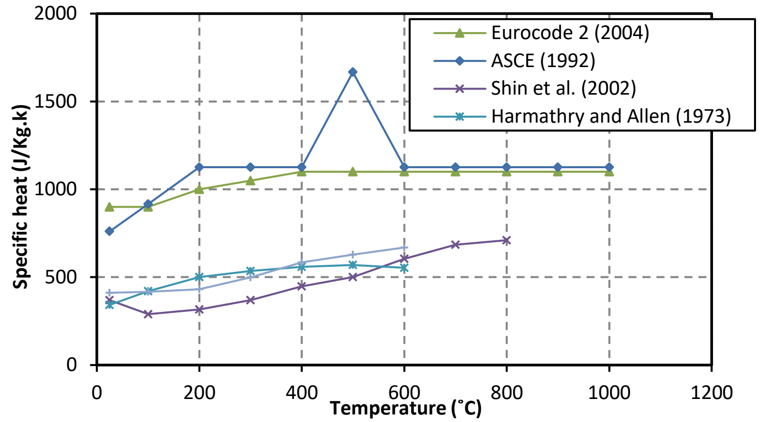
At ambient conditions, the specific heat of steels varies between 450-600 J/kg.K [3] . This property gradually increases with temperature until 600°C, at which a steep increase in specific heat is observed as carbon steel undergoes re-arrangement of crystalline structure. This transformation absorbs substantial energy while carbon steel transitions from a face-centered-cubic (*fcc*) to a body-centered-cubic (*bcc*) configuration in order to stabilize its crystalline structure (see Fig. 2c). However, this behavior is not shown in the case of stainless steel as it does not undergo such a phase change. The ambient specific heat of wood is in the narrow range of 1.8-2 kJ/kg.K which rises with a sharp peak at 100°C to represent evaporation/condensation of trapped

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206.
(https://doi.org/10.1016/j.conbuildmat.2019.04.182)

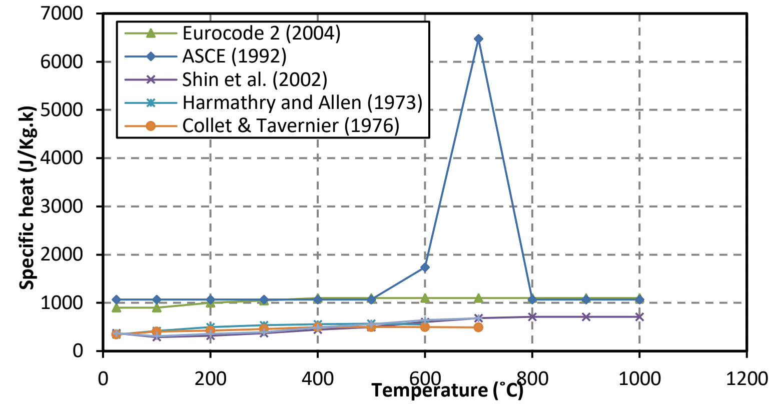
moisture. Beyond 100°C, the specific heat of wood drops back to near its value at ambient conditions as can be seen in Fig. 2d.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

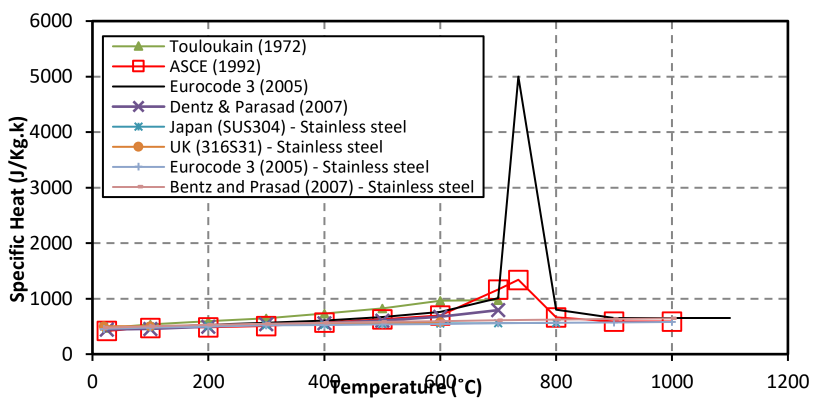
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



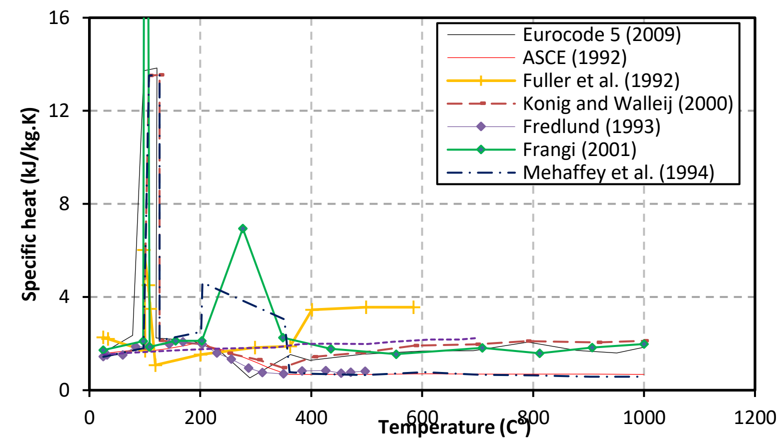
(a) Silicate-based concrete



(b) Carbonate-based concrete



(c) Various steels



(d) Wood

Fig. 2 Variation of specific heat for common construction materials with temperature [6, 9, 11, 16, 23, 24, 27-30, 33, 35, 36]

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

The density property is defined as the mass of a unit volume. Normal weight concrete and masonry has a density between 2100-2300 kg/m^3 and 1660 to 2270 kg/m^3, respectively and this density is primarily a function of the volume of water in mixture and density of aggregates – implying that drying of moisture can reduce density especially upon exceeding 100°C. The degradation in density of normal weight concrete/masonry may slightly reduce by 100 kg/m^3 and becomes stable beyond 100°C. As such, it is common for researchers to present heat capacity by lumping (multiplying) density with specific heat. In contrast, metals have a density that is independent of any rise in temperature. Thus, the density of structural steel, stainless steel and cold-formed steel can conservatively be assumed to be constant and equals to 7700-7850 kg/m^3. On the contrary, the density of wood varies between different species (approximately within 300-700 kg/m^3 at ambient conditions). It is commonly accepted for wood density to reduce by 10-20% at 100°C and then to drop to 20% upon reaching 300°C.

2.2 Mechanical properties

The mechanical properties comprise of strength, and modulus (stiffness), as well as Poisson's ratio etc. and as such they govern the magnitude of load bearing abilities of building materials. Of interest to fire engineers is two properties: strength (including compressive strength (f_c) of concrete, masonry and wood, yield strength (f_y) of various steels), and modulus (E) property. The strength property is evaluated as the ultimate (crushing in case of concrete and masonry) or yield strength (in case of metals). On the other hand, the modulus property defines the ability to resist deformation.

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

The mechanical properties of construction materials are often evaluated via small scale material tests conducted on standard-sized specimens (e.g. coupons/cubes/cylinders). These tests can be carried out in two[†] set-ups: steady-state and transient. In the first type of tests, a specimen is exposed to heat until reaches a target temperature (i.e. 500°C). Then, a linearly increasing stress is applied to measure specimen's response. In the second testing set-up, a specimen is stressed to a pre-decided level (say 40%) and is then subjected to rise in temperature, thus allowing tracing temperature propagation and stress/strain response. The reader needs to remember that these tests are very sensitive to specimen size, test set-up as well as strain and heating rates and hence there are wide discrepancies in measured data (as well as arrived at constitutive models). It should be stressed that since the absence of well-established and agreed upon testing procedure, have led to the bulk of test data being carried out on specimens of varying sizes, set-ups (i.e. restraints conditions, loading/heating rates etc.) [3, 37].

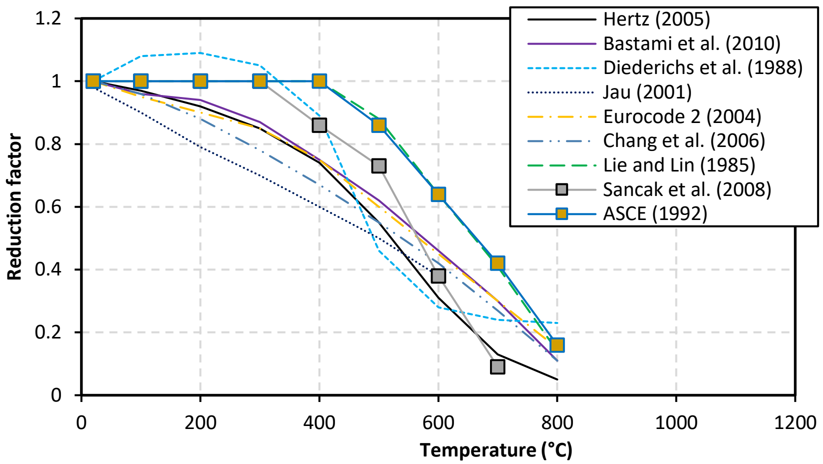
Figures 3 and 4 show that the mechanical properties degrade with rise in temperature and this degradation in normal strength concrete is governed by the type and amount of aggregates and is also governed by concrete water-cement ratio, admixtures etc. [14, 15]. While the ambient compressive strength of normal concrete can be in the range of 40 MPa, the tensile strength of concrete is crudely assumed to be 10% of that at ambient conditions. Although few researchers [3] indicated that tensile strength can be crucial under fire conditions, primary to its potential role in controlling crack propagation and fire-induced spalling, this tensile strength is frequently neglected in fire resistance analysis and design due to the present gap of knowledge on this

[†]There is a third test set-up in which material properties are measured during a post-exposure to elevated temperatures. A thorough discussion on such tests/properties can be found herein [3, 37].

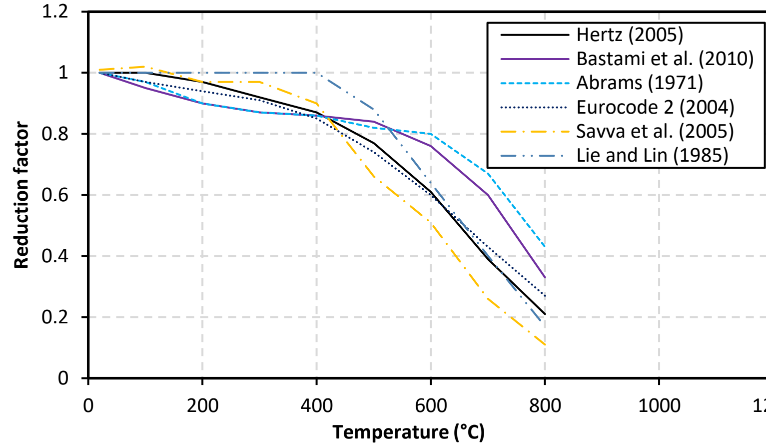
property [37]. The strength properties of masonry are very comparable to concrete and are also influenced by the constituent properties of masonry and mortar as well as molding/firing process [3, 35]. This property also degrades under fire conditions but at a much slower rate than that in concrete (see Fig. 3a-3c). Similar to thermal properties, very little research has been conducted on high temperature properties of masonry, mainly due to the fact that masonry is not commonly used in load-bearing applications in modern buildings – as oppose to other constructions i.e. European/historical structures etc.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

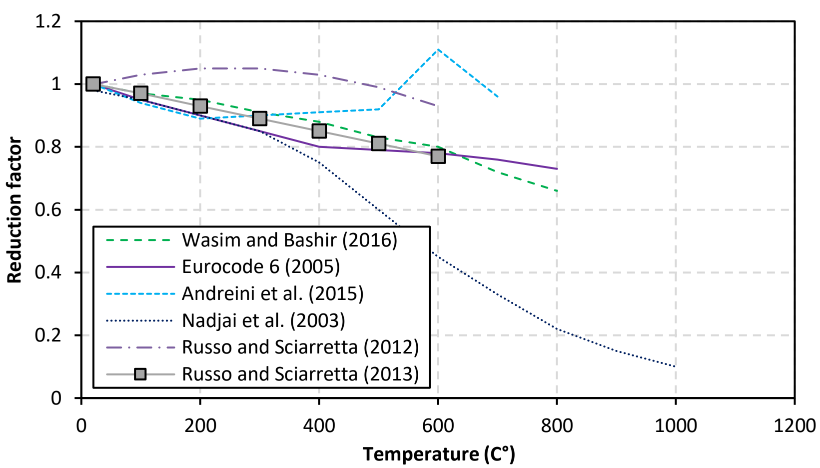
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



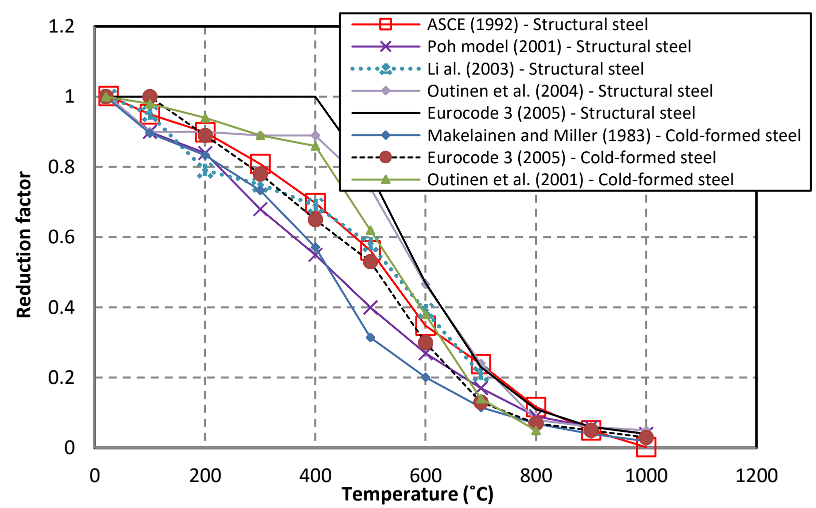
(a) Normal strength concrete – siliceous



(b) Normal strength concrete – carbonate



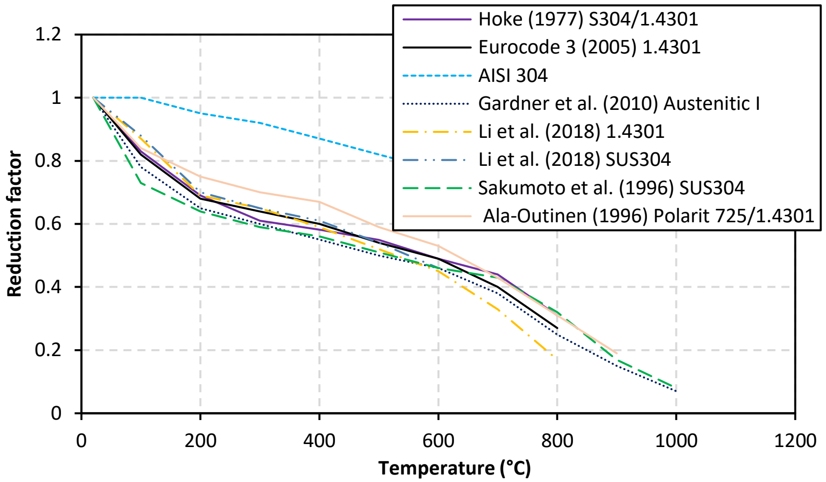
(c) Masonry



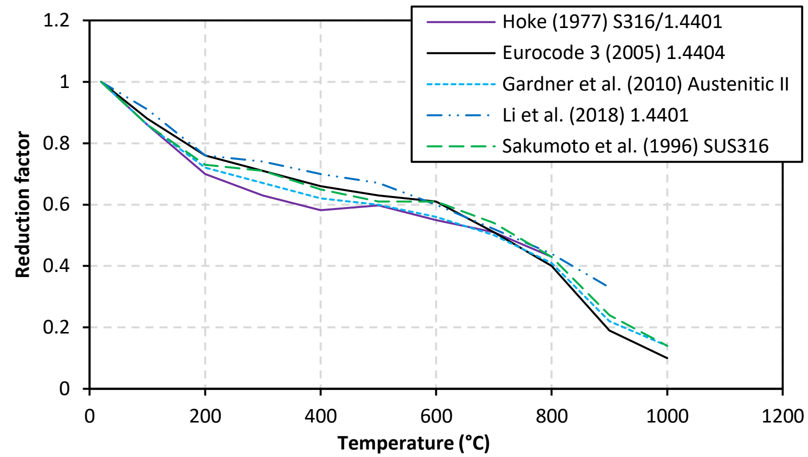
(d) Structural and cold-formed steel

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

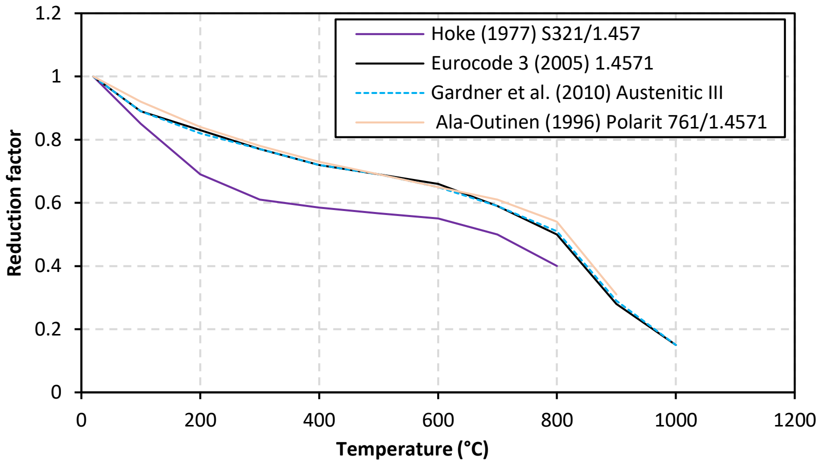
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



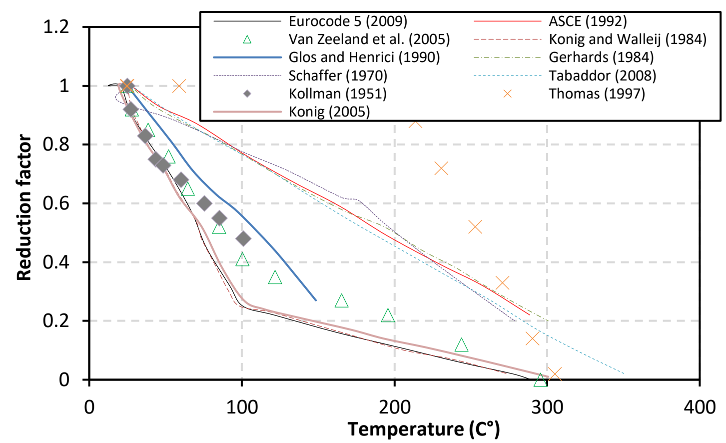
(e) Stainless steel (grade S304/1.4301)



(f) Stainless steel (grade S316/1.4404)



(g) Stainless steel (grade S321/1.4571)



(h) Wood

Fig. 3 Variation of strength property for common construction materials with temperature [6, 9, 11, 16, 18, 28, 31, 38-63]

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

In most cases, the yield strength of metals (structural steel, cold-formed steel and stainless steel) is obtained through tensile-loaded material tests on specially prepared coupons. This is because arrangements used in such tests eliminate a number of difficulties that could arise such as instability of slender specimens under compression loading [5]. This property is often characterized by a distinct point[‡] with a distinct increase in strain lacking an increase in stress. While both structural steel and cold-formed steel have an apparent yield point when tested under ambient conditions, stainless steel on the other hand does not have such a clear point. It is worth noting that there are three grades of austenitic stainless steel regularly used in construction industry and these grades are considered in this study, namely: S304/1.4301, S316/1.4404, and S321/1.4571. The yield strength of commonly used steels can range between 220-420 MPa[§]. This temperature-induced degradation in yield strength is attributed to the activation of grain slip planes facilitated by temperature rise (see Fig. 3d-3g). The rate of temperature-induced degradation is governed by chemical composition (e.g. mineral and alloys), loading/heating rate etc. [5].

Unlike tests conducted on aforementioned materials, the mechanical properties of wood only cover the range of 250-350°C as wood combusts and loses its load bearing capabilities outside of this range. The ultimate (crushing) strength of wood in the direction of grains varies from 13 to 70 MPa and is governed by the amount of moisture, density and specie of wood [38]. Figure 3h illustrates how strength of wood deteriorates with rise in temperature and how this property decreases in a linear fashion (and slow rate) with temperatures up to 75°C [38].

[‡] Often established at 0.2%, 0.5%, and 2% under fire conditions.
[§] Modern steels can have yield strengths far exceeding this range. For the sake of this study, high-strength steels are grouped under modern construction materials and will be dealt with in a companion study.

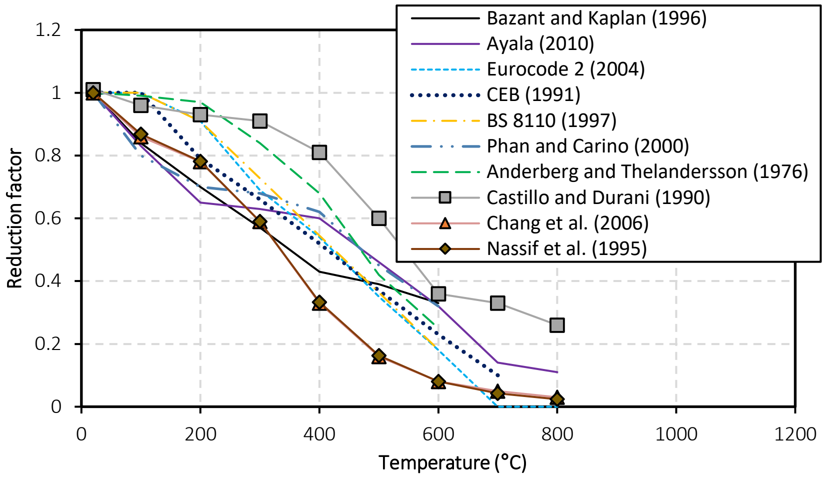
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

The modulus property of various concretes fluctuates over a large range, 5-35 GPa and is governed by the quantity and density of aggregates, water-cement ratio and curing/conditioning conditions. In parallel, the modulus of masonry is usually between 10-20 GPa [3]. Few researchers have noted that: 1) type of aggregates may not significantly affect degradation in modulus property at high temperatures, and 2) the modulus of normal-weight concretes decreases at a higher pace than that in concretes made of lightweight aggregates [15]. The degradation in modulus property can be credited to the generation of thermal stresses as well as physical and chemical changes at the microstructure scale. Neville [14] also noted that degradation in modulus property can be attributed to the continuous decrease in moisture and slackening of atomic bonds.

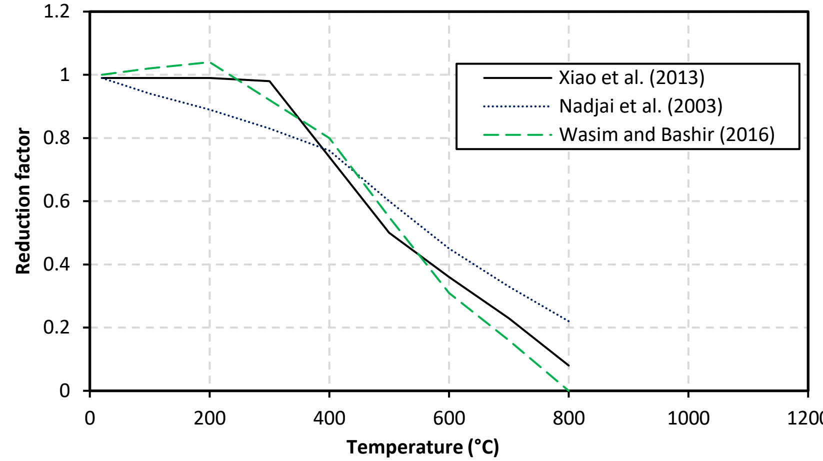
The modulus of steel is about 200-210 GPa at ambient conditions, and is common even for austenitic, ferritic and duplex stainless steels [18]. This property degrades at a much lower temperature than yield strength (see Fig. 4) as only a moderate rise in temperature is sufficient to weaken interatomic bonds and initiate dislocations in the crystalline lattice (Fig. 4c-4e) [64]. In the case of wood, the modulus of wood parallel to grains varies from 5.5-15 GPa. Figure 4f infers that most reported data show that the modulus in wet wood (0-12% moisture content) decreases slowly with rising temperatures up to 200°C. The pace of degradation in modulus of wood seems to rapidly increase beyond this temperature range and is highly accelerated by temperature-induced creep effects.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

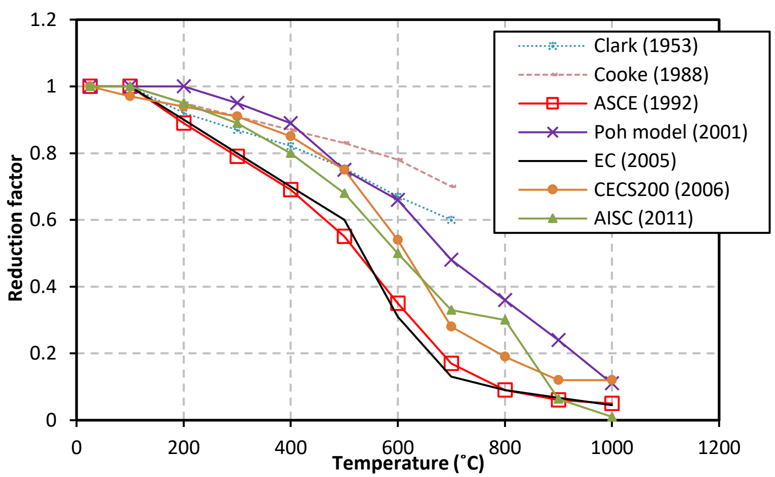
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



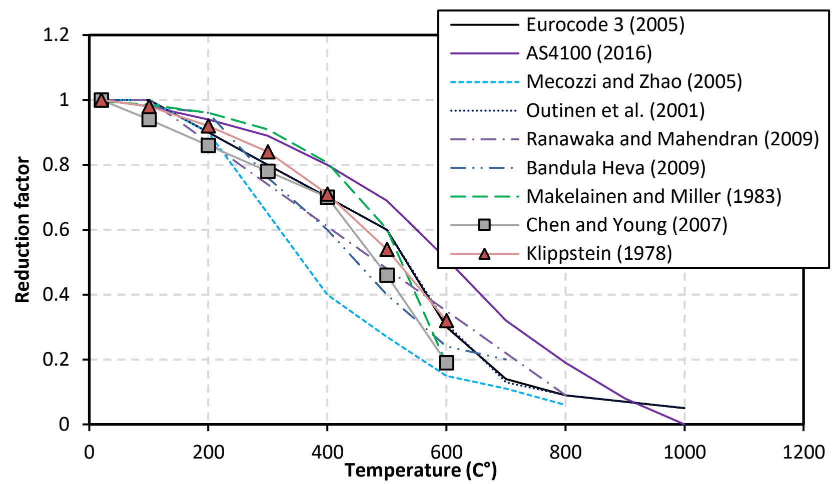
(a) Normal strength concrete



(b) Masonry



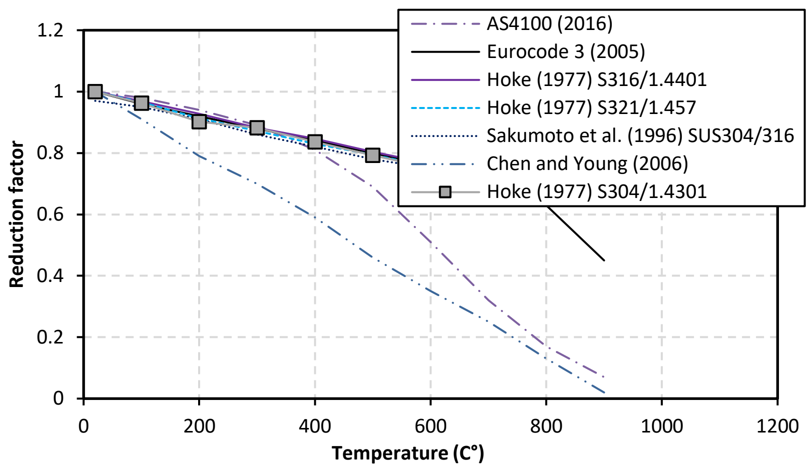
(c) Structural steel



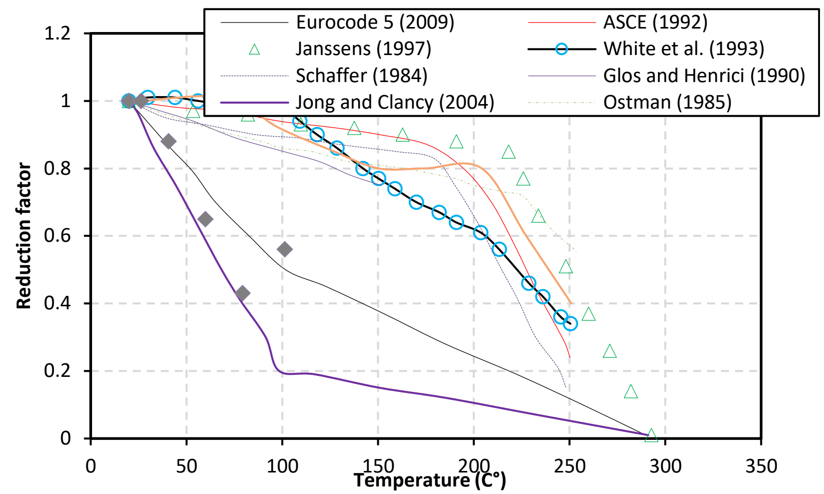
(d) Cold-formed steel

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



(e) Stainless steel (all grades)



(f) Wood

Fig. 4 Variation of modulus property for common construction materials with temperature [6, 9, 11, 16, 26, 43, 48, 53, 56, 57, 63, 65-89]

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

3.0 A NOTE ON HIGH TEMPERATURE MATERIAL TESTS

A comparison between various material models plotted in Figs. 1-4 shows the large variations in measured properties of common building materials. This variation is not only apparent when comparing test data points carried out in 1950s-70s with those carried out in late 1990s-2000s, but also in between data points obtained from tests within the same era. For example, the early works of Powell [21], Yawata [22], and Touloukain [23], which were carried out in 1960s-70s, did not capture critical phase changes in steel material occurring beyond 750°C nor captured full range of temperatures occurring in actual fires. On the other hand, modern testing equipment have the ability to simulate actual fire conditions (i.e. heating rate), to reach extremely high temperatures (exceeding 850°C), hold this temperature for quite some time (1-4 hours), and also to accurately trace material behavior and recognize associated phase changes [90].

While some construction materials may have a consistent composition and well-established production process (i.e. steel), others such as concrete/masonry, and wood significantly vary due to the different raws/admixtures/species available to researchers at the time of testing. For example, a number of fillers and additives is often utilized to improve quality and durability building materials. Despite their positive role in improving such characteristics at working conditions, specifics regarding quantity, chemical composition etc. of such additives remains largely unknown [3, 14, 15]. Thus, another observation concluded from Figs. 1-4 shows that reported data may also vary according to location/origin of research, as well as available raw materials and norms of material production.

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206.
(https://doi.org/10.1016/j.conbuildmat.2019.04.182)

Not only test data obtained from different researchers vary significantly, but the same trend is also apparent in the case of material models adopted by ASCE and Eurocodes. For example, the ASCE material model assumes degradation in compressive strength of concrete to occur according to one material model without any regard to the nature of aggregates of the concrete mix. This is unlike that adopted by Eurocode 2, in which two material models are provided to illustrate degradation in compressive strength in carbonate and siliceous concretes separately. In the case of structural steel, the Eurocode 3 model suggests a slightly slower degradation in yield strength as oppose to that adopted by ASCE under the same temperature range. Whereas Eurocode 3 suggests a constant yield strength of steel up to 400°C, the ASCE model suggests 30% degradation in yield strength at that temperature. Another key point to remember is that Eurocode's 3 model partly accounts for high temperature creep, while ASCE's does not account for such effect. Similarly, Eurocode 5 shows that modulus of wood degrades to 50% at 100°C, while the ASCE's model shows that this degradation is far beyond that suggested by Eurocode 5 and may reach about 5% of initial strength at 100°C; possibly due to testing moist wood and/or account for temperature-induced creep. As discussed in Sec. 1.0, unlike Eurocodes, the ASCE design guide does not provide material models for masonry, stainless steel or cold-formed steel.

The above observations infer that while a good amount of high-temperature material tests have been carried out over the last few decades, a significant variation in outcome of these tests is perhaps one of the only consistent features that is shared between published models. This concerning observation implies that the process of fire resistance analysis and design could potentially remain unstandardized. This not only complicates fire assessment, but also necessitates significant efforts to confer designs among researchers and engineers/practitioners for fire safety

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206.
(https://doi.org/10.1016/j.conbuildmat.2019.04.182)

applications. In other words, a fire design (or analysis for that matter) on a concrete structure, conducted using any of the above material models (say ASCE's) would not be close nor comparable to that carried out via Eurocode's 2 model. In this particular case, previous studies have pointed out that this variation can be close to 20-25% and this significantly under- or over-estimates performance of fire-exposed structures. This could prove advantageous in the first scenario despite leading to expensive or uneconomical design, and undesirable in the former scenario which may lead to premature failure. All in, this is a key challenge for achieving a standardized fire resistance assessment.

A clear solution to the above dilemma is to develop standard, uniform, and unbiased material models that can properly represent degradation in properties of building materials. These models can be arrived at through carrying out high fidelity tests with good consistency. While this solution can be realized over the next decade, the practicality and costs associated with such endeavor may be very optimistic. Another solution would be to collect currently available test data and codal models to realize at unified material models either through traditional (i.e. statistical procedure [90]) or through intelligent systems (i.e. artificial intelligence (AI)) [8, 91-94]. The outcome of recent studies deduces how AI can be effective in developing accurate models to represent material behavior under fire conditions.

4.0 DEVELOPMENT OF ARTIFICAL INTELLIGENT MODEL

In lieu of traditional deterministic methods, artificial intelligence (AI) simulates the reasoning process through cognitive layers arranged in a specific layout (e.g. Artificial Neural Network (ANN)). As such, ANNs are made of constitutive layers and accompanying neurons

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

(processing units) as shown in Fig. 5. Each layer has a number of neurons that is largely contingent on the complexity level of arriving at a relation between inputs and expected outcome. On the far left side, the input layer comprising of independent variables (or predictors), is linked to a second set of layers (hidden layers). Such layers have the capability to find linear/non-linear relations [95]. These layers are also linked to the far right layer (referred to as output layer). Herein, a multilayer perception model with "feed-forward back-propagation and supervised learning", which similar to that of the structure of the brain, is used to develop an ANN.

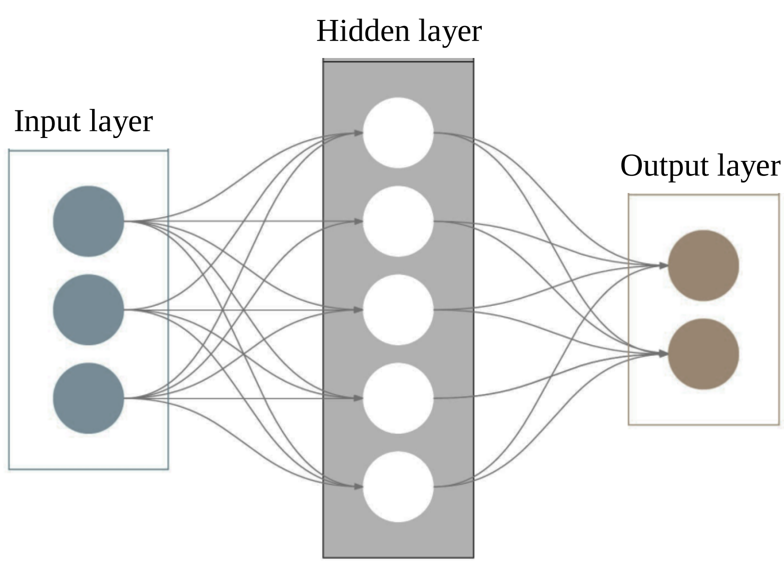


Fig. 5 Layout of an ANN

Once an ANN is developed, exposure (or training) can take place to solve the phenomenon on hand and to satisfy a set of goals(s). The primary goal of the developed ANN is to understand the logic behind various material models; thus arriving at a pattern that exemplifies such models. The ANN training starts by entering temperature-dependent thermal and mechanical material

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

models into the input layer. This data is then cross-multiplied by random weightages to activate a transfer function. After this, transformed output(s) are summed to arrive at AI-derived values for thermal and mechanical material properties. In the last stage, these values are then symbolically analyzed in a genetic programming (GP) model to derive mathematical functions to represent values predicted from ANN. The development of this AI-based model was carried out in Matlab.

5.0 DERIVING AI-BASED TEMPERATURE-DEPENDENT MATERIAL MODELS

As discussed above, all data points (in terms of measured properties or codal-adopted models i.e. ASCE, Eurocodes, AS 4100, AISC, BS5950 and so on), as well as those measured through researchers as plotted in Figs. 1-4.) for commonly used construction materials were input into the ANN. More specifically, temperature-dependent reduction factors of modulus property of concrete were first collected at specific temperatures i.e. 25, 100°C etc. (as shown in Fig. 4a) [95]. It is worth noting that the properties investigated herein are thermal conductivity, and specific heat[**], as well as yield strength and modulus properties of normal strength concrete, masonry, structural steel, stainless steel, cold-formed steel and wood.

The optimally trained ANN was applied to arrive at improved temperature-dependent material expressions for selected construction materials. The predicted values are plotted in Fig. 6 and this figure shows that predicted values precisely fit within collected data points. The same observation can also be made through examining error metrics, coefficient of determination (R^2) and mean absolute error (*MAE*) – see Table 1. A look into these metrics shows that the ANN was

[**]As discussed in Sec. 2.1, limited works have reported outcome of tests on density of construction materials under elevated temperature. Further, since degradation in this property is limited (in case of concrete and masonry) and nil (in metals) has led to neglecting this property. It is worth noting that a similar approach to the one presented here was carried out to derive a unified material model for density of wood under elevated temperature in a future study.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). “Properties and Material Models for Common Construction Materials at Elevated Temperatures.” Construction and Building Materials. Vol. 215, pp. 192-206.
(https://doi.org/10.1016/j.conbuildmat.2019.04.182)

able to properly trace changes in selected construction materials. Thus, it is reasonable to assume that predictions arrived at using the developed ANN can be used to derive representations for temperature-dependent material models.

Table 1 Performance metrics obtained through ANN

Material	**Property**	R^2	***MAE***
Normal strength concrete	Thermal conductivity	99.8	0.296
	Specific heat	90.1	0.510
	Compressive strength	98.3	0.031
	Modulus	99.5	0.014
Masonry	Compressive strength	93.4	0.015
	Modulus	94.8	0.02
Structural steel	Thermal conductivity	99.8	0.296
	Specific heat	90.1	0.510
	Yield strength	98.3	0.031
	Modulus	99.7	0.014
Cold-formed steel	Yield strength	99.4	0.231
	Modulus	95.1	0.214
Stainless steel	Thermal conductivity	93.3	0.036
	Specific heat	96.5	0.035
	Yield strength*	97.3	0.051
	Modulus of elasticity	99.8	0.019
Wood	Thermal conductivity	99.3	0.001

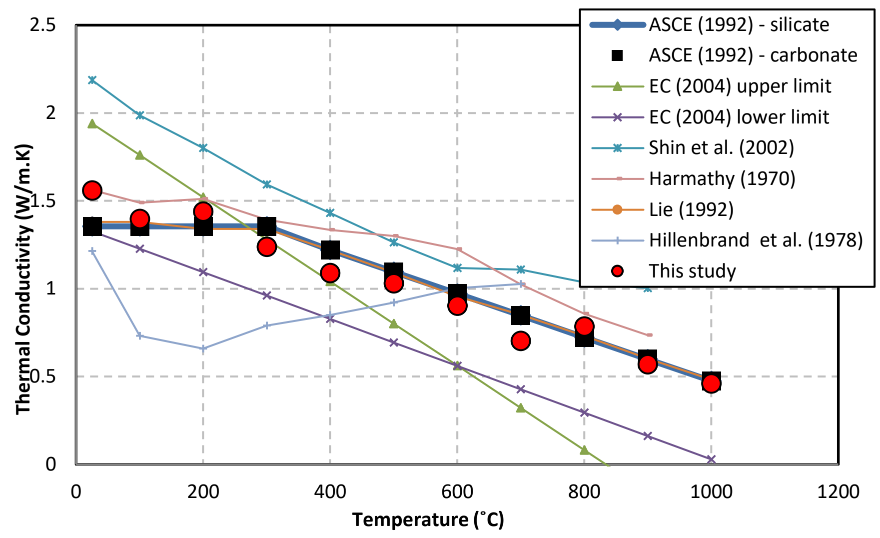
This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206.
(https://doi.org/10.1016/j.conbuildmat.2019.04.182)

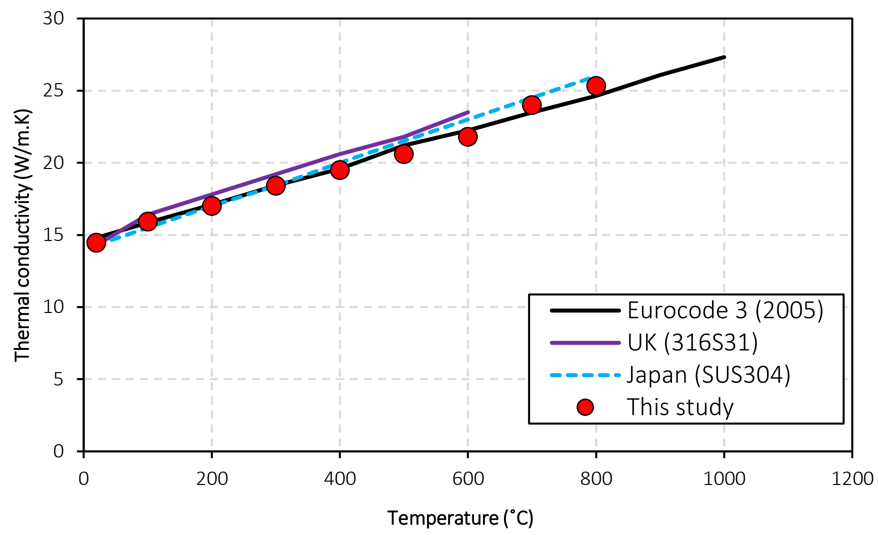
	Specific heat	98.5	0.004
	Compressive strength	94.4	0.008
	Modulus	91.3	0.004

*Average value for three grades of stainless steel

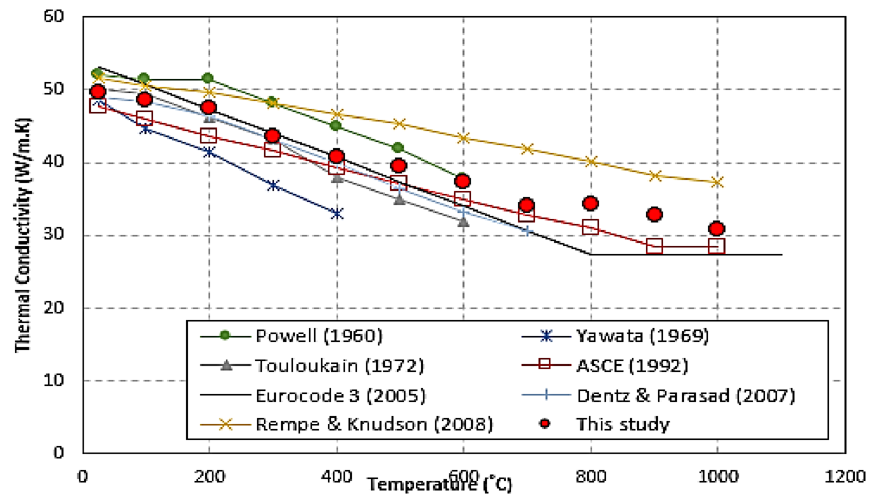
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



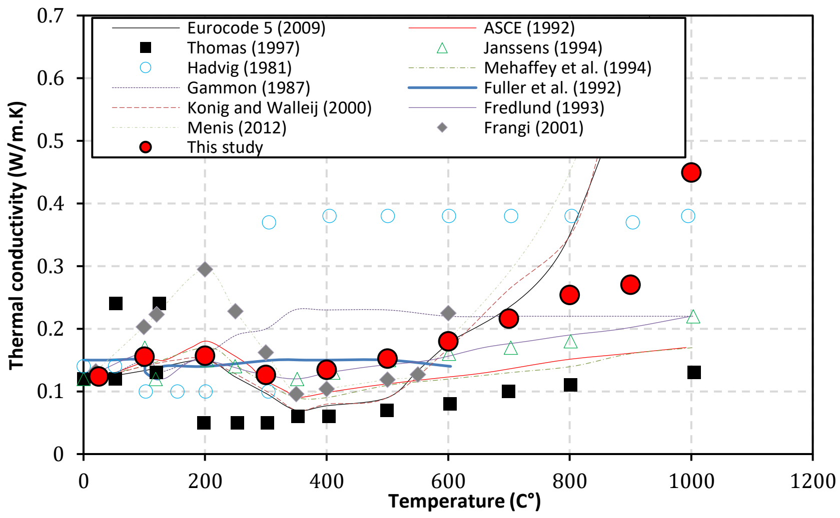
(a) Normal strength concrete



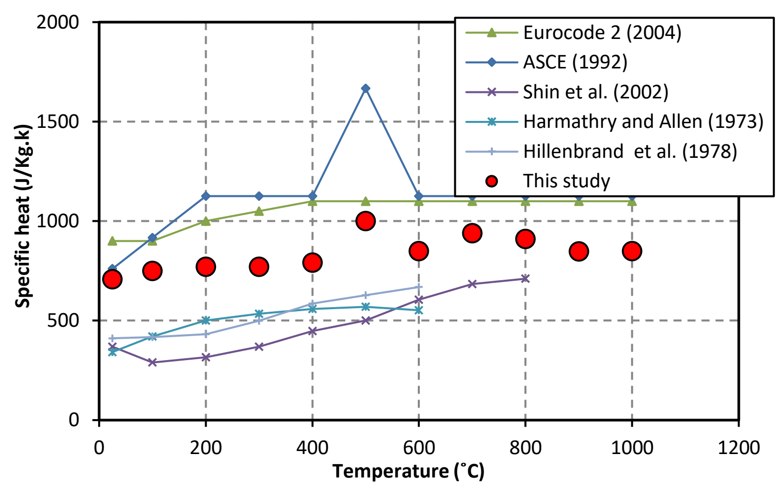
(b) Stainless steel



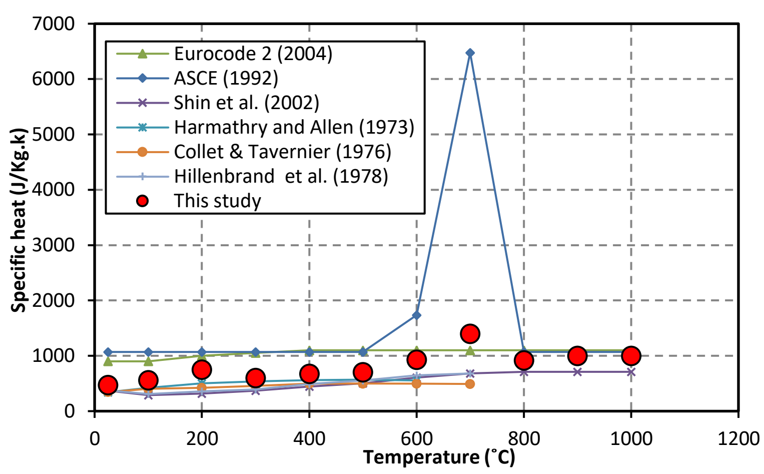
(c) Structural/cold-formed steel



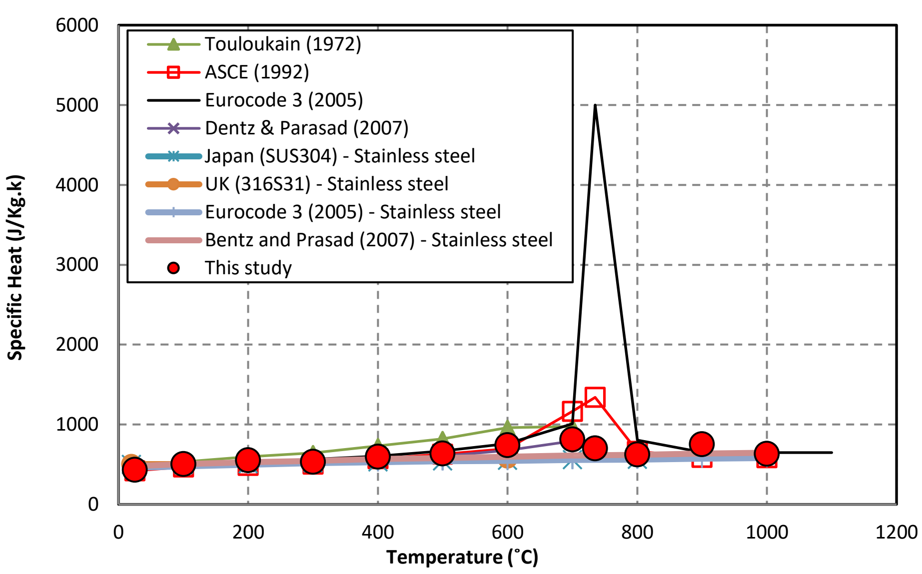
(d) Wood



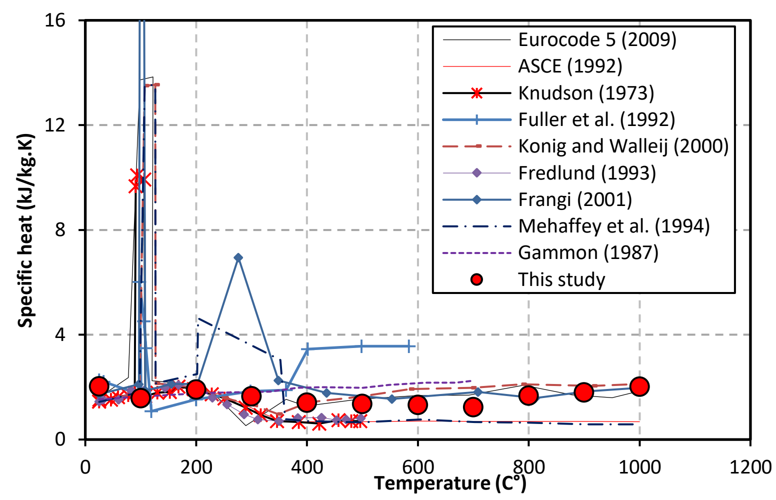
(e) Silicate-based concrete



(f) Carbonate-based concrete

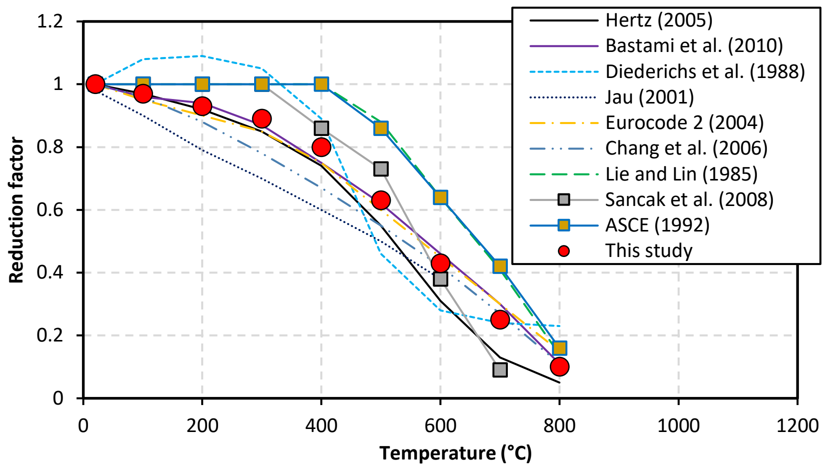


(g) Various steels

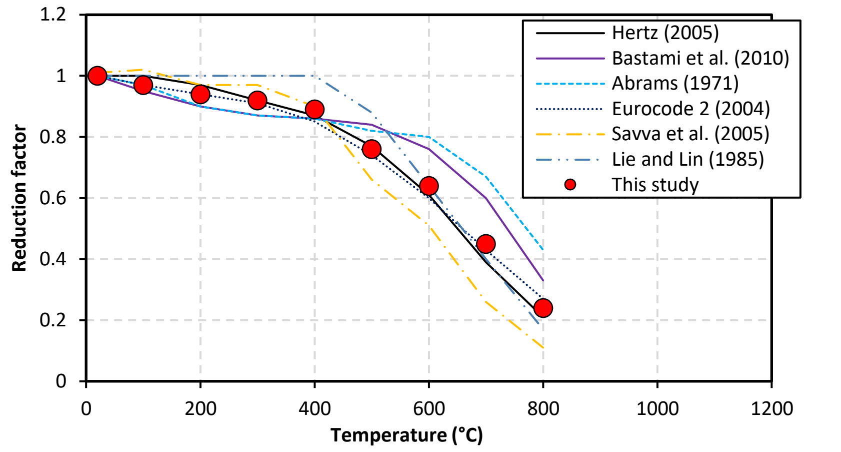


(h) Wood

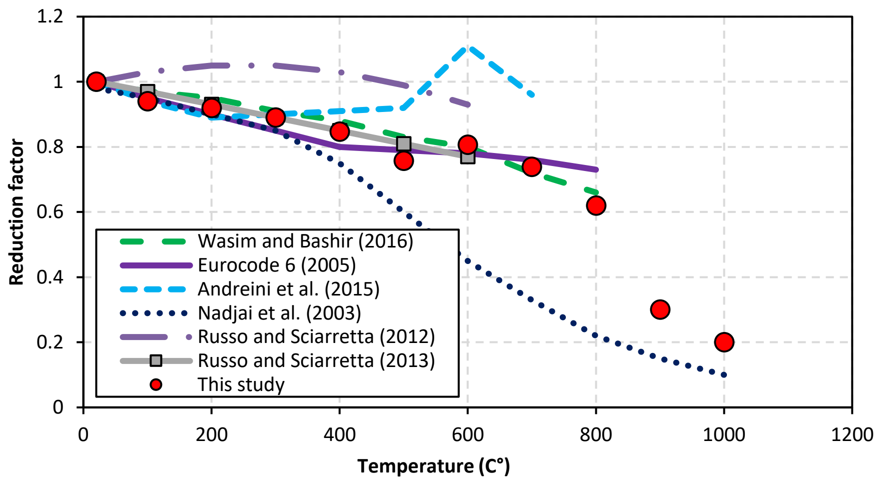
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



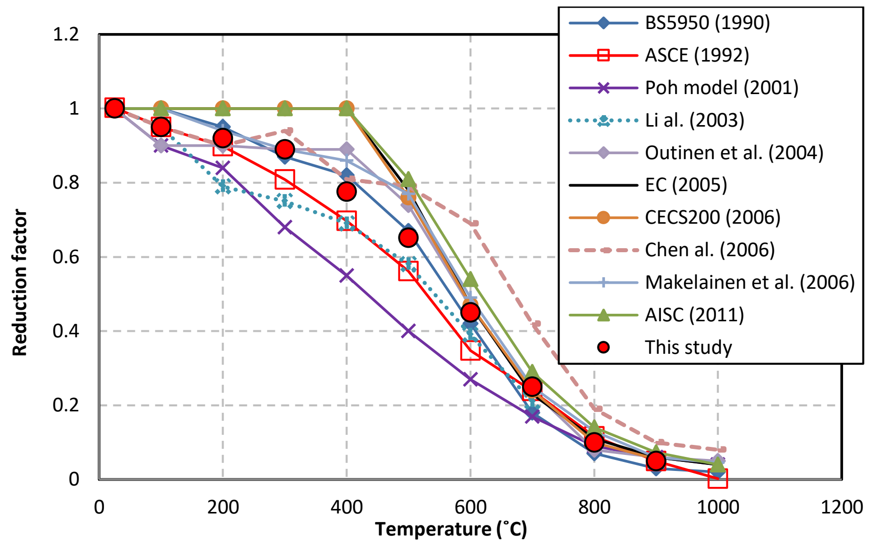
(i) Compressive strength: Normal strength concrete – siliceous



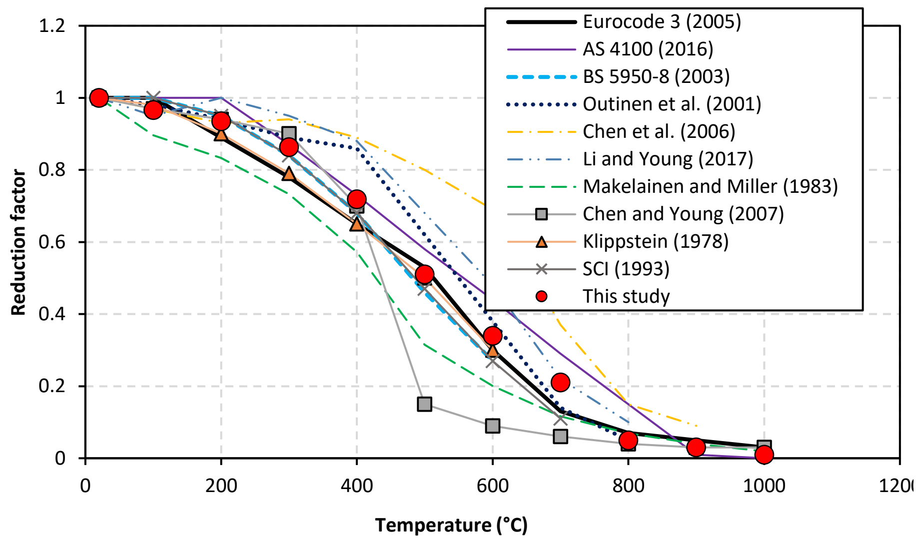
(j) Compressive strength: Normal strength concrete – carbonate



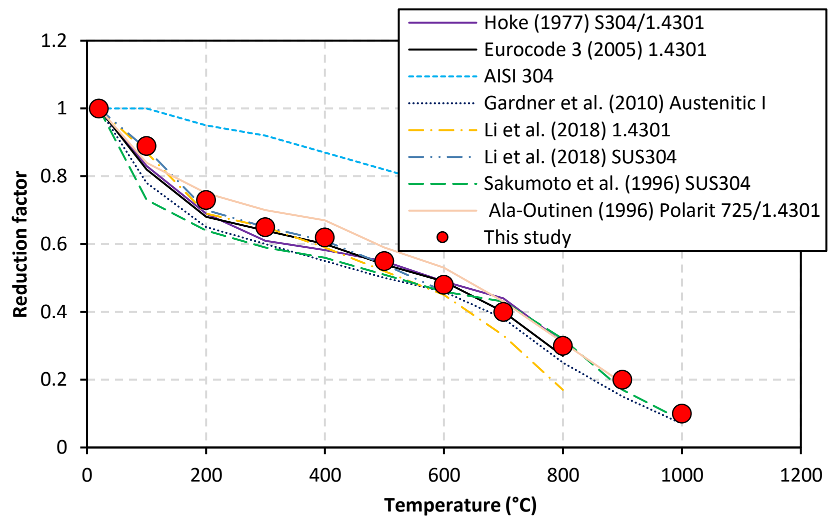
(k) Compressive strength: Masonry



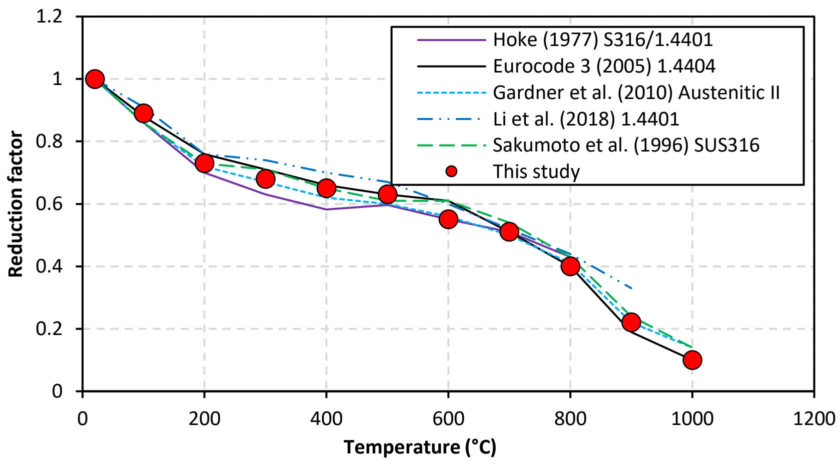
(l) Yield strength: Structural steel



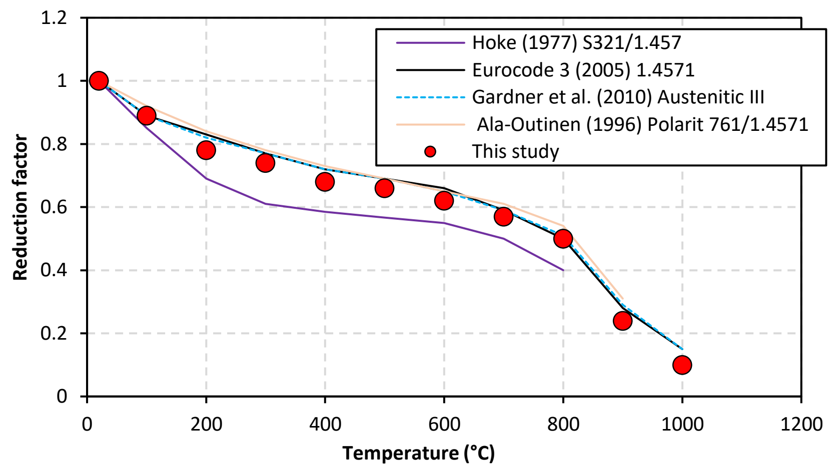
(m) Yield strength: Structural cold-formed steel



(n) Yield strength: Stainless steel (grade S304/1.4301)

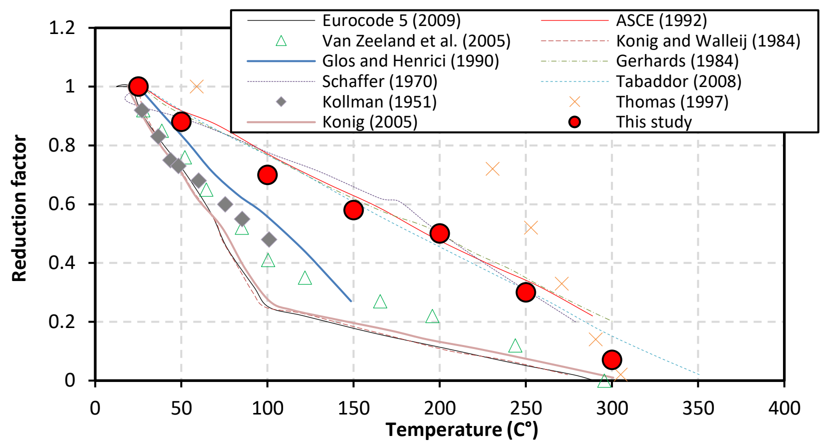


(o) Yield strength: Stainless steel (grade S316/1.4404)

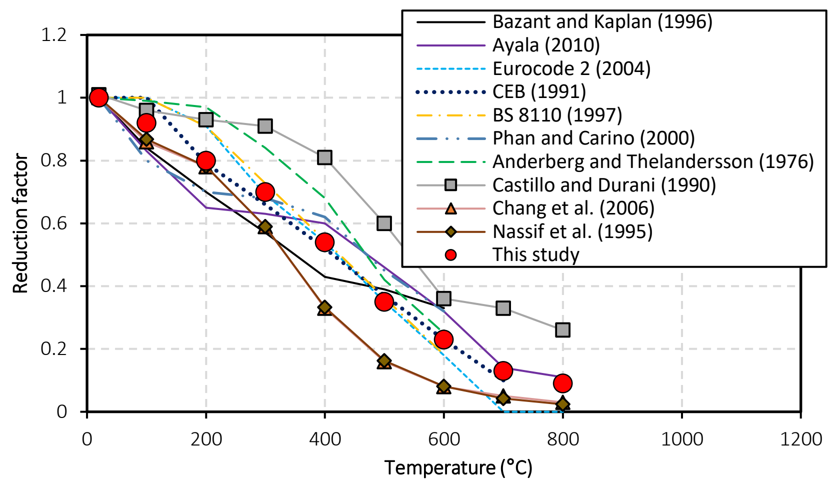


(p) Yield strength: Stainless steel (grade S321/1.4571)

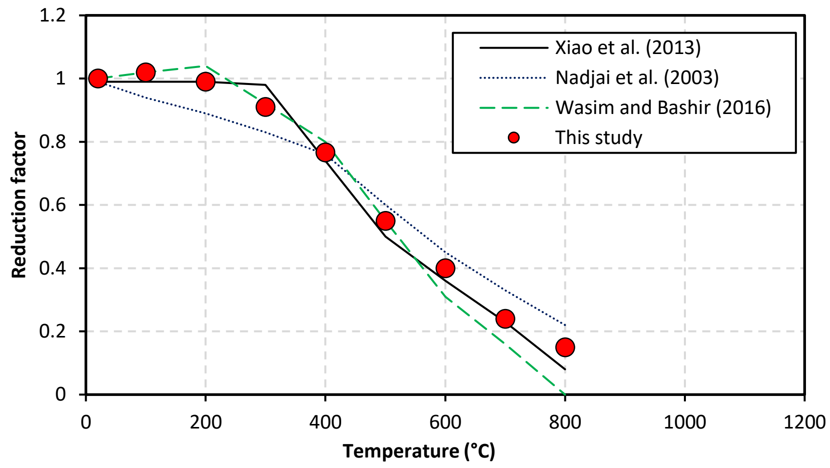
Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)



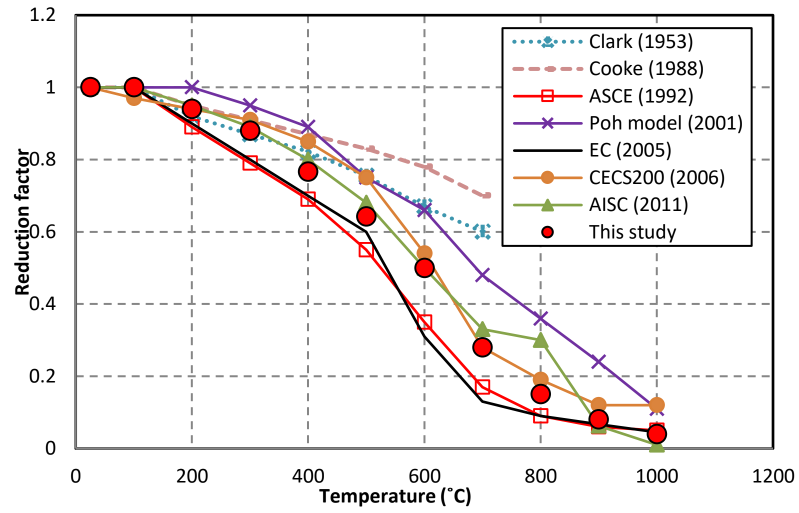
(q) Compressive strength: Wood



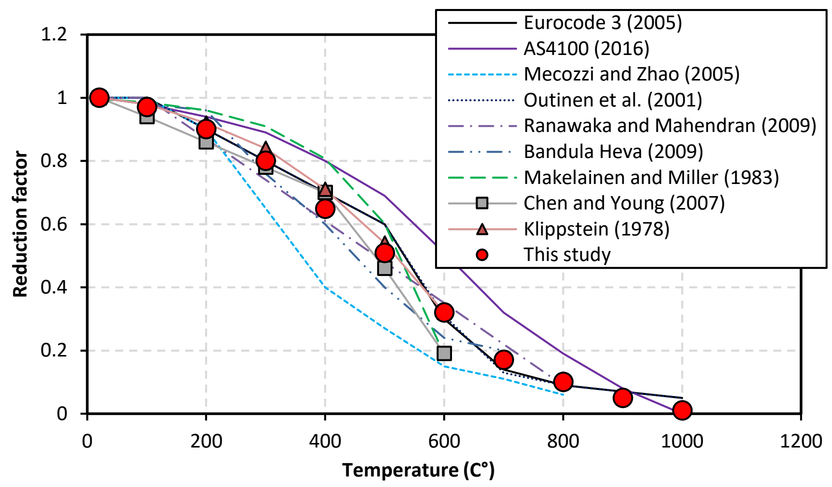
(r) Modulus: Normal strength concrete



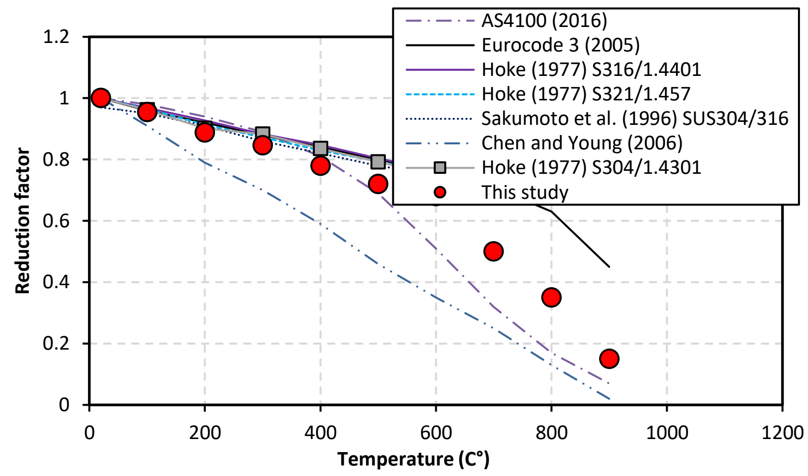
(s) Modulus: Masonry



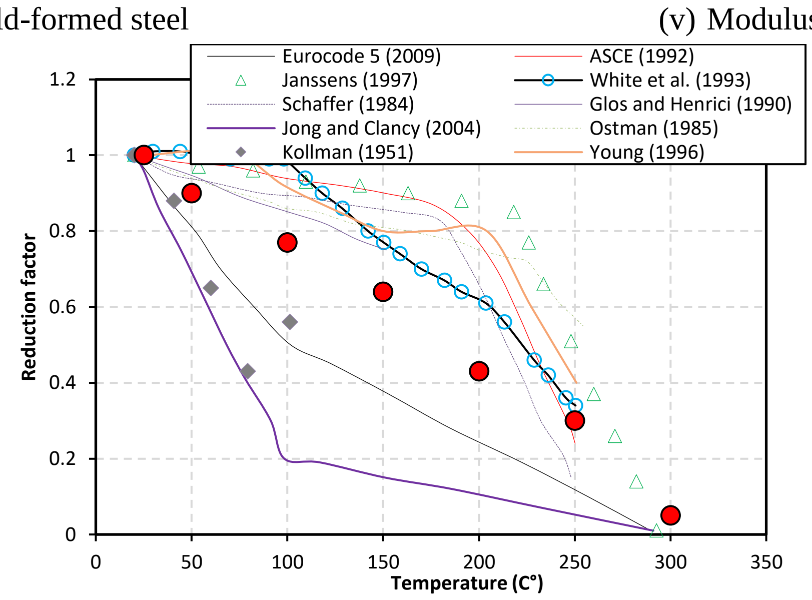
(t) Modulus: Structural steel



(u) Modulus: Cold-formed steel



(v) Modulus: Stainless steel (all grades)



(w) Modulus: Wood

Fig. 6 Evaluation of material models as obtained from AI analysis against those obtained from fire codes/standards and notable works

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

ANN predictions at specific temperatures, i.e. 25, 100°C, are input into a genetic algorithm model in Matlab to derive expressions for material models. In this model, expressions are articulated by a combination of constants and variables to describe a particular phenomenon. These expressions can be joined through functions such as multiplication (×), sine (sin) etc. to arrive at an optimum expression that satisfies a fitness metric. The fitness metric is a function of different errors (i.e. average/absolute etc.) between values predicted using a candidate expression and that of ANN. Herein, two types of expressions are derived. In the first type, a simple expression presents a specific property (e.g. thermal conductivity) for a given construction material (i.e. structural steel). In the second type, a general expression presents a specific property but for all selected materials. This expression can be useful in design scenarios by limiting the number of expressions/references a designer need to go through. All expressions, along with their fitness metric and base values (to be directly substituted in fire evaluation) are listed in Table 2 and Table 3, respectively.

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

Table 2 GP-derived expressions for for temperature-dependent material properties

Material	Property	Simple Expressions	R^2
Normal strength concrete	Thermal conductivity	$k = 1.636 + 3.682e^{-12}T^4 + 4.553e^{-7}T^2\cos(T) - 0.001404T - 0.09206\cos(T) - 3.719e^{-15}T^5$	99.4
	Specific heat	$C_{(siliceous)} = 712 + 0.2185T + 0.4447\tan(T^2)^3 + 0.1053T\sin(5.272e^{-9}T^3) - 0.013\sinh(\tan(T^2)) - 2.242e^{-11}T^4\tan(T^2)$	95.6
		$C_{(carbonate)} = 452.9 + 0.8453T + 40.55\tan(564.T) - 0.000291T^2 - 8.783\tan(564.9T) - 0.02121T\tan(564.9T)$	99.7
	Compressive strength*	$f_{c(siliceous)} = 1.016 + 4.918e^{-6}T^2 + 9.411e^{-12}T^4 - 0.000885T - 1.408e^{-8}T^3$	99.5
		$f_{c(carbonate)} = 1.013 + 3.337e^{-6}T^2 + 3.693e^{-12}T^4 - 0.0007362T - 7.486e^{-9}T^3$	99.8
	Modulus*	$E = 1.019 + 3.413e^{-12}T^4 - 0.0009538T - 3.054e^{-9}T^3$	99.8
Masonry	Compressive strength	$f_c = 1.003 + 7.156e^{-13}T^4 + 2.189e^{-11}T^2(1.037T)^{0.001886T} - 0.0003368T - 2.467e^{-7}T^2 - 2.38e^{-5}(1.037T)^{0.001886T}$	99.3
	Modulus*	$E = 1.041 + T\tanh(3.355e^{-6}T) - 0.002124T - 2.418e^{-9}T^3$	99.6
Structural steel	Thermal conductivity	$k = 49.62 + 1.556e^{-7}T^3 - 7.095e^{-11}T^4 - 0.0001034T^2$	99.2
	Specific heat	$C = 369.730 + 2.373T + 1.857e - 5T^3 + 68.988sinT^2 - 9.975e^{-9}T^4 - 0.0108T^2 - 0.324TsinT^2$	98.6
	Yield strength	$f_c = 1.022 + 4.382e^{-6}T^2 + 8.204e^{-18}T^6 - 0.001T - 4.024e^{-24}T^8 - 8.524e^{-9}T^3$	99.9
	Modulus	$E = 1.007 + 4.838e - 25T^8 - 1.419e^{-6}T^2 - 1.239e^{-7}T^2sin(0.962T)^2$	99.9
Cold-formed steel	Thermal conductivity	Similar to structural steel	-
	Specific heat	Similar to structural steel	-

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

	Yield strength	$f_y = 0.7629 + 1.085e^{-15}T^5 + 0.243\left(0.9924^{1.284e^{-14}T^6}\right) - 0.0002939T - 1.544e^{-9}T^3$	99.8
	Modulus of elasticity	$E = 1.007 + 9.888e^{-15}T^5 - 0.000348T - 6.071e^{-18}T^6 - 4.465e^{-9}T^3$	99.5
Stainless steel	Thermal conductivity*	$k = 13.13 + 0.009022T + 0.397\ln(T) + 1.969e^{-6}T^2 + 4.768e^{-12}T^4\cos(T^2)$	98.7
	Specific heat	$C = 3710 + 248.6\,\mathrm{acosh}(T) + 0.0684T\,acosh(T) - 39.24\sqrt{T} - 2686\,\mathrm{atan}(0.549T)$	99.7
	Yield strength	$f_{y(S304/1.4301)} = 1.047 + 5.535e^{-6}T^2 + T\,\mathrm{atan}(2.681e^{-12}T^3) - 0.002417T - 6.745e^{-9}T^3$	99.4
		$f_{y(S316/1.4401)} = 1.045 + 5.188e^{-6}T^2 + 8.153e^{-16}T^5 - 0.002348T - 4.594e^{-9}T^3 - 4.27e^{-12}T^3\tan(T)$	99.6
		$f_{y(S321/1.457)} = 1.024 + 1.863e^{-6}T^2 + 0.001509e^{-12}T^4 - 9.482e^{-12}T^3\tan(T)$	99.8
	Modulus of elasticity**	$E = 1.014 + 8.542e^{-7}T^2 - 0.000696T - 1.275e^{-9}T^3$	99.5
Wood	Thermal conductivity	$k = 0.37 - \frac{6.07}{T} + 0.0006T(T) + 7.66\times10^{-5}T\tan(0.071T) - 0.004T - 0.0129\tan(0.07T) - 9.5\times10^{-8}T^2\tan(0.071T)$	99.1
	Specific heat	$C = 2.48 - \frac{6.12}{T} + 3.6\times10^{-6}T^2 + \frac{29.25}{2.8T-343.6} - 0.004T - 0.046\tan(3.9\times10^{-9}T^3)$	99.5
	Compressive strength	$f_c = 1.17 + 3.19\times10^{-5}T^2 + 7.3\times10^{-13}T^5 - 0.0075T - 4.3\times10^{-10}T^4$	99.4
	Modulus	$E = 1.17 + 8.14\times10^{-5}T^2 + 1.1\times10^{-14}T^6 - .0087T - 6.84\times10^{-20}T^8 - 3.48\times10^{-7}T^3$	99.5
Property		**General Expressions*** **	R^2
Thermal conductivity		$k = \begin{Bmatrix} 1.865 + 6.906e^{-10}T^3 + 7.744e^{-5}Tm^2 - 0.001035T - 0.2679m - 5.874e^{-7}T^2 - 0.04239m^2, for\ m = 1\ and\ 4 \\ 58.6 + 0.0437Tm + 4.24e^{-8}T^3 - 0.0863T - 0.5514m^4 - 4.639e^{-5}T^2, for\ m = 2\ and\ 3 \end{Bmatrix}$ where, *m* is material number and equals to 1, 2, 3 and 4 for normal strength concrete, structural steel, stainless steel, and wood, respectively.	99.8

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

Specific heat	$C = 578.3m + 0.549T + 18.07T^4 + \ln(560.5m) + 0.549T + 18.07m^4) - 98.78m^3 - 0.008997Tm^3$ where, *m* is material number and equals to 1, 2, 3,4 and 5 for silicate and carbonate concrete, structural steel, stainless steel, and wood, respectively.	93.9
Strength	$f = 1.041 + 0.01076T - \frac{0.007624T}{m} + 0.0007304Tm^2 + 0.2694m^2 \sin(-1.67e^{-5}Tm^2) - 0.005138Tm$ where, *m* is material number and equals to 1, 2, 3,4 5, 6, 7 and 8 for normal strength concrete, masonry, structural steel, cold-formed steel, stainless steel (S304/1.4301), stainless steel (S316/1.4401), stainless steel (S321/1.457), and wood, respectively. This expression gives compressive strength for concrete, masonry and wood, together with yields strength for various steels.	92.9
Modulus	$E = 1.307\sin(1.384 + 0.0596\tan(m) + 4.5e^{-10}T^3(m^2) - 0.001311T - 0.0001632T\tan(m)) - 0.2817 - 0.0003194T\,tan(m^2)$; where, *m* is material number and equals to 1, 2, 3,4 5, and 6 for normal strength concrete, masonry, structural steel, cold-formed steel, stainless steel, and wood, respectively.	97.7
*Range up to 800°C, **Range up to 900°C, ***These expressions might result in slightly different values than those listed in Table 3. The values listed in Table 3, which are identical to those obtained via simple expressions, are of higher accuracy.		

This is a preprint draft. The published article can be found at: https://doi.org/10.1016/j.conbuildmat.2019.04.182

Please cite this paper as:
Naser M.Z. (2019). “Properties and Material Models for Common Construction Materials at Elevated Temperatures.” Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

Table 3 Base values for temperature-dependent material properties at target temperatures

Base values										
Temperature (°C)	**Normal strength concrete**						**Structural steel**			
	k **(W/m.K)**	***C*** **(J/Kg.K)***		**Reduction factor for *fc***		**Reduction factor for *E***	***k*** **(W/m.K)**	***C*** **(J/Kg.K)**	**Reduction factor for *fy***	**Reduction factor for *E***
		Silicate	**Carbonate**	**Silicate**	**Carbonate**					
25	1.57	708	476	1.000	1.000	1.000	49.6	432.9	1.00	1.00
100	1.42	750	558	0.970	0.970	0.920	48.5	505.7	0.95	1.00
200	1.38	771	750	0.930	0.940	0.800	47.4	551.1	0.92	0.94
300	1.20	771	600	0.890	0.920	0.700	43.5	531.1	0.89	0.88
400	1.14	792	677	0.800	0.890	0.540	40.7	597.0	0.78	0.77
500	1.03	1000	703	0.630	0.760	0.350	39.4	637.6	0.65	0.64
600	0.91	850	929	0.430	0.640	0.230	37.3	742.2	0.45	0.50
700	0.80	940	1400	0.250	0.450	0.130	34.0	812.7	0.25	0.28
800	0.77	910	917	0.100	0.240	0.090	34.2	701.5	0.10	0.15
900	0.61	847	1002	-	-	-	32.7	625.5	0.05	0.08
1000	0.40	850	1002	-	-	-	30.9	752.5	0.02	0.04

Temperature (°C)	**Stainless steel**						**Wood**				
	k **(W/m.K)**	***C*** **(J/Kg.K)**	**Reduction factor for *fy***			**Reduction factor for *E***	***k*** **(W/m.K)**	***C*** **(J/Kg.K)**	**Temperature (°C)**	**Reduction factor for *fc***	**Reduction factor for *E***
			S304/1.4301	**S316/1.4401**	**1.4571**						
25	14.5	480	1.00	1.00	1.00	1.00	0.12	2034	25	1	1
100	15.9	496	0.89	0.89	0.89	0.96	0.16	1579	50	0.88	0.9
200	17.0	525	0.73	0.73	0.78	0.89	0.16	1918	100	0.7	0.77
300	18.4	534	0.65	0.68	0.74	0.85	0.13	1654	150	0.58	0.64
400	19.5	542	0.62	0.65	0.68	0.78	0.13	1417	200	0.5	0.43
500	20.6	550	0.55	0.63	0.66	0.72	0.15	1367	250	0.3	0.3
600	21.8	557	0.48	0.55	0.62	0.68	0.18	1330	300	0.07	0.05
700	24.0	570	0.40	0.51	0.57	0.50	0.22	1243	-		
800	25.3	580	0.30	0.40	0.50	0.35	0.25	1675	-		
900	-	-	0.20	0.22	0.24	0.15	0.27	1798	-		
1000	-	-	0.10	0.10	0.10	-	0.45	2018	-		

Temperature (°C)	**Masonry**		**Cold-formed steel**	
	Reduction factor for *fc*	**Reduction factor for *E***	**Reduction factor for *fy***	**Reduction factor for *E***
25	1.000	1.00	1.000	1.000
100	0.940	0.86	0.966	0.970
200	0.920	0.71	0.935	0.900
300	0.890	0.64	0.863	0.800
400	0.847	0.60	0.719	0.648
500	0.757	0.50	0.510	0.509
600	0.807	0.45	0.340	0.320
700	0.738	0.37	0.210	0.170
800	0.620	0.25	0.050	0.100
900	0.300	-	0.030	0.050
1000	0.200	-	0.010	0.010

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

6.0 PRACTICAL IMPLICATIONS AND FUTRE RESEARCH PLANS

The discussion outlined in Secs. 1-3 illustrates how the result of a given fire resistance evaluation is highly sensitive to the selected material model. As the fire response of a structural member is not known beforehand, then fire resistance predictions are often viewed with caution. In such a scenario, fire designers often face a challenge as to 1) what material model to select for fire assessment, 2) justification to select such model over others. As a result, it is common for shareholders/building officials to require further validation against actual fire tests. In reality, except when a comprehensive high temperature material testing is carried out on construction materials comprising structural system(s), then a truly ideal design might not be realized. This illustrates the urgent need for a uniform and modern representation of temperature-dependent material properties. The strive to pursue development of such models is one of the first steps towards realizing a uniform/standard approach for fire assessment [96, 97].

This study attempts to apply AI as a mean to arrive at material models for commonly used construction materials suitable for use under fire conditions. Since the proposed values/expressions are derived by analyzing a series of models adopted in fire guides or in notable studies; which present an overview in variations in materials composition/origin/testing methods etc., it is then believed that the proposed models can properly convey the behavior of construction materials under fire conditions [8, 98]. It should be noted that while this work is primarily tailored to derive models for specific properties, future works are expected to extend and improve this methodology for other properties: i.e. transient strain, creep etc. [98]. These studies are to strive at developing temperature-dependent material models for post-fire exposure and account for aspects including

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

admixtures, curing, moisture content, chemical composition and milling process in metals, variation in wood species etc.

The collective product of these studies can generate databases for various construction materials. Perhaps one of the advantages of developing such databases is the opportunity of frequently updating temperature-dependent material models upon inclusion of additional data points given that AI models have the ability to improve their accuracy with continuous training, together with minimizing processing time and reducing numerical discrepancies. A key future research need is to develop fire-based AI models that are specifically designed to understand response of materials under fire conditions. Such models may integrate other AI techniques including Ant Colony (AC), Grey Wolf Optimization (GWO) etc. to further optimize fire resistance evaluation and develop improved and resilient structures [99-101].

7.0 CONCLUSIONS

This study showcases a framework to develop temperature-dependent thermal and mechanical material properties of common building materials including normal strength concrete, masonry, structural steel, stainless steel, cold-formed steel and wood. This approach applies artificial intelligence in two forms, i.e. Artificial Neural Networks (ANNs) and Genetic Programming (GP) to achieve modern temperature-dependent material models.

These following conclusions could also be gathered from the outcome of this work:

- Outcome of fire resistance evaluation is sensitive to the input constitutive material models used in the assessment process. This variation can be in the range of 20-25%.

- There is an urgent need to develop up-to-date representations of temperature-dependent properties of building materials as to modernize structural fire design/analysis and to support ongoing standardization attempts.
- The use of AI to arrive at unified and up-to-date material models could be regarded as the first step into modernizing fire resistance evaluation procedure.

Acknowledgment

The author would also like to thank Prof. Venkatesh K. Kodur for his continuous support.

Data availability

The raw data required to reproduce these findings are available to download from [www.mznaser.com/fireassessmenttoolsanddatabases]

8.0 REFERENCES

[1] Buchanan AH, Abu AK. Structural design for fire safety. John Wiley & Sons; 2017 Jan 30. ISBN: 978-0-470-97289-2
[2] Franssen JM, Kodur V, Zaharia R. Designing steel structures for fire safety. CRC Press; 2009 May 6. ISBN 9780415548281
[3] Kodur VK, Harmathy TZ. Properties of building materials. InSFPE handbook of fire protection engineering 2016 (pp. 277-324). Springer, New York, NY.
[4] Kodur VK, Garlock M, Iwankiw N. Structures in fire: state-of-the-art, research and training needs. Fire Technology. 2012 Oct 1;48(4):825-39. https://doi.org/10.1007/s10694-011-0247-4
[5] Kodur V, Dwaikat M, Fike R. High-temperature properties of steel for fire resistance modeling of structures. Journal of Materials in Civil Engineering. 2010 Apr 15;22(5):423-34. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000041
[6] Structural Fire Protection – ASCE Manuals and Reports on Engineering. Practice No. 78, New York, NY, 1992.
[7] Eurocode 3, Design of steel structures, Part1-2: General rules-structural fire design, Document CEN, European Committee for Standardization, UK, 2005.
[8] Naser MZ. Deriving temperature-dependent material models for structural steel through artificial intelligence. Construction and Building Materials. 2018 (191). https://doi.org/10.1016/j.conbuildmat.2018.09.186

[9] Eurocode 2, Design of concrete structures, Part1-2: General rules-structural fire design, ENV 1992-1-2, Document CEN, European Committee for Standardization, UK in, 2004.
[10] Eurocode 6: Design of masonry structures—Part 1-2: General rules - Structural fire design for reinforced and unreinforced masonry structures. Comité Européen de Normalisation: Brussels, Belgium. 2005.
[11] Eurocode 5. Design of Timber Structures. Part 1–2: General. Structural Fire Design. 2009.
[12] Choe L, Zhang C, Luecke WE, Gross JL, Varma AH. Influence of material models on predicting the fire behavior of steel columns. Fire technology. 2017 Jan 1;53(1):375-400. https://doi.org/10.1007/s10694-016-0568-4
[13] Khoury GA. Compressive strength of concrete at high temperatures: a reassessment. Magazine of concrete Research. 1992 Dec;44(161):291-309. https://doi.org/10.1680/macr.1992.44.161.291
[14] Neville AM. Properties of concrete. London: Longman; 1995 Jan.
[15] Kodur V. Properties of concrete at elevated temperatures. ISRN Civil engineering. 2014 Mar 13;2014. http://dx.doi.org/10.1155/2014/468510
[16] Harmathy TZ. Thermal properties of concrete at elevated temperatures. Journal of Materials. 1970 Mar.
[17] Society of Fire Protection Engineers (SFPE). Handbook of fire protection engineering, 4th Ed., Cleveland, 2008.
[18] Gardner L, Insausti A, Ng KT, Ashraf M. Elevated temperature material properties of stainless steel alloys. Journal of Constructional Steel Research. 2010 May 1;66(5):634-47. https://doi.org/10.1016/j.jcsr.2009.12.016
[19] Fredlund B. A model for heat and mass transfer in timber structures during fire: a theoretical, numerical and experimental study. 1988. http://lup.lub.lu.se/record/1669925
[20] Shin KY, Kim SB, Kim JH, Chung M, Jung PS. Thermo-physical properties and transient heat transfer of concrete at elevated temperatures. Nuclear Engineering and Design. 2002 Mar 1;212(1-3):233-41. https://doi.org/10.1016/S0029-5493(01)00487-3
[21] Powell RW, Tye RP. High alloy steels for use as a thermal conductivity standard. British Journal of Applied Physics. 1960 May;11(5):195.
[22] Yawata Iron and Steel Co. WEL-TEN 80 material datasheet Tokyo, 22 (1969).
[23] Touloukian Y, Thermal radiative properties for non-metallic solids, Thermal Physical Properties 8 (1972) 142–151.
[24] Bentz D, Prasad K, Thermal performance of fire resistive materials I. Characterization with respect to thermal performance models, Rep. No. BFRL-NIST 7401, NIST, Gaithersburg, MD, 2007.
[25] Knudson RM, Schniewind AP. Performance of structural wood members exposed to fire. Forest Products Journal (USA). 1975. ISSN : 0015-7473
[26] Janssens ML, White RH. Temperature profiles in wood members exposed to fire. Fire and Materials. 1994;18(4):263-5. https://doi.org/10.1002/fam.810180410
[27] Fuller JJ, Leichti RJ, White RH. Temperature distribution in a nailed gypsum-stud joint exposed to fire. Fire and materials. 1992;16(2):95-9. https://doi.org/10.1002/fam.810160206

[28] Konig J, Walleij L. Timber frame assemblies exposed to standard and parametric fires, Part 2: a design model for standard fire exposure. Rapport I 0001001. Swedish Institute for Wood Technology Research, Stockholm. 2000.
[29] Fredlund B. A model for heat and mass transfer in timber structures during fire: a theoretical, numerical and experimental study. 1988. http://lup.lub.lu.se/record/1669925
[30] Frangi A. Brandverhalten von Holz-Beton-Verbunddecken. ETH Zurich; 2001. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/145666/eth-24596-01.pdf
[31] Thomas GC. Fire resistance of light timber framed walls and floors. PhD Thesis, University of Canterbury, 1996. http://hdl.handle.net/10092/5877
[32] Hadvig S. Charring of wood in building fires. Technical University of Denmark Press, Lyngby. 1981. https://firedoc.nist.gov/article/AV-78e74e8PRSQSQ1DCO
[33] Mehaffey JR, Cuerrier P, Carisse G. A model for predicting heat transfer through gypsum-board/wood-stud walls exposed to fire. Fire and materials. 1994 Sep;18(5):297-305. https://doi.org/10.1002/fam.810180505
[34] Gammon BW. Reliability Analysis of Wood-Frame Wall Assemblies Exposed to Fire, Berkeley, California: University Microfilms Dissertation Information Service, University of California, 1987.
[35] Harmathy TZ, Allen LW. Thermal properties of selected masonry unit concretes. InJournal Proceedings 1973 Feb 1 (Vol. 70, No. 2, pp. 132-142).
[36] Collet Y., Tavernier E. Etude des properties du beton soumis a des temperatures elevees. Comportement du Materiaux Beton en Fonction de la Temperature, Groupe de Travail, Brussels, November 1976
[37] Kodur VK, Dwaikat MM, Dwaikat MB. High-temperature properties of concrete for fire resistance modeling of structures. ACI Materials Journal. 2008 Sep 1;105(5):517.
[38] Gerhards CC. Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood and Fiber Science. 2007 Jun 27;14(1):4-36. https://wfs.swst.org/index.php/wfs/article/view/501
[39] Hertz KD. Concrete strength for fire safety design. Magazine of Concrete Research. 2005 Oct;57(8):445-53. https://doi.org/10.1016/S0379-7112(02)00051-6
[40] Bastami M, Aslani F, ESMAEILNIA OM. High-temperature mechanical properties of concrete. International Journal of Civil Engineering. 2010.
[41] Diederichs U, Jumppanen UM, Penttala V. Material properties of high strength concrete at elevated temperatures. InIABSE 13th congress, Helsinki 1988 Jun (pp. 489-494).
[42] Chang CH, Jau WC. Study of fired concrete strengthened with confinement (Doctoral dissertation, MS thesis, National Chiao Tung University, Hsinchu, Taiwan).
[43] Chang YF, Chen YH, Sheu MS, Yao GC. Residual stress–strain relationship for concrete after exposure to high temperatures. Cement and Concrete Research. 2006 Oct 1;36(10):1999-2005. https://doi.org/10.1016/j.cemconres.2006.05.029
[44] Lie TT, Lin TD. Fire performance of reinforced concrete columns. InFire Safety: Science and Engineering 1985 Jan. ASTM International.

[45] Sancak E, Sari YD, Simsek O. Effects of elevated temperature on compressive strength and weight loss of the light-weight concrete with silica fume and superplasticizer. Cement and Concrete Composites. 2008 Sep 1;30(8):715-21.
[46] Abrams MS. Compressive strength of concrete at temperatures to 1600F. Special Publication. 1971 Jan 1;25:33-58.
[47] Savva A, Manita P, Sideris KK. Influence of elevated temperatures on the mechanical properties of blended cement concretes prepared with limestone and siliceous aggregates. Cement and Concrete Composites. 2005 Feb 1;27(2):239-48.
[48] Khaliq W, Bashir MF. High temperature mechanical and material properties of burnt masonry bricks. Materials and Structures. 2016 Dec 1;49(12):5195-208. https://doi.org/10.1617/s11527-016-0854-0
[49] Andreini M, Caciolai M, La Mendola S, Mazziotti L, Sassu M. Mechanical behavior of masonry materials at high temperatures. Fire and Materials. 2015 Jan;39(1):41-57. https://doi.org/10.1002/fam.2229
[50] Russo S, Sciarretta F. Masonry exposed to high temperatures: mechanical behaviour and properties—an overview. Fire safety journal. 2013 Jan 1;55:69-86. https://doi.org/10.1016/j.firesaf.2012.10.001
[51] Russo S, Sciarretta F. Experimental and theoretical investigation on masonry after high temperature exposure. Experimental Mechanics. 2012 Apr 1;52(4):341-59. https://doi.org/10.1007/s11340-011-9493-0
[52] Outinen J, Mäkeläinen P. Mechanical properties of structural steel at elevated temperatures and after cooling down. Fire and materials. 2004 Mar;28(2-4):237-51. https://doi.org/10.1002/fam.849
[53] Poh KW. Stress-strain-temperature relationship for structural steel. Journal of materials in civil engineering. 2001 Oct;13(5):371-9. https://doi.org/10.1061/(ASCE)0899-1561(2001)13:5(371)
[54] Li GQ, Jiang SC, Yin YZ, Chen K, Li MF. Experimental studies on the properties of constructional steel at elevated temperatures. Journal of Structural Engineering. 2003 Dec;129(12):1717-21. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:12(1717)
[55] Mäkeläinen P, Outinen J, Kesti J. Fire design model for structural steel S420M based upon transient-state tensile test results. Journal of constructional steel research. 1998 Oct 1;48(1):47-57. https://doi.org/10.1016/S0143-974X(98)00005-4
[56] Hoke JH, Mechanical properties of stainless steels at elevated temperatures, Handbook of stainless steels—Chapter 21, McGraw-Hill (1977)
[57] Sakumoto Y, Nakazato T, Matsuzaki A. High-temperature properties of stainless steel for building structures. Journal of structural engineering. 1996 Apr;122(4):399-406. https://doi-org.proxy1.cl.msu.edu/10.1061/(ASCE)0733-9445(1996)122:4(399)
[58] Li Y, Li W, Zhang X, Ma J, Shao J, Kou H, Deng Y. Modeling of temperature dependent yield strength for stainless steel considering nonlinear behavior and the effect of phase transition. Construction and Building Materials. 2018 Jan 20;159:147-54. https://doi.org/10.1016/j.conbuildmat.2017.10.106
[59] Ala-Outinen T. Fire resistance of austenitic stainless steels Polarit 725 (EN 1.4301) and Polarit 761 (EN 1.4571). Technical Research Centre of Finland; 1996.

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

[60] Tabaddor M. Thermal and mechanical finite element modeling of wood floor assemblies subjected to furnace exposure. Underwriters Laboratories. 2008.

[61] Kollmann F. The Mechanical Properties of Wood of Different Moisture Content Within-200 Degrees to+ 200 Degrees C Temperature Range. National Advisory Committee for Aeronautics; Washington, DC, United States. 1941. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930094432.pdf

[62] König J. Structural fire design according to Eurocode 5—design rules and their background. Fire and Materials: An International Journal. 2005;29(3):147-63. https://doi.org/10.1002/fam.873

[63] Glos P, Henrici D. Compression Modulus Of Elasticity Of Pine Structural Timber At Temperatures Up To 150-Degrees-C. Holz Als Roh-Und Werkstoff. 1991;49(7-8):298-. https://doi-org.proxy1.cl.msu.edu/10.1007/BF02663793

[64] M. Naser, Response of Steel and Composite Beams Subjected to Combined Shear and Fire Loading, PhD Dissertation, Michigan State University, East Lansing, US, 2016, https://d.lib.msu.edu/etd/4107

[65] Bažant ZP, Kaplan MF. Concrete at high temperatures: material properties and mathematical models. 1996. Prentice Hall. ISBN-10: 0582086264

[66] Ayala FR, Rene F. Mechanical properties and structural behaviour of masonry at elevated temperatures (Doctoral dissertation, University of Manchester). 2010.

[67] Fire design of concrete structures: in accordance with CEB/FIP Model Code 90. 1991. ISBN: 2883940134.

[68] BS 8110: Part 2. Structural use of concrete, Part 2, Code of practice for special circumstances. British Standards Institution, London, 1997.

[69] Phan LT, Carino NJ. Fire performance of high strength concrete: research needs. InAdvanced Technology in Structural Engineering 2000 (pp. 1-8).

[70] Anderberg Y, Thelandersson S. Stress and deformation characteristics of concrete at high temperatures. 2. Experimental investigation and material behaviour model. Bulletin of Division of Structural Mechanics and Concrete Construction, Bulletin 54. 1976.

[71] Castillo C, Durrani A. Effect of Transient High-Temperature on High-strength Concrete-Closure. ACI Materials Journal. 1990 Nov 1;87(6):653-.

[72] Nassif A. Postfire full stress–strain response of fire-damaged concrete. Fire and Materials: An International Journal. 2006 Sep;30(5):323-32. https://doi.org/10.1002/fam.911

[73] Nadjai A, O'garra M, Ali F. Finite element modelling of compartment masonry walls in fire. Computers & structures. 2003 Aug 1;81(18-19):1923-30. https://doi.org/10.1016/S0045-7949(03)00212-8

[74] Xiao Z, Ling TC, Poon CS, Kou SC, Wang Q, Huang R. Properties of partition wall blocks prepared with high percentages of recycled clay brick after exposure to elevated temperatures. Construction and Building Materials. 2013 Dec 1;49:56-61. https://doi.org/10.1016/j.conbuildmat.2013.08.004

[75] Cooke GM. An introduction to the mechanical properties of structural steel at elevated temperatures. Fire safety journal. 1988 Apr 7;13(1):45-54. https://doi-org.proxy1.cl.msu.edu/10.1016/0379-7112(88)90032-X

[76] Clark C, High-temperature alloys, Pitman, New York. 1953.

Please cite this paper as:
Naser M.Z. (2019). "Properties and Material Models for Common Construction Materials at Elevated Temperatures." Construction and Building Materials. Vol. 215, pp. 192-206. (https://doi.org/10.1016/j.conbuildmat.2019.04.182)

[77] American Institute of Steel Construction, Inc. (AISC), Specifications for structural steel buildings, Appendix 4, Chicago, IL, 2017.
[78] China Association for Engineering Construction Standardization. Technical Code for Fire Safety of Steel Structures in Buildings (CECS200-2006). China Plan Press, 2006.
[79] AS 4100-1998, Steel structures - Standards Australia. 2016.
[80] Mecozzi E, Zhao B. Development of stress–strain relationships of cold-formed lightweight steel at elevated temperatures. InProceedings of 4th European Conference on Steel and Composite Structures-Eurosteel 2005 2005 (pp. 41-49).
[81] Ranawaka T, Mahendran M. Experimental study of the mechanical properties of light gauge cold-formed steels at elevated temperatures. Fire Safety Journal. 2009 Feb 1;44(2):219-29. https://doi.org/10.1016/j.firesaf.2008.06.006
[82] Heva YB. Behaviour and design of cold-formed steel compression members at elevated temperatures (Doctoral dissertation, Queensland University of Technology). 2009.
[83] Makelainen P, Miller K. Mechanical Properties of Cold-Formed Galvanized Sheet Steel Z32 at Elevated Temperatures. Helsinki University of Technology, Finland. 1983.
[84] Chen J, Young B. Experimental investigation of cold-formed steel material at elevated temperatures. Thin-Walled Structures. 2007 Jan 1;45(1):96-110. https://doi.org/10.1016/j.tws.2006.11.003
[85] Klippstein KH. Strength of cold-formed steel studs exposed to fire. 1978. http://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=1768&context=isccss
[86] White RH, Nordheim EV. Charring rate of wood for ASTM E 119 exposure. Fire Technology. 1992;28(1):5-30. https://doi.org/10.1007/BF01858049
[87] Östman BL. Wood tensile strength at temperatures and moisture contents simulating fire conditions. Wood science and technology. 1985;19(2):103-16. https://doi.org/10.1007/BF00353071
[88] Jong F, Clancy P. Compression properties of wood as functions of moisture, stress and temperature. Fire and materials. 2004;28(2-4):209-25. https://doi.org/10.1002/fam.859
[89] Young, S.A., 1996. Elevated temperature mechanical properties of radiata pine in compression. Internal report for CESARE. Melbourne: Victoria University.
[90] Seif M, Choe L, Gross J, Luecke W, Main J, McColskey D, Sadek F, Seif M, Weigand J, Zhang C. Temperature-dependent material modeling for structural steels: formulation and application. US Department of Commerce, National Institute of Standards and Technology; 2016 Apr 15. http://dx.doi.org/10.6028/NIST.TN.1907
[91] M. Naser, G. Abu Lebdeh, R. Hawileh, Analysis of RC T-Beams Strengthened with CFRP Plates under Fire Loading using Artificial Neural Networks, Construction & Building Materials 37 (2012) 301–309. https://doi.org/10.1016/j.conbuildmat.2012.07.001
[92] Chan YN, Jin P, Anson M, Wang JS. Fire resistance of concrete: prediction using artificial neural networks. Magazine of Concrete Research. 1998 Dec;50(4):353-8. https://doi.org/10.1680/macr.1998.50.4.353
[93] Noorzaei J, Hakim SJ, Jaafar MS, Thanoon WA. Development of artificial neural networks for predicting concrete compressive strength. International Journal of Engineering and Technology. 2007;4(2):141-53.

[94] Mandal S, Sivaprasad PV, Venugopal S, Murthy KP. Artificial neural network modeling to evaluate and predict the deformation behavior of stainless steel type AISI 304L during hot torsion. Applied Soft Computing. 2009 Jan 1;9(1):237-44. https://doi.org/10.1016/j.asoc.2008.03.016

[95] Schalkoff R, Artificial neural networks, New York: McGraw-Hill, 1997.

[96] Romeiro Ferreira JD, Gernay T, Franssen JM, Discussion on a systematic approach to validation of software for structures in fire, 2018. http://hdl.handle.net/2268/223208

[97] Naser MZ. Properties and material models for modern construction materials at elevated temperatures. Computational Materials Science. 2019 Apr 1;160:16-29. https://doi.org/10.1016/j.commatsci.2018.12.055

[98] Naser MZ, Chehab AI. Materials and design concepts for space-resilient structures. Progress in Aerospace Sciences. 2018 Mar 23. https://doi.org/10.1016/j.paerosci.2018.03.004

[99] Naser MZ. Autonomous and resilient infrastructure with cognitive and self-deployable load-bearing structural components. Automation in Construction. 2019 Mar 1;99:59-67. https://doi.org/10.1016/j.autcon.2018.11.032

[100] Naser MZ, Kodur VK. Cognitive infrastructure-a modern concept for resilient performance under extreme events. Automation in Construction. 2018 Jun 30;90:253-64. https://doi.org/10.1016/j.autcon.2018.03.004

[101] Naser MZ, Degtyareva NV. Temperature-induced instability in cold-formed steel beams with slotted webs subject to shear. Thin-Walled Structures. 2019 Mar 1;136:333-52. https://doi.org/10.1016/j.tws.2018.12.030