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Properties and Material Models for Modern Construction Materials at Elevated Temperatures

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ABSTRACT

The construction industry has adopted a number of new building materials over the past few years. While these materials are specifically designed to achieve improved strength and durability characteristics at ambient conditions, the performance of modern construction materials (MCMs) under extreme conditions such as fire is still not understood. Under elevated temperatures, MCMs not only undergo a series of physio-chemical degradations, but these degradations are often of a much severe magnitude than that in traditional construction materials (TCMs). Despite ongoing efforts, there continues to be a lack of guidance/provisions on how to account for such temperature-induced degradations in MCMs. This adds another dimension of complexity to researchers and engineers seeking to carry out fire resistance evaluation and also presents a major challenge towards promoting standardization and performance-based solutions for fire engineering applications. In order to bridge this knowledge gap, this paper presents a methodology to develop temperature-dependent material models for MCMs such as high strength/performance concrete (HSC/HPC), high/very high strength steels (HSS/VHSS), and fiber-reinforced polymer (FRP) composites, using two techniques of artificial intelligence (AI) namely: artificial neural networks (ANNs) and evolutionary genetic algorithms (GAs). The outcome of this study showcases the merit of integrating AI into understanding the complex behavior of MCMs under fire conditions as well as in deriving temperature-dependent material models for these materials.

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Keywords: Material models; Concrete; Steel, FRP; Fire resistance; Artificial neural network (ANN); Genetic algorithm (GA).

1.0 INTRODUCTION

In order to keep up with the advent rise of complex and leaner architectures, traditional construction materials (TCMs) are being substituted by modern building materials such as high strength/performance concretes and steels as well as composites. Modern construction materials (MCMs) have much improved characteristics in terms of strength and environmental resilience (resistance to chemicals, weathering etc.) as compared to their parent TCMs. Attaining such characteristics is a result of incorporating a number of additives/fillers, applying novel production/fabrication/milling process, and altering micro-structure of MCMs [1, 2]. Thus, these construction materials offer contemporary solutions, i.e. higher strength-to-weight ratio, thinner/lighter sections, better quality control etc. [1-3].

Since modern construction materials are specifically designed to outperform traditional building materials at ambient (working) conditions, little interest is directed towards examining their performance under harsh loading conditions such as fire (thermal effects). This can be attributed to: 1) building codes often classify fire loading under secondary/accidental events (as breakout of fire is rare) and hence may not be a primary design consideration in some structures [4], 2) shortage/limited accessibility to testing equipment, and complexities associated with fire testing (i.e. sensor survivability/reliability at elevated temperatures >700°C), and 3) the common misconception that if a material has superior properties (e.g. high strength) at ambient conditions, then this material is also expected to perform well under fire conditions [5]. In fact, few researchers have highlighted how traditional building materials can outperform MCMs, from fire point of view; as traditional materials are less prone to fire-induced phenomena (i.e. fast degradation in strength/modulus properties, spalling in high strength concrete/high performance concrete etc.) [5].

Since the ability of a material to withstand the adverse effects of fire and development of fire-induced phenomena/forces depends on how properties of the material are influenced by rise in temperature, then a clear understanding of properties of construction materials at elevated temperatures is of great importance. In general, the variation of temperature-dependent properties can be evaluated through small scale material tests. These tests are carried out on small specimens (i.e. steel coupons) subjected to high temperatures. The outcome of such tests is then prepared into charts or simple expressions that can be used to trace properties of materials under elevated temperatures [6-8]. These tools prove valuable as they provide researchers/engineers; especially those with limited accessibility to testing facilities, with required inputs (i.e. temperature-dependent properties) to perform fire resistance analysis/design without the need for conducting small scale material tests [9].

There are two temperature-dependent material models commonly adopted in fire resistance evaluation i.e. ASCE design guide [6] and Eurocodes [7, 8]. While these models have been well-established for traditional building materials such as normal strength concrete (NSC) and structural steel (SS) [9, 10], it is interesting to note that both provisions do not present material models for modern construction materials such as high performance concrete (HPC)[*], high and very high strength (HS/VHS) steel[†], as well as fiber-reinforced polymer (FRP) composites. This often leaves

[*]This study considers HPCs as concretes that incorporate high-end additives such as steel, polypropylene fibers, fly ash etc. [11]. This also includes high strength concretes (HSCs), fiber-reinforced concretes (FRCs) and self-consolidating concretes (SCCs).

[†]High and very high strength steels are those with a yield strength in the range of 400-690 MPa and exceeding 690 MPa, respectively.

designers with limited room for creativity and exponentially complicates fire resistance evaluation; particularly for unique/modern structures such as those with untraditional or retrofitted (FRP-strengthened) structural members etc.

Since building codes provide provisions (i.e. material models) to represent temperature-induced degradation in traditional building materials (such as NSC), a designer may choose to apply these provisions to represent temperature-induced degradation in modern construction materials (e.g. HPC). However, this may not deem appropriate as there are: 1) fundamental differences between traditional and modern construction materials with regard to micro-structure, amount/type of supplementary minerals/additives used in production process, as well as 2) differences arising from processing or fabrication/milling procedures [1, 2]. Thus, designers often commission small scale material tests to be carried out at elevated temperatures. A close examination of outcome of such tests reveals a great magnitude of discrepancies due to differences in testing methods and equipment, specimen preparation/size and processing techniques used in carrying out high temperature tests [5, 12]. Such discrepancies may be in the range of 15-25% [12, 13].

Since it may not be possible (or practical) to regularly perform high temperature material testing, hence the predicament for the need for a generalized presentation of temperature-dependent models for MCMs. In order to overcome some of the above discussed challenges, and in support of current efforts to promote a more standardized procedure for fire resistance analysis and design, this paper hypothesizes that integrating Artificial Intelligence (AI) and machine learning tools could potentially aid in developing such material models and could also facilitate standardization and harmonization efforts in this field. More specifically, this study incorporates

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a combination of artificial neural networks (ANNs) and genetic algorithms (GAs) to comprehend response of MCMs at elevated temperatures and to derive appropriate representations of materials behavior. Thus, this paper presents the development of temperature-dependent thermal and mechanical material models for modern/advanced construction materials such as high strength/performance concrete (HSC/HPC), high/very high strength steel (HS/VHS), and fiber-reinforced polymer (FRP) composites. In order to ensure high precision, as well as wide range of applicability and acceptance, the AI-derived material models integrate test data collected from notable works published in the open literature[‡].

2.0 OVERVIEW OF TEMPERATURE-DEPENDENT MATERIAL PROPERTIES FOR MODERN CONSTRUCTION MATERIALS

Fire resistance of structures is generally governed by how properties of building materials respond to elevated temperatures. From this sense, four types of properties are of interest; thermal, mechanical, deformational and unique (or special) properties. While the thermal properties (i.e. thermal conductivity (k), specific heat (c), and density (ρ)) determine the progression of temperature within a structural member, the mechanical properties (strength (f), modulus (E), stress-strain relations etc.) dictate the magnitude of stress and overall structural response (load bearing abilities) of construction materials. The deformational properties (such as thermal expansion and creep) determine the extent of deformations under fire conditions. On the other hand, the special properties are unique to certain materials such as: spalling in concrete etc.[§]

[‡] All data points for the selected construction materials were collected from tests carried out at elevated temperatures (without any cooling phase).

[§] For brevity, both deformational (i.e. creep, buckling) and material specific properties (e.g. porosity, combustibility, debonding etc.) of MCMs will not be addressed herein due to the limited amount of works carried out on these properties at elevated temperatures [5, 14] and as such will be dealt with separately in future studies.

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The first two types properties are of utmost importance to fire resistance evaluation, as this procedure comprises of two stages. In the first stage, temperature rise and distribution in a structural member is obtained given due consideration to thermal-based material properties. The temperatures are then input to the second stage of fire resistance evaluation whereas temperature rise in mechanical properties is accounted for to determine the degrading behavior of the material. Thus, in order to perform a proper fire resistance evaluation, thermal and mechanical properties, preferably in the temperature range of 25-800°C, are needed. Both thermal and mechanical properties vary with rise in temperature and are highly dependent on material phase changes that take place under elevated temperatures.

The reader is encouraged to remember that, from fire properties point of view, steels and concrete derivatives are considered to be homogeneous materials in which the temperature-induced degradation in their properties is assumed to be uniform in all directions. While this is unlike FRP composites, an orthotropic material with properties varying in longitudinal and transverse directions, still the properties in the longitudinal direction of FRPs are of main interest to fire engineers and hence properties in this direction are examined herein [15]. This section provides a concise overview on essential properties needed to carry out fire resistance evaluation on MCMs. These properties include: thermal conductivity, specific heat, density, strength and modulus. The variation in other related properties i.e. creep, spalling, Poisson's ratio can be found in the following references which are crucial to review for complete understanding of behavior of MCMs under elevated temperatures [5, 16].

2.1 Thermal properties

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The thermal material properties influence temperature rise and distribution in a structural member and the variation of these properties at elevated temperatures depends on the composition of MCMs as well as characteristics of fire i.e. intensity (heating rate/duration etc.) [17]. For a start, the thermal conductivity (*k*) is the property that indicates the rate at which a material transmits heat across its medium. As such, the thermal conductivity is a structure-sensitive property and highly depends upon the crystalline structure of atoms and crystals [5].

The thermal conductivity of HPC, including high strength concrete (HSC), self-consolidating concrete (SCC) and fiber-reinforced concrete (FRC), at ambient conditions ranges between 1.6-3.6 W/m.K (with HSC and SCC being on the higher side of this range) [17]. This conductivity is relatively higher than that in normal strength concrete but is still considered low as compared to metals (see Fig. 1a). The thermal conductivity seems to be influenced by permeability, moisture content and type of aggregate; where concretes of higher crystallinity (i.e. siliceous aggregates) are of slightly higher conductivity than concretes made of carbonate aggregates. Higher crystallinity also causes faster decrease in thermal conductivity with rise temperature. As a rule of thumb, the thermal conductivity of HPCs decreases gradually with temperature rise (see Fig. 1a). For most HPCs, the thermal conductivity stabilizes at 50% its initial value at temperatures exceeding 800°C. It is worth noting that Khaliq and Kodur [18] noted that there is no significant effect of steel or polypropylene fibers on thermal conductivity of HPCs in a 20–800°C temperature range.

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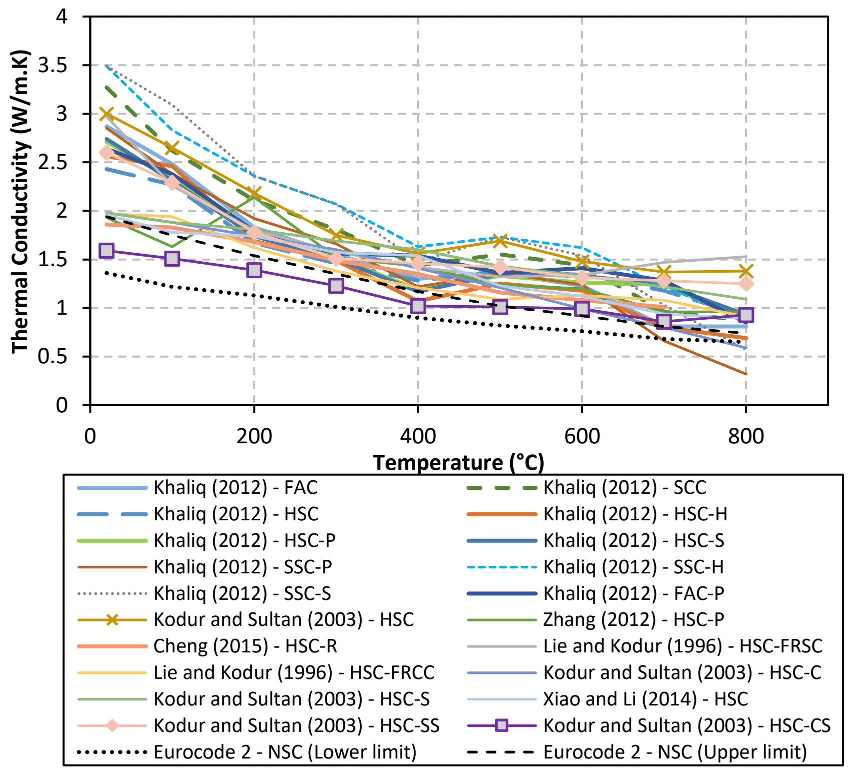
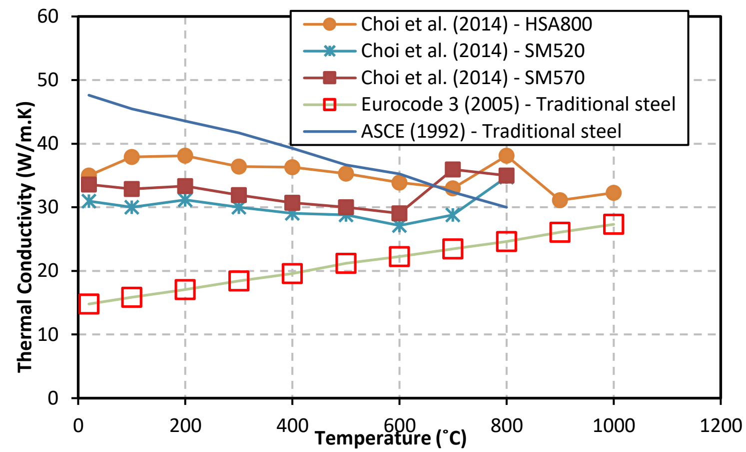
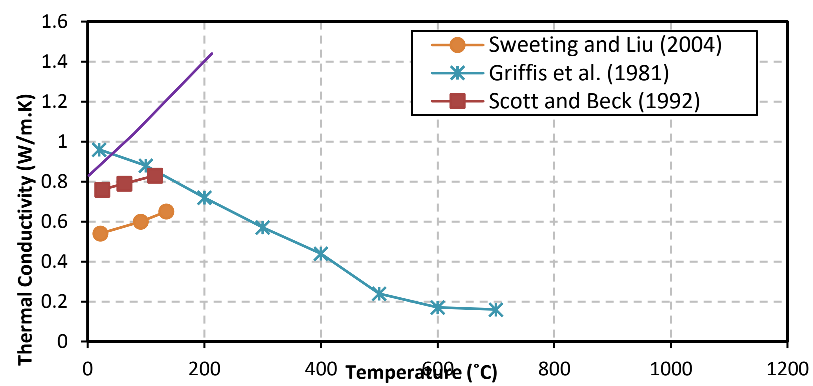


(a) High performance concrete (including HSC, SCC and FRC)



(b) High/very high strength steels



(c) Fiber-reinforced polymers

Fig. 1 Temperature-dependent variation in thermal conductivity of modern construction materials [6, 7, 20-30]

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Overall, the thermal conductivity of steels is much higher than that of concretes or FRP composites (see Fig. 1b). This conductivity varies between 35–55 W/m.K at ambient conditions and decreases with rise in temperature due to the associated decrease in mean free path of molecules. The thermal conductivity of FRPs is comparable to that in normal strength concrete and often ranges between 0.4-1.4 W/m.K. Because of the orthotropic nature of FRP materials, the properties of matrix resin govern the thermal conductivity of the composite in the transverse direction. On the other hand, the high volume and presence of the fibres in the longitudinal direction, governs the thermal conductivity in the longitudinal direction. It is worth noting that very little work has been carried out on thermal properties of HS/VHS steels as well as FRP composites at elevated temperatures in the range of 25-800°C [5, 19]. Figures 1b and 1c compiles the outcome of some of these works.

Specific heat is the second thermal property that is important in fire resistance evaluation. This property describes the amount of heat required to raise a unit mass of material a unit temperature. The specific heat of HPC at room temperature can vary between 700-1000 J/kg.K (see Fig. 2a). Similar to thermal conductivity, the specific heat is also influenced by moisture content and mix proportions (i.e. fillers/aggregates) as these two components govern development of physicochemical changes that take place at temperatures exceeding 600°C. In HSC, the specific heat of carbonate aggregate concrete is generally higher than that of siliceous aggregate concrete due to the substantial amount of heat needed to dissociation of the dolomite in the carbonate aggregates (approximated at 10 times the heat needed to produce the same temperature rise in concrete made of siliceous aggregates) [20]. This may not be apparent in HPC and SCC due to the controlled amount and size of aggregates in the concrete mix. It is worth noting that the addition

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of steel or polypropylene fibers has a marginal influence on the specific heat of concrete up to 600°C, beyond which the specific heat tends to slightly increase in concretes incorporating steel fibers (due to changes occurring to steel) or decrease in concretes made of polypropylene fibers due to burning of these fibers.

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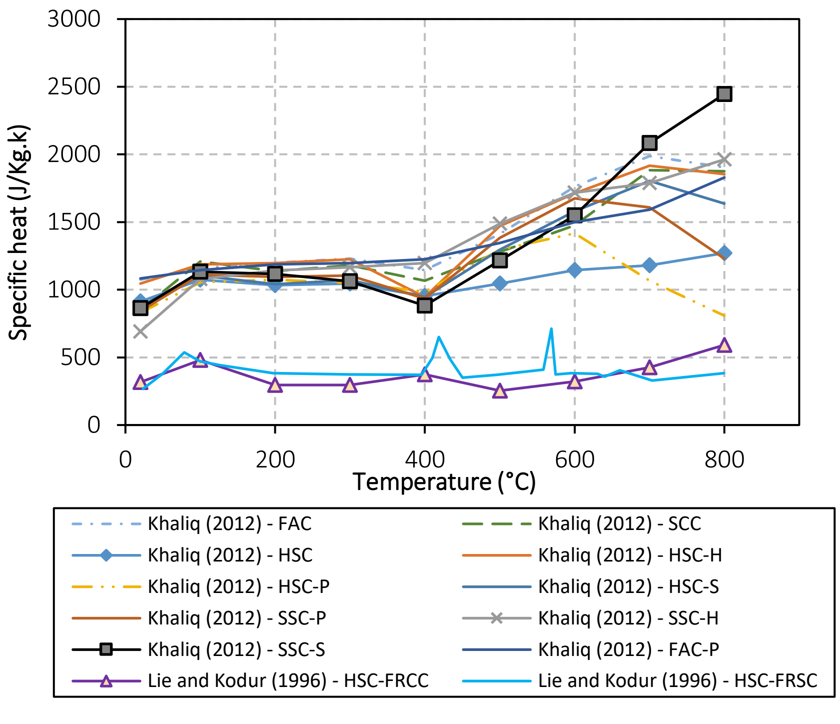
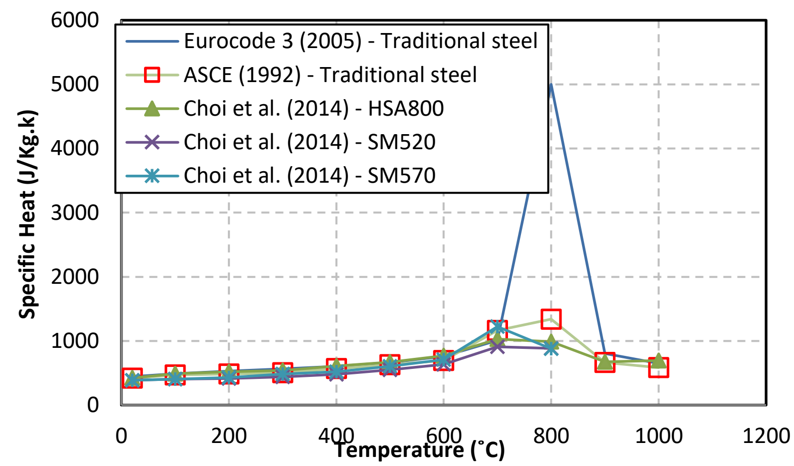
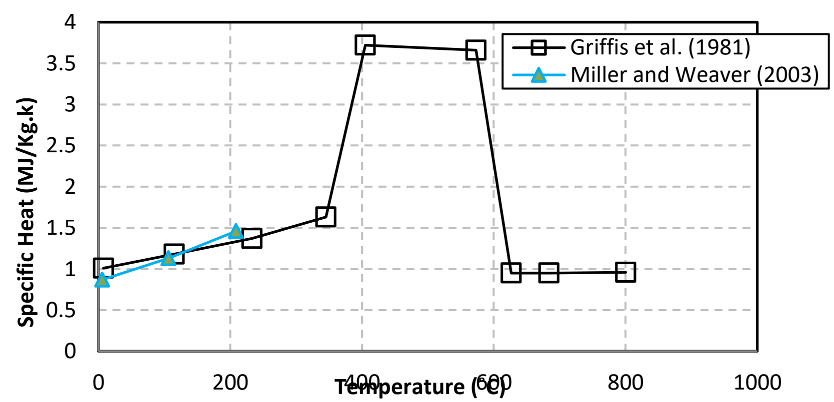


(a) High performance concrete (including HSC, SCC and FRC)



(b) High/very high strength steels



(c) Fiber-reinforced polymers

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Fig. 2 Temperature-dependent variation in specific heat in modern construction materials [6, 7, 20, 23, 26, 28, 29]

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The specific heat of steels can vary in the narrow range of 425-600 J/kg.K [5]. For most steels, the specific heat increases steadily with rise in temperature until reaching 600°C. At this temperature, the specific heat rapidly increases as carbon steel undergoes a phase transformation requiring re-arrangement of crystalline structure. In order to stabilize crystalline structure beyond this temperature, carbon steel undergoes a transformation from a face-centered-cubic (fcc) to a body-centered-cubic (bcc) structure (see Fig. 2b). The specific heat of FRPs on the other hand significantly varies with the increase of temperature. Of the limited works available on this property, Kalagiannakis and Van Hemdrijck [31] reported specific heat of 800 J/kg-K for both glass and carbon/epoxy FRPs at room temperature. This variation is a reflection of the complex chemical reactions within the composites (i.e. decomposition of resin/epoxy etc.) [32].

The density is defined as the mass of a unit volume. The density of HPC at ambient conditions is in the range of 2400-2800 kg/m^3. The presence of moisture in concrete derivatives implies that the density of these materials can reduce especially upon exceeding 100°C. This reduction is typically minor (of about 3% of initial density) in siliceous-based HSC, but can exceed 30% in carbonate HSC between 600 and 750°C due to the dissociation of dolomite in aggregates. Once carbonate concrete is supplemented with steel fibers, loss in density can be limited to 20% of initial density at temperatures exceeding 800°C (due to the higher density of fibers). On the other hand, the density of metals is often presumed to be independent of temperature rise and hence the density of HS/VHS structural steel is assumed to remain constant at 7700-7850 kg/m^3 within temperature range (25-1000°C). Similar to concrete, the density of FRPs remains constant up to approximately 550°C then undergoes a slight decrease of 20% after which it remains constant until 1000°C [28].

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2.2 Mechanical properties

The mechanical properties of interest to fire resistance evaluation are: strength and modulus (stiffness). The strength of a given construction material is often measured as the ultimate (crushing) strength or yield strength (in case of metals). The modulus property measures the ability of a material to resist deformation. In this study, the considered mechanical properties include compressive strength (f_c) of HPC derivatives, yield strength (f_y) of HS/VHS steels, tensile strength (f_t) of FRPs and modulus (E) property of these selected construction materials.

The mechanical properties are often measured through material tests carried out on small specimens (cylinders/coupons). The high temperature tests can be conducted under three different set-ups: steady-state, transient and residual. In the first two types of tests, the properties of the test specimen are measured during exposure to elevated temperatures, while in the third material test, the properties are measured after a fire-exposed specimen is cooled down to ambient conditions (i.e. through air or water cooling)[**].

Under steady-state testing, a test specimen is heated to a target temperature (i.e. 400°C) while being allowed to expand freely. Once this temperature is reached, tensile (or compressive) forces are applied to the specimen to measure strength and stiffness (modulus) at that particular temperature. In the case of transient tests, a specimen is first loaded at a predefined load level (say 30% of ultimate strength at ambient conditions) and is then exposed to uniformly increasing temperatures. In this procedure, temperature rise, as well as stress/strain development are recorded

[**]The properties obtained using this testing procedure is outside the scope of this study and will be dealt with in a future work. The reader is encouraged to review the following references for detailed discussion on post-fire (residual) properties of construction materials [33, 34].

until failure of specimen. In general, measurements obtained from transient tests are slightly lower than that obtained from steady-state tests due to the longer loading history the specimen undergo, especially towards temperatures exceeding 400-500°C at which effects of thermal creep are apparent. All of these testing methods are highly sensitive to test set-up, specimen features (shape, size), as well as loading (stress/strain and heating) rates. Due to the lack of well-established testing procedures under elevated temperatures and limitation in testing equipment, unfortunately, a large amount of test data was published on specimens with varying sizes, tested under different set-ups and/or without reporting information on key aspects such as strain/heating rates etc. [5, 12].

Generally, the mechanical properties of a material decrease gradually with rise in temperature (see Figs. 3 and 4). The degradation in strength properties in HPC derivatives is mainly influenced by the mix proportions, water-cement ratio and fillers/admixtures etc. [5, 11]. The compressive strength of HPC at ambient conditions can be in the range of 70-200 MPa and could potentially exceed this range by lowering the water-to-cement ratio and using additives such as silica fume, superplasticizers, reactive/high strength cement etc. Kodur [17] noted how other factors such as initial curing and moisture content at the time of testing may influence the rate and pace at which compressive strength of concrete degrades at elevated temperatures. High performance concretes in general, and HSC in particular, may experience higher rates of strength loss; especially in the 50-250°C range[††]. Due to their dense mixture and significantly low permeability, these concrete are prone to fire-induced spalling arising from trapped pore pressure [35, 36]. A note to remember is that unlike HSC and FRC, HPC do not include large-sized coarse

[††] Few researchers reported that FRCs may be able to maintain up 90% of its initial strength at 400°C [5].

aggregates in their mix and this leads to a distinct behavior in their properties at elevated temperatures which can be seen in Fig. 3a and 3b.

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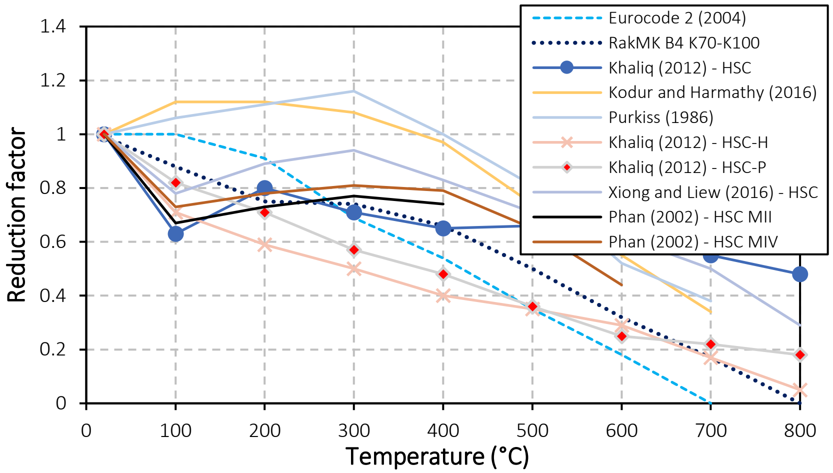
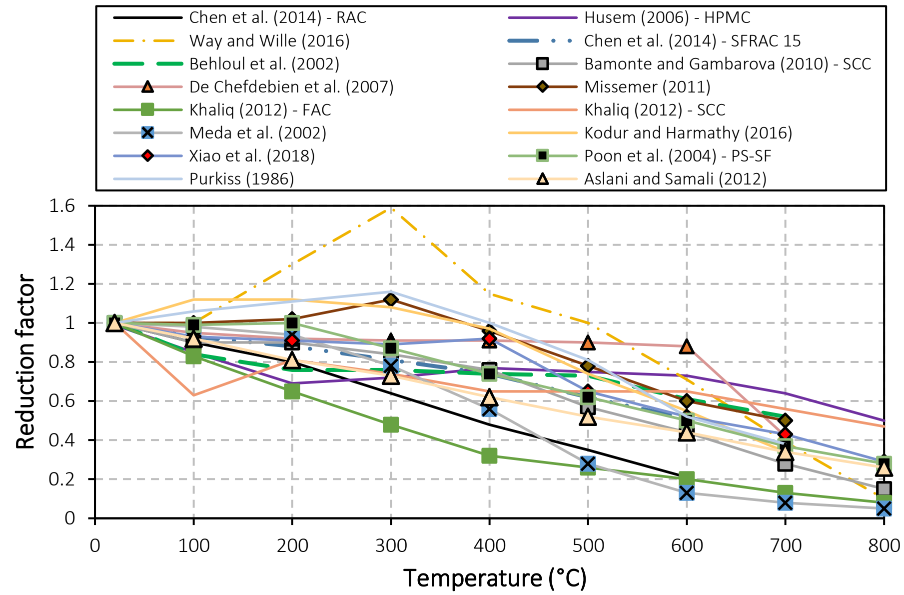
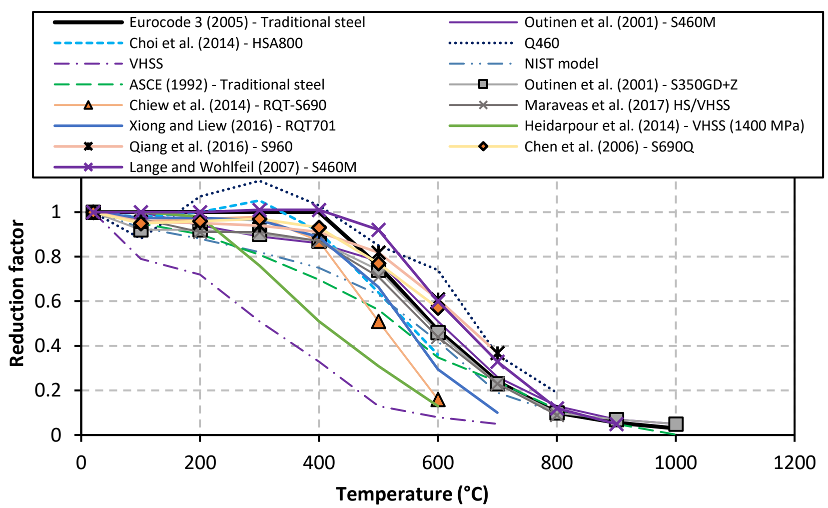
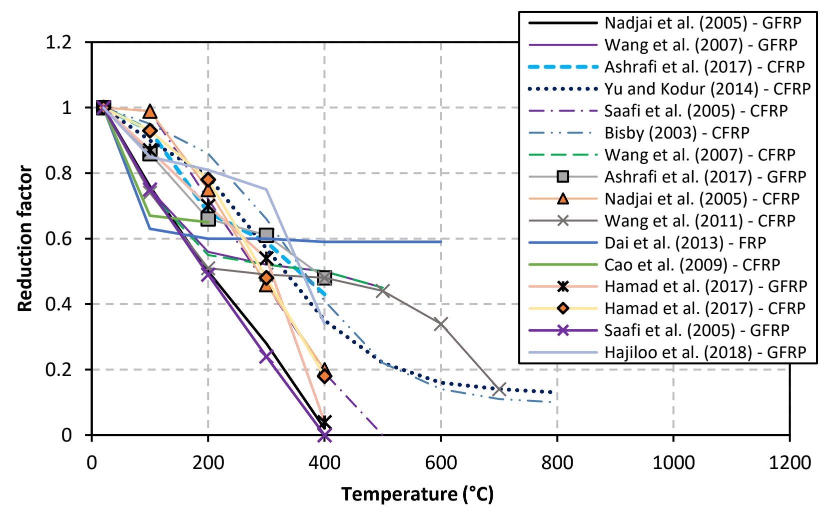




(a) High strength concrete (HSC)

(b) High performance concrete (including SCC and FRC)





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(c) High/very high strength steels

(d) Fiber-reinforced polymers

Fig. 3 Variation in strength property in modern construction materials at elevated temperatures [5, 6- 8, 19, 20, 26, 37-66]

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The yield strength of structural steels greatly influences fire resistance analysis/design of steel structures. This property is often measured in tensile-based tests carried out on steel coupons as such set-ups eliminate complications that may arise due to instability (i.e. buckling) if steel specimens were to be tested under compression loading [5, 12]. The yield strength is often characterized by a distinct point[‡‡] at which a pronounced increase in strain is observed without a corresponding increase in applied stress. The yield strength of modern steels can vary between 400-960 MPa (and may exceed 1300 MPa) [55]. As such, HS/VHS steels have a yield strength that is 2-6 times higher than that in traditional structural steel. This improved strength is often achieved by either adding alloying elements or through incorporating heat treatments/work hardening. It should be stressed that modern steels are susceptible to damage under fire conditions as their crystalline structure is not stable at high temperatures. In fact, the yield strength of HS/VHS steels may degrade at a higher pace than that in traditional steel (see Fig. 3c[§§]). This degradation can be minimized when HS/VHS steels are supplemented with appropriate amounts of chromium and niobium [67]. The degradation in yield strength in steel is ascribed to the increased probability of activating grain slip planes triggered through rise in temperature. The rate of temperature-induced degradation in HS/VHS steels is a function of steel chemical composition (mineral and alloys), as well as heating rate etc. [67].

[‡‡] Under fire conditions, this distinct point is often established at 0.2%, 0.5%, and 2% as stress-strain response of steel smoothens. For example, Eurocode 3 recommends yield strength to be based on the strain level 2.0%, while BS 5950 provides guidance on three strain levels 0.5%, 1.5% and 2.0%.%. Other codal provisions such as that adopted by AISC, ASCE and AS 4100, do not provide guidance on a strain level to specify yield strength at elevated temperatures.
[§§] The yield strength of some VHS steels such as HSA800 might slightly increase up to 300°C after which it starts to degrade as reported by Choi et al [26].

In the case of composites, two types of FRPs are often used; namely, carbon (CFRP) or glass (GFRP)[***]. When heated to moderate temperatures, the resin component in the composite changes from hard and brittle to viscous and rubbery, in a process referred to as glass transitioning. The critical temperature at which this transition occurs, T_g occurs is in the range of 50–120°C. A number of researchers consider properties of FRPs to start degrading in this temperature range, primarily due to combustibility, decomposing and weakening of cross linked bonds in epoxies/resins [32]. However, it is worth noting that the fibres (i.e. carbon or glass) are still able to retain a considerable fraction of their ambient temperature tensile properties even after the glass transition and decomposition processes of the resin matrix is complete. For example, Fig. 3d shows that FRPs may only lose up to 50% of their strength between 200 and 400°C (with GFRPs being more vulnerable to elevated temperatures). This degradation in FRPs is mainly governed by the type of FRP i.e. thermoset or thermoplastic, constituent materials, fiber/resin content and glass temperature etc.

The second mechanical property discussed herein is the modulus. The modulus of various concretes at ambient conditions depends on the amount and density of aggregates, water-cement ratio and method of curing/conditioning. The modulus property of HPC varies over a wide range, 35-60 GPa. Similar to the strength property, the modulus also degrades with rise in temperature. This degradation is mainly attributed to the disintegration of hydrated cement products and breakage of bonds in the microstructure of cement paste, as well as generation of thermal stresses and progressive decrease in moisture content (leading to relaxation of atomic bonds). Figure 4a

[***] Other types of FRPs are also used in modern constructions such as those made from aramid and basalt. Very little research has been carried on these composites at elevated temperatures and hence they were not further discussed herein [68].

shows that the modulus is slightly affected by temperature rise up to 200°C, after which it rapidly decreases reaching 20% around 600-700°C.

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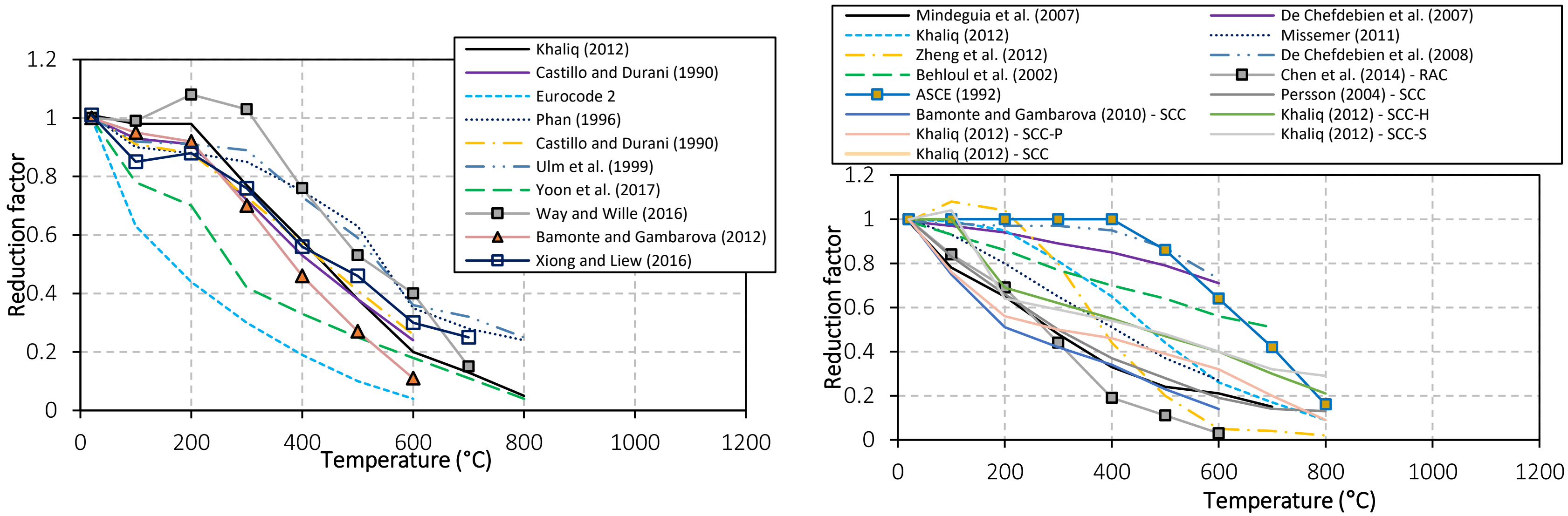
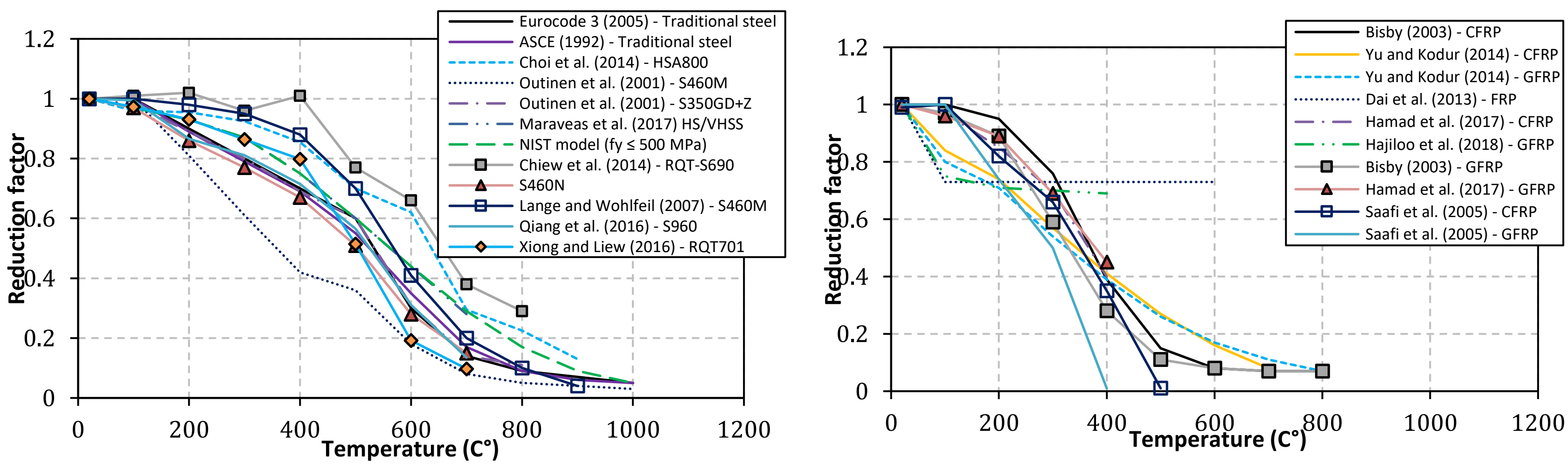


(a) High strength concrete (HSC) (b) High performance concrete (including SCC and FRC)



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(c) High/very high strength steels

(d) Fiber-reinforced polymers

Fig. 4 Variation in modulus property in modern construction materials at elevated temperatures [6-8, 19, 20, 26, 39, 41-43, 46, 48, 51-54, 56, 57, 61-63, 65, 66, 70-76]

The modulus of HS/VHS steel is generally assumed to be between 200-210 GPa at room temperature, regardless of steel type [5, 12]. The modulus of steel starts to degrade at relatively lower temperatures and often at faster pace than that in yield strength (see Figs. 3c and 4c). This is due to the fact that only a slight increase in temperature is needed to weaken interatomic bonds in the crystalline lattice and to initiate dislocations [69]. A collection of material models presenting temperature-based degradation in modulus for various types of HS/VHS steels is plotted in Fig. 4c. In the case of FRPs, the modulus property also degrades with rise in temperature. This degradation follows that of tensile strength and is attributed to the loss of bond between the fibers and the matrix due to the softening/relaxation and creep of the epoxy resin [32]. It should be stressed that data points presented in Fig. 4d are intended to present the general trend in degradation of mechanical properties of FRPs as this data was compiled from tests on FRPs with varying types of epoxy resin and fibers, as well as fiber volume fraction etc. [61-66].

3.0 A CRITIQUE ON OBSERVATIONS FROM HIGH TEMPERATURE MATERIAL TESTS

The first observation one can deduce from Figs. 1-4 is that there are large discrepancies in reported data on thermal and mechanical properties of modern construction materials (MCMs). This variation is apparent not only in materials with complex composition and production process (i.e. HPCs and FRPs), but also in those of consistent composition and standard production process (i.e. HS/VHS steels). This variation stems from two aspects. The first is the availability of a wide range of fillers/admixtures at the time of fabrication/testing of MCMs. While such additives i.e. alloys, fibers etc., can be used to improve quality and durability characteristics of MCMs, specifics to such additives in terms of quantity/chemical composition as well as their effect(s) on material

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behavior under fire conditions remains largely unknown nor rarely investigated [5]. The second aspect that leads to significant variations in plotted data shown in Figs. 1-4 arises from the lack of codal-based guidance/provisions on how to properly carry out high temperature material property tests on various MCMs. This lack of guidance has led researchers to conduct tests on specimen of varying features and under varying test set-ups and loading conditions [12].

A close examination of models adopted in ASCE and Eurocodes for traditional construction materials, which are also plotted for reference in Figs. 1-4, show that 1) there is also large deviation between these two models and that of MCMs, and more importantly 2) these two models do not adequately present temperature-dependent behavior of MCMs under elevated temperatures. This not only infers that applying codal models may not yield appropriate fire resistance predictions, but also leaves designers/researchers without authoritative resources/guidance on to how to account for temperature-induced effects in MCMs.

These interesting, and to some extend concerning, observations imply that carrying out fire resistance evaluation could potentially remain an unstandardized and tedious task. This further complicates fire evaluation procedure and requires tremendous efforts to validate and confer proposed designs between engineers/practitioners and governmental officials. As a result, an evaluation of fire performance of a structure (say made of HPC), carried out using any of the above plotted material models would not be equivalent nor similar to that carried out using any other model (including ASCE's or Eurocode 2). In fact, previous studies have noted that the variation in fire resistance analysis can vary up to 15-25% [12, 13].

As a result, such fire resistance evaluation could potentially underestimate or overestimate performance of structures. While a designer may use advantage of a material model that yields faster degradation in strength and modulus property to arrive at a conservative (or safer) design, such design may still be uneconomical (or perhaps impractical i.e. includes large-sized structural members etc.). On the other hand, a designer may also exploit (or unknowingly take advantage of) this situation by choosing a material model that yields slow degradation in properties to arrive at leaner (and cheaper) structural members. In this scenario, the outcome of such decision may lead to premature failure under fire conditions, especially if the behavior of the material used in construction does not match that in the selected material model for fire design. It can be seen that this is a pressing issue and a major limitation towards realizing uniform/standardized methodology for fire resistance design and analysis.

This paper hypothesizes that a solution to mitigate the above issues can be achieved through adopting generalized materials models to represent temperature-induced degradation in properties of MCMs. Arriving at such models can be achieved through conducting state-of-the-art high temperature material tests on various MCMs available in different parts of the world. These tests are to be properly planned to represent similar fire conditions to that may occur in modern constructions and the outcome of these tests is to be replicated to ensure their consistency and wide applicability. This solution can be carried out over the coming decade.

Given the fact that MCMs have been used in construction industry for quite some time and realizing that planning, timing, practicality and costs associated with above solution is nothing but short of hopeful, a more contemporary solution would be to compile published works (i.e. test data, code-adopted models etc.), and analyze this data to arrive at integrated material models. This analysis can be carried out through statistical procedures [57] or through application of expert systems (based on artificial intelligence (AI)). AI systems have been proven to outperform traditional statistical approaches, especially in understanding complex phenomena similar to that associated with material behavior under fire conditions [13, 78].

The integration of AI into similar applications to that of interest to this study was first examined by Chan et al. [79] who developed an artificial neural network (ANN) to predict temperature-induced degradation in compressive strength of normal strength concrete [79]. In a more recent study, Naser [13] managed to incorporate genetic algorithms (GA) to derive temperature-dependent material models for traditional construction materials such as normal strength concrete, structural steel and wood. The AI-derived models were thoroughly verified against actual structural members tested in full-scale fire tests and showed high prediction capability when compared to commonly used material models. The outcome of these studies, as well as others carried out at ambient and harsh conditions [80], infers that using AI can be effective in developing temperature-dependent material models. Thus, this study applies principles of AI to in order to arrive at generalized material models that could be suitable for use in fire resistance evaluation.

4.0 DEVELOPMENT OF AN ARTIFICAL INTELLIGENT MODEL

Unlike traditional statistical methods, artificial intelligence (AI) does not require lengthy processing or assumptions to start an analysis. This soft computing method simulates the reasoning process in the human brain by incorporating a number of computing layers. These layers are arranged in a specific layout in order to develop an Artificial Neural Network (ANN). Each layer contains a number of processing units (neurons). The number of neurons in each layer largely depends on the complexity of the relationship between inputs and expected outcome(s). Figure 5 shows that on one side, the input layer, which contains the independent variables, is connected to hidden layers; with the ability to establish linear and/or non-linear relations. The hidden layers are also connected to the output layer. In this study, and similar to a companion work [13], a multilayer perception model, inspired by the structure of the human brain, with "feed-forward back-propagation and supervised learning" is used to develop an ANN. The rationale behind using ANN as the main technique to arrive at an understanding of behavior of MCMs under elevated temperatures stems from the fact that ANNs have the ability to learn patterns hidden in input data points through systematic and repeated analysis and hence are useful in analysis complex phenomena.

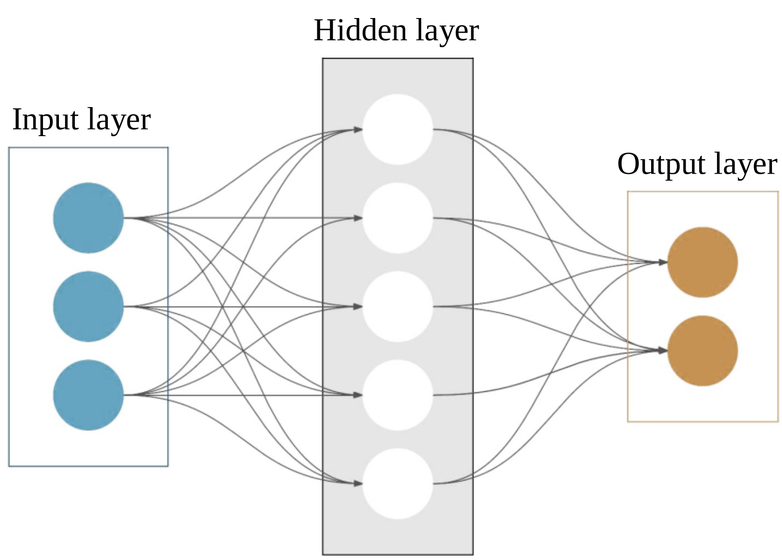

Fig. 5 Layout of an ANN

Once the layout of the ANN is established, training of this ANN begins as to solve a given phenomenon/problem and satisfy accompanying objective(s). The main objective of the ANN developed herein is to comprehend the logic behind various high temperature material models and

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arrive at a general representation that best exemplify these models. Such an ANN can be developed using the deep learning tool in Matlab [81] or could be built using other commercially available software such as NeuroShell Predictor [82]. The training of an ANN starts by inputting data points (i.e. temperature-dependent thermal and mechanical material models or values i.e. reduction in modulus of high strength concrete at 100, 200, 300… and 800°C = 1.0, 0.92, 0.91… 0.25, as measured by Ulm et al. [72], and so on for other material models or reported properties by other researchers) into the input layer. The collected data was first randomly arranged such that no specific model was used as a benchmark [83]. These randomly arranged input data points are then multiplied by random weightage factors. The result of this multiplication is used to activate a transfer function (i.e. addition, multiplication etc.). Transformed outputs from connected nodes are then automatically summed to yield predictions (i.e. AI-predicted values for material properties at target temperatures, i.e. 25, 100, 200.. 800°C).

The ANN-based (predicted) values are then input into an open source genetic algorithm (GA) based model [84]. In the case of GA, this computing technique strives on the Darwinian concept of survival of the fittest and reproduction to arrive at simple and predictive expressions. GA starts with a random set of population comprising of candidate solutions generated through arithmetic operators and mathematical functions i.e. addition (+), trigonometric functions (i.e. tangent) etc. [47]. These operations may include mutation (randomly changing a fit candidate) and/or crossover (combining two, or more, candidate solutions to get an improved solution). This GA model is able of analyzing predictions from ANN (i.e. material behavior at target temperatures) to arrive at simple mathematical expressions to represent these predictions. A candid solution (i.e. expression) is required to satisfy a fitness metric; usually governed by coefficient of determination

(R^2) and maximum error (ME) predicted by a possible expression and values obtained from ANN, with parsimony corrections to favor easy-to-apply (compact) expressions. The development of both ANN and GA-based model were carried out using Matlab simulation environment and deep learning tool.

5.0 DERIVING AI-BASED TEMPERATURE-DEPENDENT MATERIAL MODELS

In this study, collected data points in terms of values for properties of modern construction materials (MCMs) in the increasing temperature range of 25-800°C (and did not incorporate cooling phase), as plotted in Figs. 1-4, were input into the ANN. The thermal material properties investigated herein are thermal conductivity, and specific heat[†††]. On the other hand, the mechanical properties of interest are strength and modulus properties of HPCs, HS/VHSSs, and FRPs. Diligence was taken to develop separate models for HSC and HPC (FRC/SCC), as well as CFRP and GFRP due to differences in material characteristics as discussed in Sec. 2 and shown in corresponding figures. The successfully trained ANN was used to predict generalized thermal and mechanical temperature-dependent material models. Figure 6 shows that predictions from ANN lie within the range of the collected data. The developed ANN also managed to achieve a close match with the data that is randomly selected for "testing and validation" as can be seen from performance metrics (coefficient of determination (R^2) and mean absolute error (MAE)) listed Table 1. Given the high performance of the ANN, it can then be inferred that the developed ANN was able to accurately capture the behavior of selected MCMs at elevated temperatures. Thus, it

[†††]As discussed in Sec. 2.1, the fact that degradation in density is minor (in case of HPCs) and nil (in case of HS/VHSSs) has led to dismissing this property from this study. Further, due to the very limited works on thermal properties of FRPs, these properties were not considered herein.

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is safe to conclude that the developed ANN can be used with confidence to develop temperature-dependent material models and associated expressions.

Table 1 Metrics for different material properties obtained from developed ANN

Material	Property	Coefficient of determination (R^2)	Mean absolute error (MAE)
High performance concrete (including HSC, SCC, and FRC)	Thermal conductivity	97.8	0.275
	Specific heat	95.1	0.576
	Compressive strength	98.8	0.048
	Modulus	98.5	0.033
High/Very high strength steel	Thermal conductivity	97.6	0.278
	Specific heat	95.1	0.817
	Yield strength	96.8	0.021
	Modulus	95.9	0.014
Fiber-reinforced polymers	Tensile strength	95.5	0.085
	Modulus	97.9	0.014

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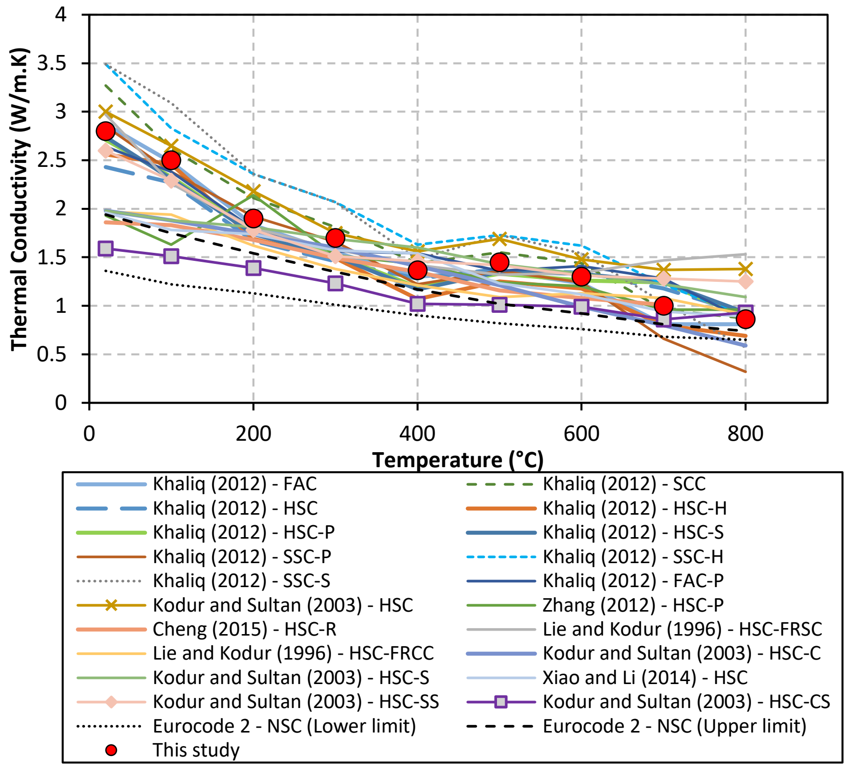
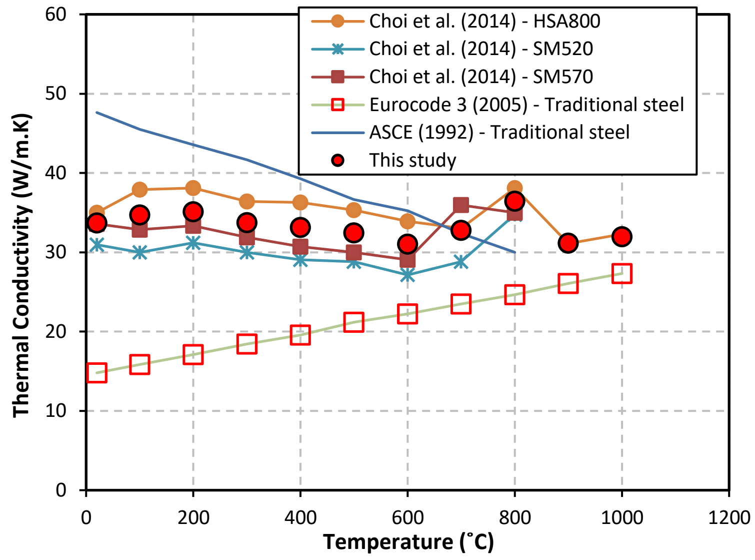
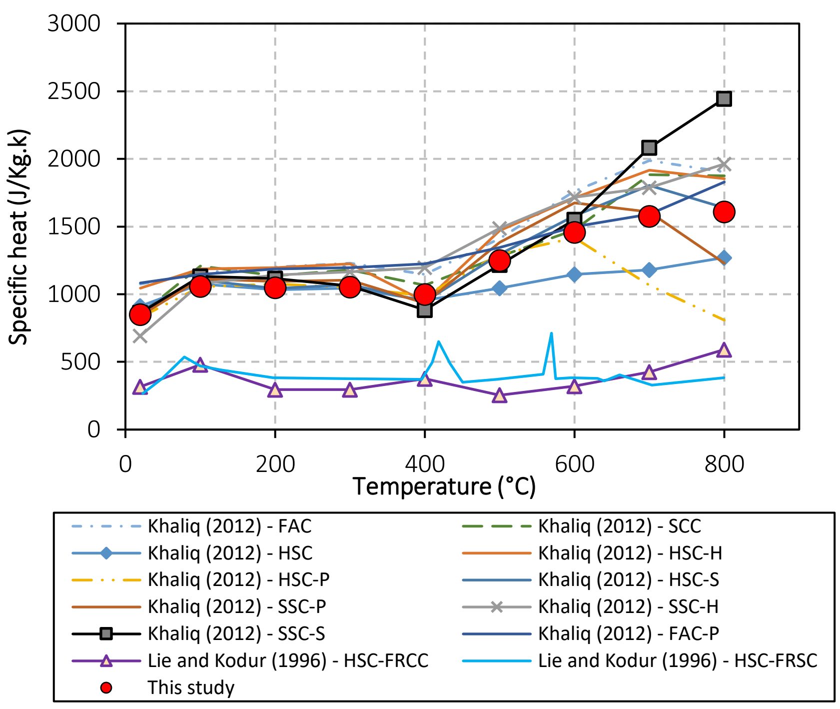
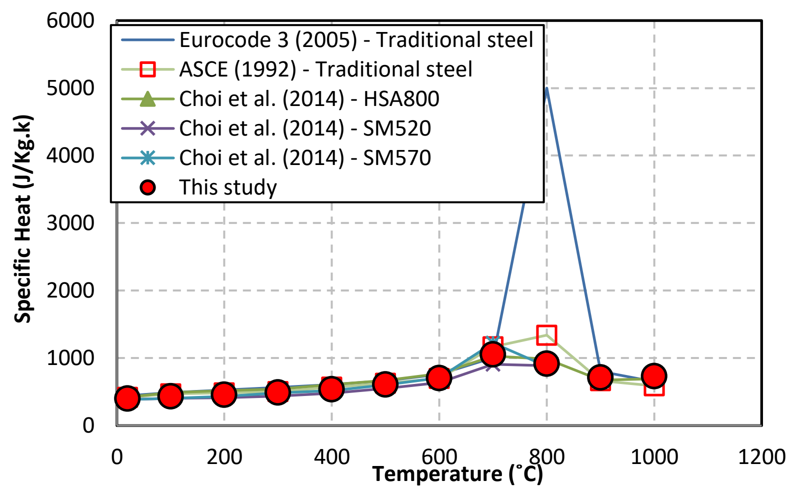




(a) High performance concrete (including HSC, SCC and FRC)

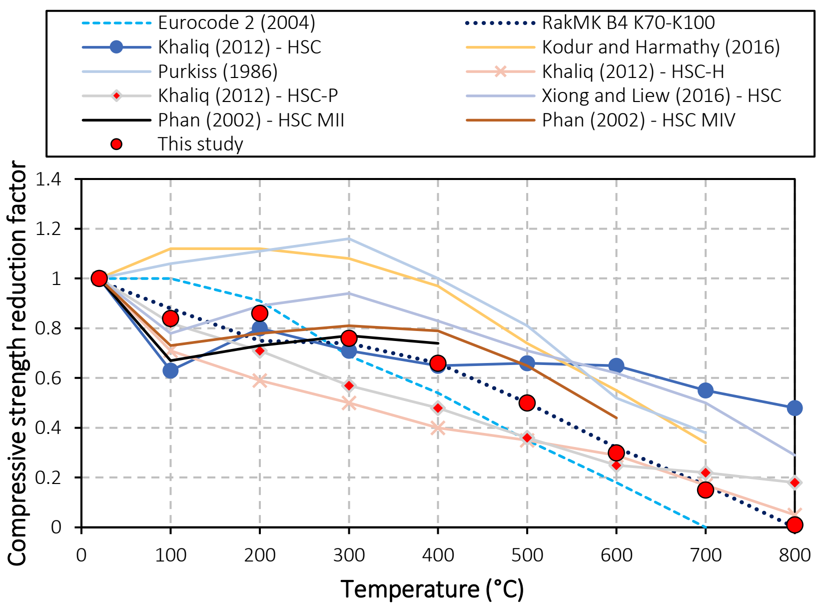
(b) High/Very high strength steels

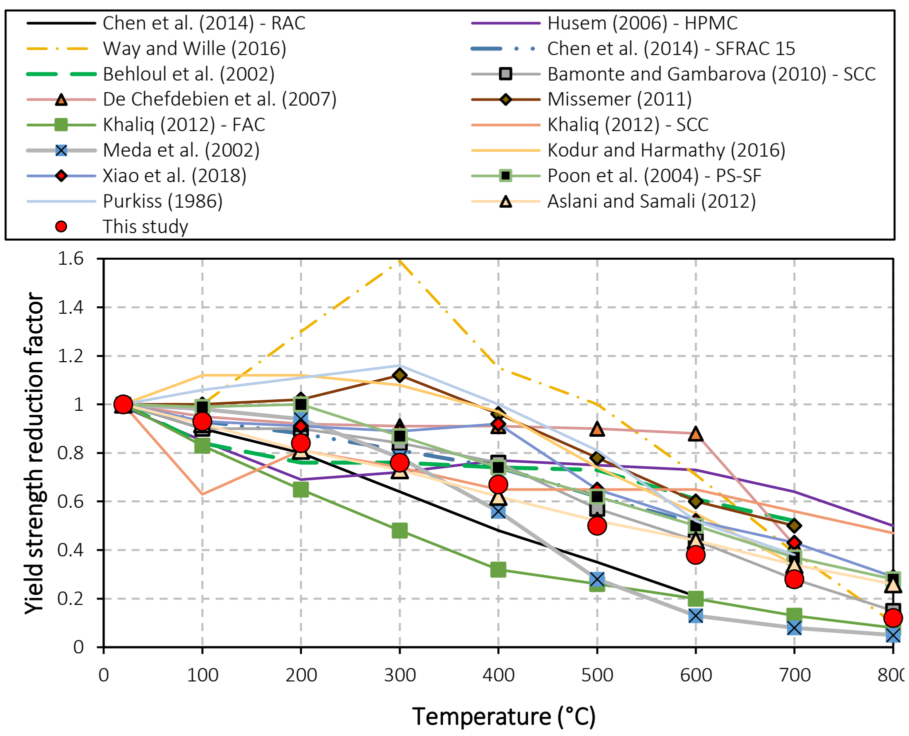




(c) High performance concrete (including HSC, SCC and FRC)

(d) High/Very high strength steels





(e) High strength concrete

(f) High performance concrete (including SCC and FRC)

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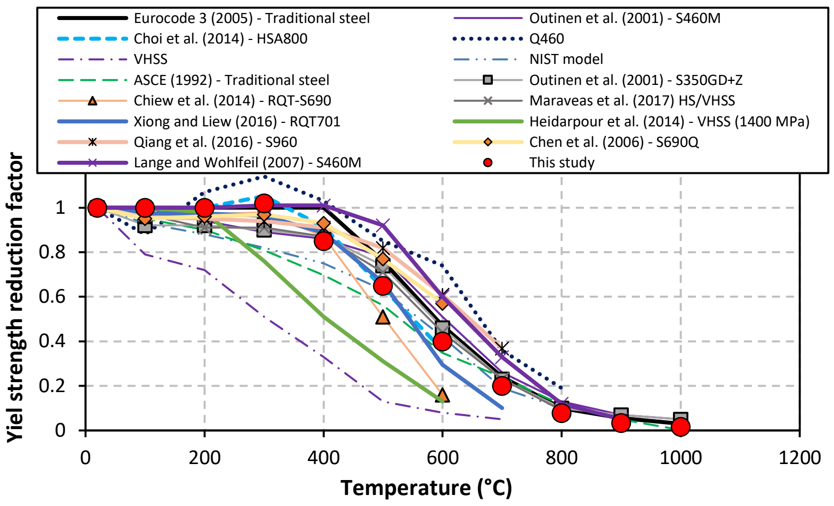
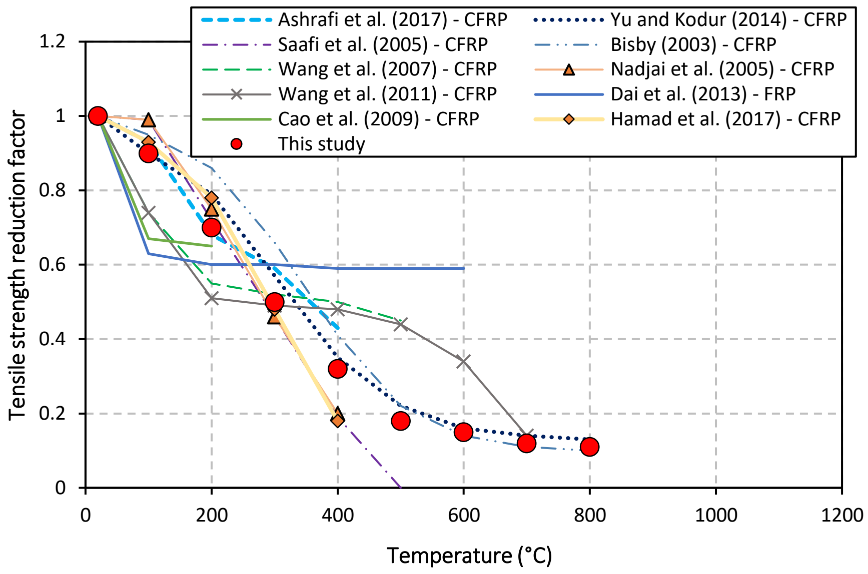
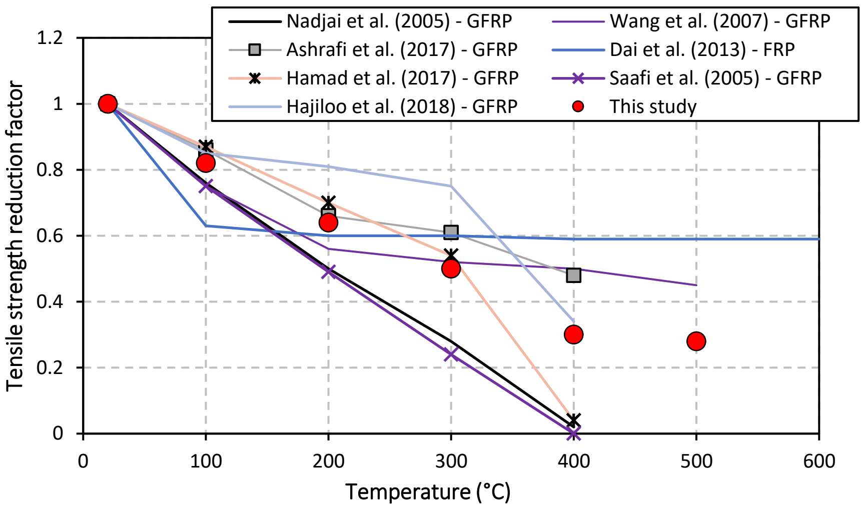


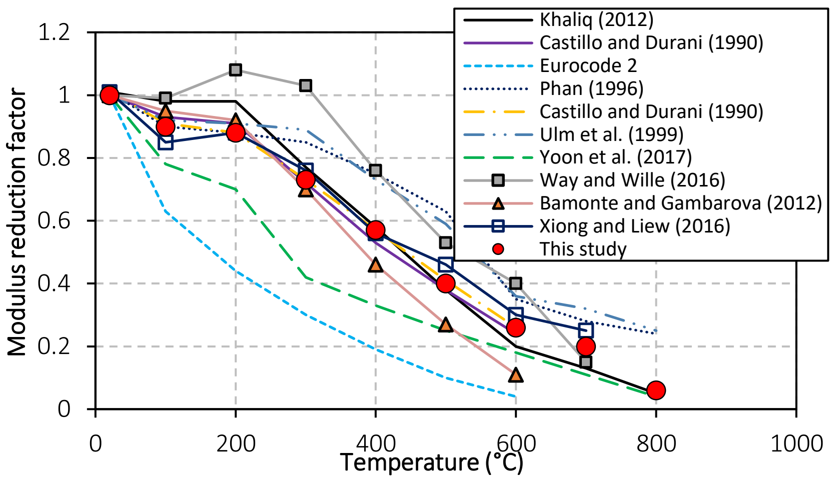
(g) High/Very high strength steels



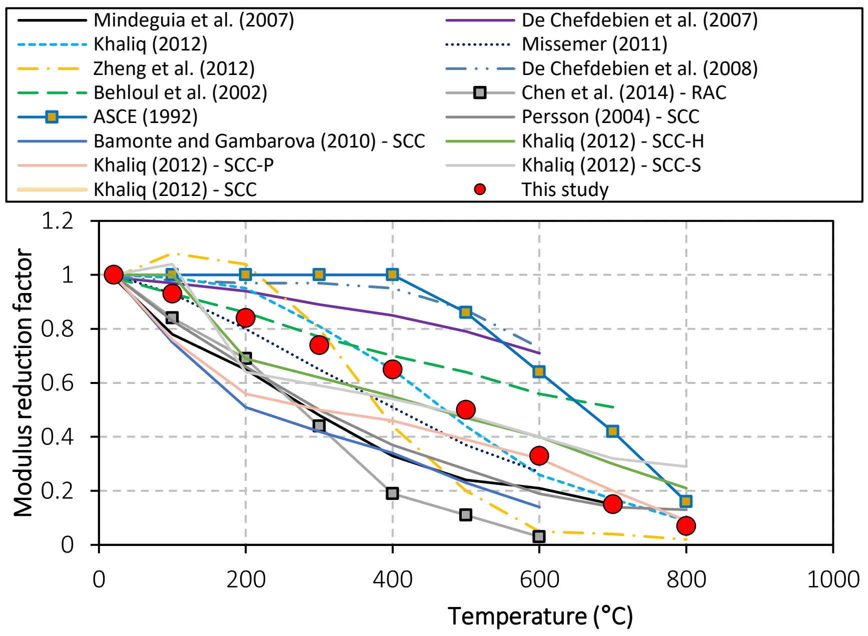
(h) Fiber-reinforced polymers (CFRP)



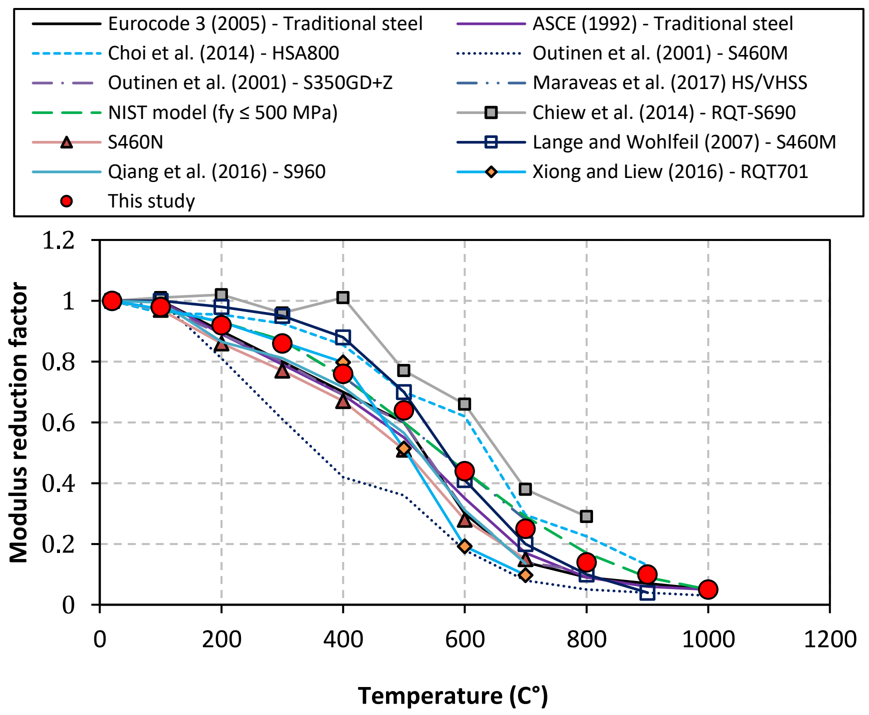
(i) Fiber-reinforced polymers (GFRP)



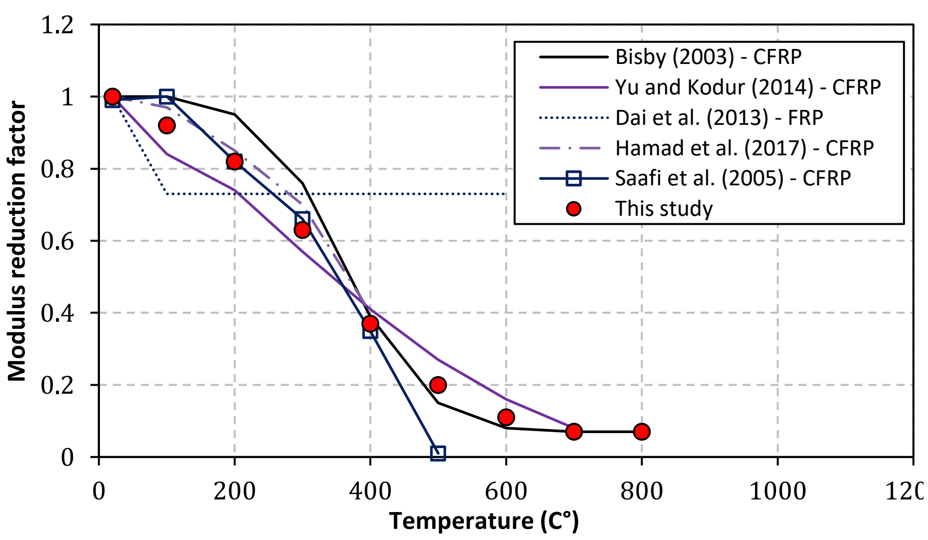
(j) High strength concrete



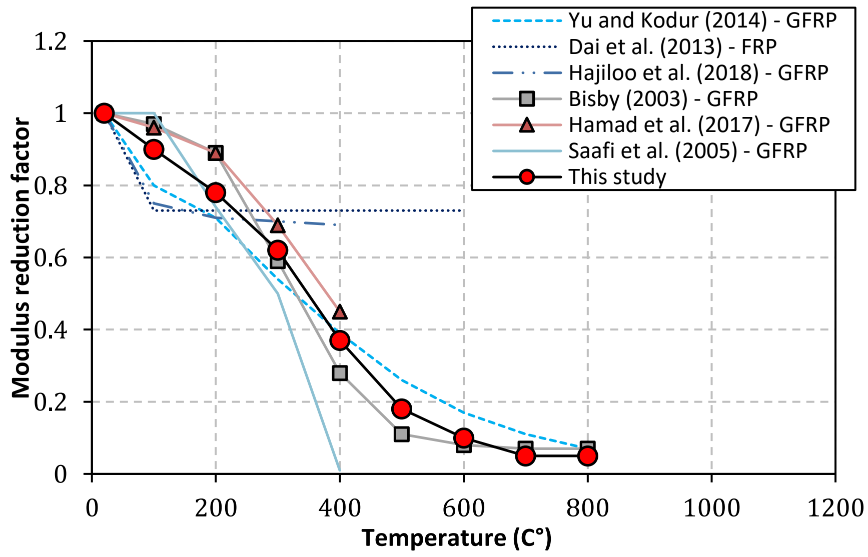
(k) High performance concrete (including SCC and FRC)



(l) High/Very high strength steels



(m)Fiber-reinforced polymers (CFRP)



(n) Fiber-reinforced polymers (CFRP)

Fig. 6 Comparison between material models obtained from AI analysis and notable works

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The values for material properties at target temperatures (25, 100, 200°C etc.) arrived at using ANN and plotted in Fig. 6 are then fitted into simple expressions using the previously described GA model. In this study, simple expressions are derived for thermal and mechanical properties. These expressions can come in handy especially in research or design scenarios as there is limited guidance on how to present temperature-dependent material properties of MCMs. These expressions, together with their coefficient of determination (R^2), maximum error (ME) and base values; which could be directly used in fire evaluation (i.e. through advanced calculation methods i.e., finite element etc.), are listed in Table 2 and Table 3, respectively[‡‡‡]. A close examination of fitness metrics in these expressions show their high accuracy in presenting temperature-dependent material degradation in MCMs.

[‡‡‡] Please note that despite composition and chemical differences, both high and very high strength steels are grouped together in Table 2 due to, 1) the lack of associated works (experiments carried out at elevated temperatures for these steels as compared, for instance, with other construction materials such as high strength concrete), and 2) the fact that a similar strategy was used by fellow researchers [56]. Please note that additional and independent expressions for these steels are also listed in the appendix. These expressions were derived based on tests carried out specifically on high strength steels and very high strength steels as shown in Fig. 6g and are perhaps more suitable for use depending on the application/need of a designer/scientist/engineer.

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Table 2 Derived expressions for temperature-dependent material properties*

Material	**Property**	**Simple Expressions**	R^2	***ME***
High performance concrete (including HSC, SCC, and FRC)	Thermal conductivity	$k = 2.877 - 0.00341T - 6.966e^{-7}T^2 - 2.757e^{-9}T^3 \sin(-17.02T) - 0.0925\tan(0.0966 + 1.394e^{-7}T^3)$	99.9	0.054
	Specific heat	$c = 771.1 + 3.418T + 4.784\tan(T) + 0.000837T^2 - 2.536e^{-6}T^3 - 1123\tanh(4.77e^{-8}T^3)$	99.8	7.92
	Compressive strength	$f_c = 1.021 + 0.08866 sin(T^2) - 0.000644T - 0.0547m - 1.958e^{-7}T^2 - 3.362e^{-10}mT^3$ where, *m* is material number and equals to 1 and 2 for HPC (SCC and FRC) and HSC, respectively.	99.5	0.027
	Modulus	$E = 1.094 + 0.000164Tm + 2.725e^{-9}T^3 - 0.0311\ln(T) - 3.422e^{-6}T^2 - 2.815e^{-10}mT^3$ where, *m* is material number and equals to 1 and 2 for HPC (SCC and FRC) and HSC, respectively.	99.4	0.035
High/Very high strength steel	Thermal conductivity	$k = 34.24 + 0.005T\sin(0.0669T^2) + 0.0018T\, sin(0.0669T^2)^2 \sin(0.0669T)\sin(-0.0254T^2) - 0.00279T\sin(0.0252 + T) - 0.959\sin(-0.0254T^2)$	99.9	0.033
	Specific heat	$c = 431.5 - \frac{500}{T} + 0.0007592T^2 - 9.67\tan(9.144T) - 1.063e^{-12}T^5\cos(2.86 + 4.95e^{-7}T^3)$	99.9	12.6
	Yield strength$	$f_y = 0.9664 + \frac{0.6417}{T} + 3.97e^{-6}T^2 + 2.26e^{-14}T^5 - 1.299e^{-17}T^6 - 1.453e^{-8}T^3$	99.7	0.031
	Modulus$	$E = 1.007 - 0.0003954T - 4.041e^{-13}T^4 - 1.997e^{-12}T^4\text{atan}(\frac{2.98e^{11}}{T^4} - 0.2188)$	99.9	0.025
Fiber-reinforced polymers	Tensile strength	$f_t = 1.033 + 6.524e^{-15}T^5m^2 - 0.001614T - 7.735e^{-7}mT^2 - 6.077e^{-21}T^7m^3$ where, *m* is material number and equals to 1 and 2 for carbon and glass FRP, respectively.	99.5	0.037
	Modulus**	$E = 0.9225 + \frac{1.697}{T+m} + 5.112e^{-11}(T+m)^4 + 2.88e^{-14}(T+m)^5 - 2.416e^{-8}(T+m)^3$ where, *m* is material number and equals to 1 and 2 for carbon and glass FRP, respectively.	99.8	0.027

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[*] *T* is temperature in (°C), [**] Range up to 500°C for Glass FRP.
Please refer to Table A.1 for *specific* expressions suitable for high strength steel and very high strength steels.

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Table 3 Temperature-dependent material properties at target temperatures (base values)

Base values															
Temperature (°C)	**HPC (including HSC, SCC and FRC)**						**HS/VHSS**				**FRP**			
	***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***	**Reduction factor for *ft***		**Reduction factor for *E***	
			FRC/SCC	**HSC**	**FRC/SCC**	**HSC**					**CFRP**	**GFRP**	**CFRP**	**GFRP**
25	49.6	850	1.00	1.00	1.00	1.00	33.7	399	1.000	1.00	1.000	1.000	1	1
100	48.5	1060	0.95	0.84	0.90	0.93	34.7	434	1.000	0.98	0.900	0.820	0.92	0.9
200	47.4	1050	0.90	0.86	0.88	0.84	35.1	454	1.000	0.92	0.700	0.640	0.82	0.78
300	43.5	1055	0.86	0.76	0.73	0.74	33.7	489	1.020	0.86	0.500	0.500	0.63	0.62
400	40.7	1000	0.70	0.66	0.57	0.65	33.1	536	0.850	0.76	0.320	0.300	0.37	0.37
500	39.4	1250	0.57	0.50	0.40	0.50	32.5	608	0.650	0.64	0.180	0.280	0.20	0.18
600	37.3	1460	0.43	0.30	0.26	0.33	31.0	704	0.400	0.44	0.150	-	0.11	0.10
700	34.0	1577	0.32	0.15	0.20	0.15	32.8	1054	0.200	0.25	0.120	-	0.07	0.05
800	0.86	1610	0.25	0.01	0.06	0.07	36.4	918	0.077	0.14	0.110	-	0.07	0.05
900	-	-	-	-	-	-	31.1	711	0.033	0.10	-	-	-	-
1000	-	-	-	-	-	-	32.0	731	0.017	0.05	-	-	-	-

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6.0 INSIGHTS INTO DESIGN IMPLICATIONS AND FUTURE RESEARCH NEEDS

The presented discussion demonstrates that in order to carry out a proper fire resistance evaluation, knowledge on temperature-dependent properties of construction materials is of utmost importance. This is due to the fact that the outcome of a fire resistance assessment (say fire rating of a structural member or sectional capacity under fire conditions etc.) is highly dependent upon the selected material model in such assessment. Since the behavior of a structural member under fire conditions is 1) complex, and 2) often not known before hand, then predictions from fire resistance evaluation are to be perceived with caution unless a comprehensive testing program is carried out to examine high temperature thermal and mechanical properties of the construction material comprising the structural member in question. In order to facilitate fire research and design of structures, a generalized, accurate and up-to-date representation of material properties at elevated temperatures is warranted.

This study presents an attempt to derive such temperature-dependent material models for modern construction materials (MCMs) using artificial intelligence. Since the derived material models are arrived at through cognitive analysis of various material models compiled from open literature; with the intent to present a balanced overview of variations in materials (in terms of composition or origin), occurrence of certain phenomenon (i.e. creep effects, thermal gradients), as well as differences in testing methods (e.g. set-ups, heating and loading rate, specimen sizes etc.), it is believed that the AI-derived models can express a generalized behavior of MCMs at elevated temperatures. This conclusion has been arrived at through a rigorous analysis procedure carried out in an earlier study [13]. It is worth noting that the derived material models herein can be further improved by 1) incorporating additional material models in lieu of those plotted in Figs.

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1-4, and 2) utilizing advanced AI optimization techniques such as Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO) etc.

While this study is concerned with deriving material models for MCMs using AI, future studies are invited to extend and improve this approach to derive constitutive material models for other construction and insulation materials [85, 86] as well as properties of these materials such as creep, transient strain, thermal expansion, debonding and spalling etc. Such studies may also specifically account for factors that were not accounted for herein such as quantity/type of admixtures, curing and moisture content at the time of testing in concrete derivatives, chemical composition of steels and composites etc. Further, future studies are also encouraged to examine post-fire (residual) properties of various construction materials as these properties are necessary in post-fire investigations.

The outcome of future studies can be used to develop databases (libraries) for construction materials to be freely available for practitioners and researchers. A key advantage of developing such databases is the possibility of transparency as well as continuous examination and updating of temperature-dependent material models. This can be carried out with ease as AI-based computing techniques have the ability to improve their accuracy with proper training. Another advantage to developing such material libraries lies in facilitating standardization efforts which could help promote performance-based design approaches into structural fire engineering and fire safety applications. In order to further improve prediction capability of AI-based algorithms, a collaboration between interdisciplinary researchers of civil, fire and computer science backgrounds can be fruitful. Such collaboration might yield development of techniques/algorithms specific to fire engineering applications with the ability to comprehend behavior of materials as well as structures under fire conditions [87].

7.0 CONCLUSIONS

This paper presents an approach to derive temperature-dependent thermal and mechanical material models for modern construction materials including high strength/performance concrete (HSC/HPC), high/very high strength (HS/VHS) steels, and fiber-reinforced polymer (FRP) composites. This approach applies a hybrid combination of Artificial Neural Networks (ANNs) and Genetic Algorithms (GAs) to realize generalized material models suitable for fire resistance evaluation.

The following conclusions could also be drawn from the results of this investigation:

- There is a lack of guidance on representation of temperature-dependent properties of modern construction materials as available test data show large discrepancies (which may exceed 25% in some cases). This further complicates fire design and analysis of structures and leave researchers and designers with limited room for creativity.
- There is a need to develop a generalized and up-to-date presentation of material properties at elevated temperatures to improve the current state of structural fire design and supports standardization efforts.
- The use of AI techniques to derive material models can be the first step towards modernizing fire assessment and design of materials and structures.

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Compliance with ethical standards

The author declares no conflict of interest.

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Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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9.0 APPENDIX

Table A.1 Derived expressions for temperature-dependent mechanical material properties for high and very high strength steels*

Material	Property	Simple Expressions	R^2	*ME*
High strength steel	Yield strength	$f_y = 0.996 + 0.000338T + 5.74e^{-12}T^4 - 3.92e^{-6}T^2 - 1.69e^{-6}T^2\sin(T)$	99.8	0.007
	Modulus	$E = 0.999 + 6.22e^{-10}T^3 - 1.91e^{-6}T^2 - 3.49e^{-10}T^3\cos(1.3e^{-21}T^9)$	99.9	0.005
Very high strength steel	Yield strength	$f_y = 0.991 + 1.4e^{-14}T^5 - 1.33e^{-11}T^4$	99.8	0.026
	Modulus	$E = 0.867 + \frac{13.5}{T} + 6.93e^{-18}T^6 - \frac{216}{T^2} + 6.25e^{-12}T^4$	99.9	0.008
*T is temperature in (°C) and range up to 800°C.				