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Performance of High Strength Concrete Subjected to Elevated Temperatures: A Review

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Abstract. Advancement in the field of construction has given rise to the modification of conventional materials in order to utilize the full potential of their components to achieve high durability, strength, and other engineering characteristics. Construction materials should ideally be environmental friendly. These diverse requirements resulted in the invention of high strength concrete (HSC). A rapidly increasing use of HSC in most of the construction projects has encouraged researchers to identify its behavior at elevated temperatures. This has led to the recognition of an inadequate understanding of elevated temperatures' effects on the behavior of HSC. This paper initially provides necessary information about HSC and relates its benefits. A number of different design standards for the preparation of HSC are also presented and compared. Previous research activities performed on HSC to identify the effect of elevated temperatures on the properties of HSC are reviewed. Findings showed that the mechanical properties of NSC decreases at a 10% to 20% higher rate than HSC ranging between ambient temperature and approximately 350°C, depending upon the mix proportions and initial compressive strength of the concrete. The differences become narrower at temperature above 350°C. Major failure modes are identified and future recommendations are presented.

Keywords: High strength concrete, Elevated temperatures, Compressive strength, Stress–strain-relationship, Concrete design

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1. Introduction

Structural systems made up of concrete are widely used in residential and commercial buildings due to the versatility of concrete and its numerous advantages as compared to the other construction materials [1, 2]. For example, concrete can be molded or cast into almost any desired shape on site which is not possible for other construction materials. Compared to steel, it is relatively less expensive and its ingredients are easily available. Concrete does not rot, corrode, or decay as other building materials. Furthermore, unlike timber, concrete is a non-combustible material, which makes it fire-safe and able to withstand high temperatures. It also does not require additional fire retardant coatings. Concrete has the ability to save energy at a higher rate as compared to most other construction materials. When combined with active radiant heating and cooling systems, the thermal mass of a concrete structure can reduce heating and cooling energy requirements by 29% or more. Several types of concrete are commercially available and prepared according to their type of use, expenditures' limitations, strength, stiffness and durability requirements and environmental conditions to which the concrete will be exposed. The performance of concrete is determined by its several characteristics including, compressive strength, elastic modulus, stress–strain relationship, thermal strain and shrinkage, transient state creep and restraint and modeling [3]. However, extensive tests on the performance of concrete are usually required to demonstrate compliance with specific project needs [4–6]. Moreover, the rapidly increasing use of concrete as a construction material has shown that the maintenance cost required to retain the desired durability of concrete throughout its life is not economical. This has encouraged the researchers to produce economically feasible concrete with increased compressive strength. The generally considered range of the 28-day compressive strength of ready mixed concrete is from 20 MPa to 40 MPa, and commercially used concrete mostly lies between 28 MPa and 35 MPa. Considering the needs of modern construction, research performed in the last few decades have resulted in the invention and development of several forms of concrete with increased compressive strength. One of those forms is 'high strength concrete' (HSC). In recent years, HSC has attained the position of a substitute to conventional normal strength concrete (NSC) [7]. There is no precise difference between the composition of HSC and NSCexcept for structural behavior which is different in terms of strength loss and explosive spalling [8]. Due to its low porosity, HSC is more vulnerable to explosive spalling than NSC. Initially, HSC was considered suitable for the construction of offshore and infrastructure applications. However, in the last two decades, its versatility has also attracted the builders to use it in high rise buildings [9]. Nevertheless, there is a lack of information about the long-term performance of concrete under severe environmental impacts [10].

The exact definition of HSC in terms of numerical values is not possible, without a sound degree of rationale [11]. The updated draft of American Concrete Institute (ACI) "ACI 363R-92″ [12] defines concrete with a compressive strength greater than 55 MPa or greater as HSC. Eurocode 2 [13] permits to use the concrete strengths of up to 105 MPa cube strength. There is no definition of high strength concrete in Eurocode 2, but the measures and formulae change when the concrete strength is greater than C50/60 so this may be a reasonable working definition. The Australian Bridge Code AS 5100 [14] covered a low range of HSC and define it as a concrete with a compressive strength of up to 65 MPa. However, the definition of high strength concrete is continually developing. Nowadays, HSC with a compressive strength of up to 140 MPa is frequently used for structural applications [7].

The benefits of HSC are its high strength and stiffness, decreased permeability to injurious materials and high abrasion resistance. These benefits have made HSC a progressively more attractive construction material in the last few years [15]. The use of HSC allows higher load carrying capacity of members at a lower cost, increases in usable space by decreasing the member dimensions, and lower unit weight for a given strength which can be advantageous in seismic zones. However, care is needed for the placing, consolidation, and curing of HSC. Because of the large number of combinations of cementitious materials and chemical admixtures, HSC achieves higher peak of temperature due to its own heat of hydration. Therefore, it is essential to measure the initial setting time of HSC and the temperature of concrete, not the temperature of enclosure [11]. Early application of heat may adversely affect the long-term strength and durability of HSC. On the other hand, a delay in the application of heat may reduce the rate of production [11]. Further, the literature recommends water curing to achieve object compressive strength [16]. Inadequate consolidation may decreases the strength and durability of the concrete. Reduced width to breadth ratio makes HSC stickier, hence the required consistency of HSC cannot be achieved [16]. The immediate delivery and placing, and proper consolidation may give better strength [17]. In general, complete knowledge about the behavior of HSC may allow it to be used with confidence.

Fire in buildings may cause losses of both geometrical and material properties of structural members, such as thermal expansion and reduction in the strength and stiffness [18]. The effect of fire on structural members is an important factor to be understood by the designers [19]. In modern construction, adequate fire safety provisions are considered highly essential for longer life span of structural members and to provide sufficient resistance to unwanted fire [1]. Conventionally, for fire safety design with HSC, strict experimental-theoretical approaches based on standard fire tests and empirical methods are adopted [13]. In the last few years, performance-based fire resistance design approaches for HSC have been introduced [20]. Various aspects of HSC need to be considered to ensure proper utilization of HSC in different civil engineering structures subjected to fire. The accuracy of prevailing fire-design approaches should be assessed from time to time and if essential, new provisions should be introduced [21].

Along with other benefits, NSC is preferred for use in construction due to its good resistance to temperature [22, 23]. The rapidly increasing utilization of HSC as a replacement of NSC encouraged the researchers to identify its behavior when subjected to fire. It is a general concept that elevated temperatures reduce the mechanical properties of concrete structures [24–27]. The resistance of NSC to elevated temperatures is influenced by many factors, including the type of cement and aggregates used, the intensity and duration of the fire, member sizes and geometry, and the moisture content of concrete [24, 28–30]. Literature has revealed considerable differences between the fire performances of HSC and NSC [15, 20, 31–36]. Most importantly, the failure mode of HSC is different from that of NSC under fire. HSC fails by explosive spalling when subjected to rapid heating [37]. Spalling affects the upper layers of concrete which consequently exposes the deeper layers to fire. This results in increased heat transfer to the inner layer of concrete as well as the steel reinforcement.

This study initially presents necessary information about the usage, benefits and composition of HSC. Thereafter, the design provisions suggested by recent standards and researches are highlighted. Finally, a review of studies into the fire behavior of HSC is presented. The effect of fire on the mechanical properties of HSC are presented and major failure modes are discussed. Based on the observations, the needs for future researchers are highlighted.

2. Composition of HSC

The distinctive feature of HSC is its increased strength and durability at an optimal cost while addressing the needs of structures exposed to hazardous conditions [38, 39]. Coupled with several other advantages, its easy availability has led to the rapidly increasing use of HSC in many types of structural applications.

The general definition of HSC is exclusively based on its compressive strength at a specific age [40]. HSC can be easily prepared at any concrete plant with the use of advanced additives such as silica fume and water-reducing admixtures. HSC is similar to that of NSC, but manufacturing HSC demands optimum utilization of the basic ingredients that constitute NSC. Those involved in the production of HSC must recognize the key factors influencing the compressive strength and how these factors can be manipulated to obtain the desired strength. Important considerations include selection of high grade cement, selection of surface characteristics of aggregates, optimization of aggregates and their bond with cement paste, water cement ratio, optimization of the proportion of concrete ingredients and most importantly, the selection and optimization of admixtures [40]. Generally, the mineral admixtures used in HSC are Silica Fume (SF), Fly Ash, and Ground Granulated Blast Furnace Slag (GGBFS). SF is a surplus by-product obtained from silicon and its alloys. Though there are several forms of SF commercially available, however, it is usually used in its densified form. The use of densified form of SF is recommended to achieve greater compressive strength with less efforts as it can be achieved without SF [41].

The dosage rate of fly ash used in HSC is 15% of cement quantity. The chemical and physical properties of fly ash significantly differ from those of SF, however, using major admixture constitues of fly ash has resulted in increased compressive strength of HSC [42]. The literature recommends that to achieve greater strength, both SF and fly ash should be used [35, 43]. Slags have also been used to increase the compressive strength of concrete. Usually dosage rates less than 40% of different types of slags for sand substitution as a fine aggregate [44] and less than 25% cement weight [45] generally results in good compressive strength for HSC.

Selection of aggregates and chemical admixtures play an important role to increase the strength of concrete [40]. In addition to these two parameters, it is also important which methods are used to prepare HSC. Various methods of preparing HSC include seeding, re-vibration, inhibiting cracks, using admixtures and sulphur impregnation. Aitcin [46] presented the microstructure of a HSC as shown in Fig. 1a, b.

According to Burg and Ost [47], the compressive strength of commercially-used HSCs is usually high, as shown in Table 1. However, to achieve such strength, the preparation of HSC calls for rigorous techniques and expertise. Strictly following of design standards regarding laboratory and field testing before production is mandatory.

It is essential to discuss the slight variation in chemical and physical composition of concrete and the method of preparation and curing lead to significant changes in the compressive strength at both ambient and elevated temperatures. The behaviors of NSC and HSC have been found to be significantly different at both ambient and elevated temperatures [20, 48, 49]. These differences in behavior include differences in the compressive strength and elastic modulus and failure modes of the two types of concrete. It has been shown that HSC has a greater tendency to fail by explosive spalling when exposed to fire [34, 50, 51].

3. Research Progress on HSC Under Fire

The pioneering research on the factors affecting the performance of concrete under fire was performed by Lea [52, 53]. Following that, several studies were conducted to determine the fire resistance of various types of concrete at different temperatures using different investigation methods. Experimental testing is the basic type of investigation; however, it is time consuming, expensive and usually difficult to repeat. Further, it is limited to simple elements [54]. Current investigations prefer the use of numerical modeling. However, the exact simulation of the procedure is not easy to perform unless fully understood and the required simulator is available [54]. Thus, simple calculation methods are considered necessary for application to most simple cases in everyday practice [54].

A great deal of literature is available which discusses the fire behavior of NSC and other types of concrete [7, 24, 26, 55–65]. However, the increasing popularity of HSC as a construction material demands an overview of researches performed into the behavior of HSC under fire. Similar to NSC, the effect of temperature modify various properties of HSC including compressive strength, elastic modulus, stress–strain relationship, thermal strain and shrinkage, transient state creep, and restraint and modelling approaches. The following section presents information about the behavior of various properties of HSC when subjected to fire.

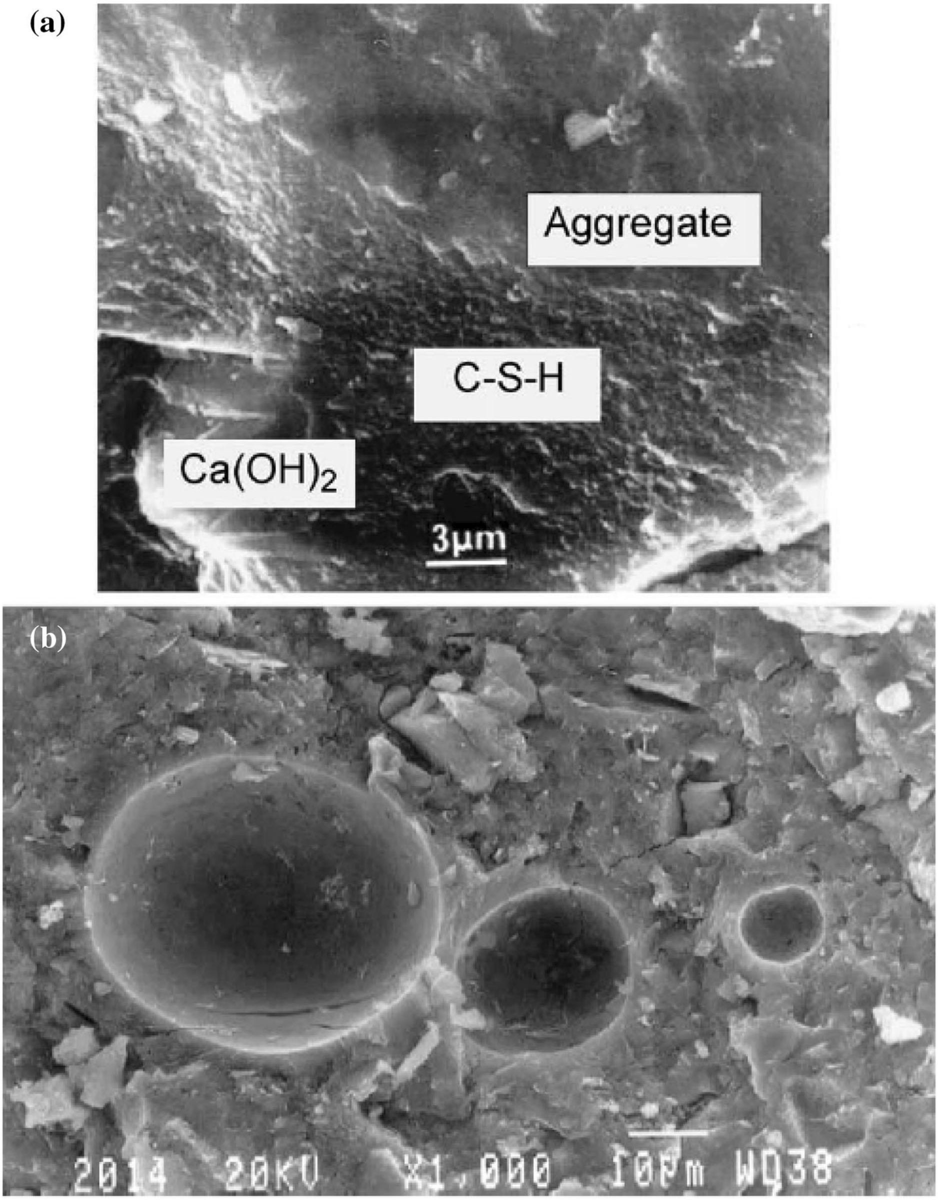

Figure 1. Microstructure of a HPC: low porosity and homogeneity of the matrix [46]: (a) absence of transition zone between the aggregate and cement paste; (b) dense cement paste in an air entrained high performance concrete.

Table 1
Mixture Proportions and Properties of Commercially Available High-Strength Concrete [47]

	Mix number					
Units/m^3	1	2	3	4	5	6
Cement, Type I, kg	564	475	487	564	475	327
Silica fume, kg	–	24	47	89	74	27
Fly ash, kg	–	59	–	–	104	87
Coarse aggregate SSD (12.5 mm crushed limestone), kg	1068	1068	1068	1068	1068	1121
Fine aggregate SSD, kg	647	659	676	593	593	742
HRWR Type F, l	11.6	11.6	11.22	20.11	16.44	6.3
HRWR Type G, l	–	–	–	–	–	3.24
Retarder, Type D, l	1.12	1.05	0.97	1.46	1.5	–
Water to cementing materials ratio	0.28	0.29	0.29	0.22	0.23	0.32
Fresh concrete properties						
Slump, mm	197	248	216	254	235	203
Density, kg/m3	2451	2453	2433	2486	2459	2454
Air content, %	1.6	0.7	1.3	1.1	1.4	1.2
Concrete temp., °C	24	24	18	17	17	23
Compressive strength, 100 × 200-mm moist-cured cylinders						
3 days, MPa	57	54	55	72	53	43
7 days, MPa	67	71	71	92	77	63
28 days, MPa	79	92	90	117	100	85
56 days, MPa	84	94	95	122	116	–
91 days, MPa	88	105	96	124	120	92
182 days, MPa	97	105	97	128	120	–
426 days, MPa	103	118	100	133	119	–
1085 days, MPa	115	122	115	150	132	–
Modulus of elasticity in compression, 100 × 200-mm moist-cured cylinders						
91 days, GPa	50.6	49.9	50.1	56.5	53.4	47.9

3.1. Effect of Temperature on Compressive Strength of HSC

In spite of the recognized good resistance of concrete to fire, a considerable loss of mechanical properties may occur. The main effect of temperature is experienced by compressive strength. Early research on the effect of fire on the behavior of concrete having compressive strength above 40 MPa of concrete includes the testing performed by Abrams [58]. He used all three types of tests on the temperature up to 1600°C. Specimens were prepared using normal weight aggregates (NWA) (carbonate and siliceous) and lightweight aggregates (LWA). 150 mm high cylindrical specimens with 75 mm diameter were tested. No explosive spalling was observed up to 350°C. The compressive strength of most of the specimens decreased gradually after 350°C. Several studies on the compressive strength of HSC observed considerable yet gradual strength degradation at 350°C and a sharp decrease thereafter [51, 66–70]. The major failure mode of HSC was spalling. The details of these studies are presented in Table 2 [34]. Hertz [71] used 14% to 20% SF in HSC and prepared the specimens up to a compressive strength

Table 2
Details of Early Studies Performed on HSC Under Fire

Researchers	Compressive strength (MPa)	Test method	Aggregate type	Specimen dimensions (mm) (diameter × height)	Temperature at explosive spalling observed (°C)
Abrams [58]	23–45	Stressed, Unstressed, Unstressed residual	NWA and LWA	75 × 150	Not observed
Hertz [71]	170 150	Unstressed residual	SF with steel fiber	100 × 200 57 × 100 28 × 52	350–650
Diederichs et al. [66]	33–114	Unstressed	SF, fly ash, GGBFS, OPC	100 × 100 × 100 80 × 300	350
Castillo [51]	28, 62 31, 63, 89	Stressed, Unstressed	OPC	51 × 102	320–360
Sullivan and Shansar [68]	38–65	Unstressed, Unstressed residual	Combinations of OPC, SF, GGBFS	64 × 64	Not observed
Morita et al. [67]	20, 39, 59 20,74	Unstressed residual	OPC	100 × 200	Not observed
Hammer [75]	69–118	Unstressed	SF with NWA and LWA	100 × 310	300
Furumura et al. [69]	21, 42, 60 38, 55, 79	Unstressed, Unstressed residual	OPC	50 × 100	300
Noumowe et al. [70]	38, 61	Unstressed residual	SF with calcareous aggregates	160 × 320 100 × 100 × 400	300
Felicetti and Gambarova [76]	72, 95	Unstressed residual	SF	100 × 300 100 × 150 80 × 275 × 500	Not observed

of 170 MPa. He reported that the failure mode of HSC considerably affects compressive strength. Out of fifteen 100 × 200 mm cylindrical specimens, five exploded due to spalling and cracking at 650°C. Similar to a number of previous studies, it was observed that the average residual compressive strength of HSC was gradually decreased up to 350°C and an abrupt reduction occurred thereafter. Hertz [72] tested HSC made up of granite aggregate and SF contents of 0%, 5%, 10%, and 15% of cement by weight, and a moisture content in equilibrium with air conditions. No explosion was observed till 600°C when heat was applied at the rates of 1°C/min and 5°C/min. The conclusion of the study revealed that SF densified HSC with increased moisture content has greater tendency towards explosion. He recommended that in order to avoid spalling, an upper limit of 10% of cement weight on SF should be used. Similar findings were achieved by Sanjayan and Stocks [73] in a study performed on a monolithic beam-slab (T-beam) sample

at 8% SF. Sarshar and Khoury [74] declared that by replacing the 10% weight of OPC by SF, no considerable benefits could be achieved. The residual strength of 10% SF densified HSC was worse than those made up of 100% OPC. Hammer [75] applied a temperature up to 600°C at a rate of 2°C/min on HSC specimens containing 0–5% of SF and made with NWAs and LWAs. The strength degradation and spalling were less in the densified concretes made up without SF. Felicetti and Gambarova [76] used the HSC specimens with 6.7% and 9.7% densified SF, flint aggregates, and Type V OPC. They achieved the results similar to [75]. They verified the applicability of the ACI rectangular stress block parameters to HSCs. However, new rectangular stress block parameters were proposed based on a probabilistic analysis using a stress–strain relationship for HSC, including estimates of variability and distribution of the input properties. The compression failure and moment capacity of the specimens were significantly affected by the stress blocks.

Balendran et al. [77] investigated the effect of elevated temperature on the flexural and split cylinder strength of HSC. Four concrete mixes of 50, 90, 110, and 130 MPa grade were prepared and subjected to elevated temperature exposure of 200°C and 400°C, and cooled under slow and quick cooling conditions. In addition, 130 MPa grade concrete specimens were subjected to 100°C and 600°C. Flexural strength was observed to experience a sharp loss at low temperatures and became gradual loss at high temperatures. A gradual loss for split cylinder strength was also observed, however, this loss was greater than that observed for flexural strength. The results indicated that cooling had a significant effect on the residual values and quick cooling caused greater loss than slow cooling at elevated temperatures in flexural and split cylinder strengths of HSC.

Phan and Carino [34] performed experimental testing on NSC and HSC exposed to fire and presented compiled data of their tests distinguished by the experimental methods and characteristics of aggregates. Distinct differences in compressive strength and elastic modulus of HSC and NSC was observed at ambient and elevated temperatures up to 400°C. The loss in NSC was 10% to 15% greater than HSC in that range. However, above 400°C, the behavior of both type of concretes started to become similar. Compressive strengths of HSC at 800°C decrease to approximately 30% of original room-temperature strengths.

Chan et al. [43, 78] investigated the behavior of HSC when exposed to various temperature ranges up to 1200°C on the residual compressive strength and tensile splitting strength of HSC and of the pore structure in HSC and NSC. In contrast to previous studies which report a significant difference in the behavior of NSC and HSC at elevated temperatures [59, 69, 79, 80], they reported that the strength reduction behavior of NSC and HSC is similar and the greater loss occurs between 400°C and 800°C. The damage extents for NSC and HSC were similar, while, the permeability of HSC was greatly damaged and consequently, durability was affected at a higher extent compared to NSC. Nevertheless, HSC attained a higher residual strength than NSC. In between ambient temperature and 400°C, the NSCs lost their residual strength by 8% to 25% whereas the residual strength loss in HSCs was 0% to 8% in that range. Between 400°C and 600°C, the residual strength loss were 31% to 61% and 41% to 45% in NSC and HSC, respectively.

Noumowe et al. [81] also tested the permeability of HSC subjected to elevated temperatures up to 600°C. Three different mixtures were tested including control HSC, polypropylene fiber (PF) contained HSC and LWA-HSC. The permeability, compressive strength and splitting tensile strength of all three mixtures were measured. The permeability increased proportionally with the increase in thermal loading. The addition of 2% of SF to HSC had no noticeable influence on both types of concrete strengths measured. A 36% and 38% reduction was observed when ordinary aggregates were replaced with LWA, in the compressive and splitting tensile strengths, respectively. Only the LWA showed explosive spalling.

Poon et al. [82] used all three major admixtures including SF, fly ash and GGBFS and tested and compared the compressive strength and durability of NSC and HSC. The specimens were heated to 800°C. Unstressed residual compressive test was used to determine the compressive strength whereas the rapid chloride diffusion test, mercury intrusion porosimetry (MIP), and crack pattern observations were deployed to measure durability. Concrete withGGBFS and fly ash had better compressive strength up to 600°C than the sole OPC-HSC. The failure mode of SF contained HSC was explosive spalling, however, the concretes contained with the contents of fly ash and GGBFS showed crack propagation and no spalling was observed. HSC exhibited a considerable reduction in the permeability-related durability rather than compressive strength. The best performance at elevated temperatures was shown by HSCs containing 30% fly ash as a cement replacement, finally attaining higher compressive strength.

Kodur et al. [9] investigated the behavior of HSC columns exposed to fire. During the test, the column specimen was exposed to heat, controlled in such a way that the average temperature in the furnace followed, as closely as possible, the ASTM E119-88 [83], or CAN/ULC-S101 [84] standard temperature–time curve. The study demonstrated that aggregate characteristics, porosity, loading, detailing and distance between ties all influence the performance of HSC columns exposed to fire. The study also highlighted the causes of spalling in HSC. It was reported that the spalling occurs due to the increasing pore pressure because of increasing temperature. This pressure cannot escape due to the high density of HSC, and this pressure often reaches the saturation vapor pressure Since HSC has comparatively lower permeability as compared to NSC, pore pressure urges the HSC to spall. In another study, Kodur et al. [85] compared the effect of fire on the strength of HSC columns. A comparison was also made between the behaviors of NSC and HSC columns under fire and a significant difference in the behavior of two types of concrete was observed. Plain HSC columns were less resistant to fire than NSC column. The fire resistance times for NSC and plain HSC columns were 278 and 202 min, respectively.

Husem [30] identified the changes in the compressive and flexural strengths of NSC and HSC at ambient and elevated temperatures and compared experimental results. Twelve samples for each of the two types of concrete were compared and a comparison between the strength loss curves of experiments and Eurocode [86] and Finnish code [87] were provided. The strength of HSC was 71 MPa at the time of testing. The samples were heated to 200, 400, 600, 800 and 1000°C and cooled in both air and water. The NSC lost strength at a relatively higher rate compared to HSC. The strength of HSC showed variable behavior. It reduced up to 200°C, then increased up to 400°C. A permanent nonstop reduction occurred after 400°C. The samples cooled down in air showed a higher increasing rate between 200°C and 400°C than water-cooled samples. Spalling in the specimens occurred between 400°C and 500°C. The experimental results and Finnish code guidelines were in close agreement.

Hernández-Olivares and Barluenga [87] used a novel approach to minimize the strength loss of HSC subjected to high temperatures. HSC contained SF and altered with various quantities of recycled particles of crumbed used truck tires was tested under different temperatures. Concretes containing the low fractions of rubber minimized the explosive spalling at elevated temperatures due to the water vapors exiting from the passages existing as the polymeric particles burnt. The effects of temperature after a fixed depth were reduced with the increase in the rubber content. This supports to increase the material ductility thereby keeping the strength as required. HSC filled with 3% volumetric fraction of rubber resulted in only 10% loss of compressive strength. Using waste materials as aggregates in HSC exposed to fire, Xiao et al. [88] tested the fire resistance and post-seismic behavior of superimposed HSC shear wall with precast recycled aggregate concrete (RAC) panels. Their study indicated the RAC panel as an efficient thermal barrier to decrease HSC spalling by 60% compared with bare walls HSC. Based on seismic tests results, the fire exposure deteriorated the load bearing capacity, lateral stiffness, and energy dissipation capacity of walls, while the application of RAC panels improved the load bearing capacity by about 10% even when the superimposed wall was exposed to the fire for a long time. Though several studies are available on the use of waste materials in NSC or LWA under fire [89–91], the number of studies utilizing the waste materials in HSC are far fewer. This issue demands the greater attention of researchers.

Min et al. [93] identified the effects of fire profiles, content of water, size of samples and grading of strength on compressive, splitting tensile and bending strengths of HSC. The HSC had C40, C60, and C70 grades. At 200, 400, 600 and 1000°C, the reduction in compressive strength was 17.7%, 36.8%, 41.9% and 72.7%, At the same temperature values, the splitting tensile strength was reduced by 14.3%, 18.2%, 48.1% and 83.6%, respectively, and bending strength was reduced by 15.5%, 56.3%, 83.7% and 92.6%, respectively. The study declared that increasing the size of specimens may result in reduced loss of compressive strength. Water content did not exhibit a noticeable effect on compressive strength above 800°C.

Behnood and Ghandehari [91] tested HSCs with and without polypropylene (PP) fibers up to 600°C and determined the compressive and splitting tensile strengths. Mixtures were prepared with water to cementitious materials ratios of 0.40, 0.35, and 0.30 containing SF at 0%, 6%, and 10% as cement replacement and polypropylene fibers content of 0, 1, 2, and 3 kg/m^3. The results showed that in spite of better performance at ambient temperature, the HSC contained higher contents of SF resulted in higher loss in strength of HSC. Aslani and Samali [92] developed constitutive relationships NSC and HSC strength PP fiber reinforcement concrete (FRC) exposed to fire. Relationships were developed for unconfined PPFRC specimens that include compressive and tensile strengths, elastic modulus, modulus of rupture, strain at peak stress as well as compressive stress–strain relationships at elevated temperatures. The proposed relationships at elevated temperature were compared with experimental results and good agreement was found.

Modern research uses realkalization of concrete. Realkalisation is a method used to stop and permanently prevent reinforcement corrosion in carbonated concrete structures by increasing their pH to a value greater than 10.5, which is sufficient to restore and maintain a passive oxide film on the steel. Realkalisation involves a technique, in which a current is passed through the concrete to the reinforcement by means of an externally applied anode attached temporarily to the concrete surface [93]. Recently, Xiong et al. [94] performed an experimental study on compressive strength recovery effect of fire damaged HSC after realkalisation treatment. The compressive strength of fire-damaged HSC before and after realkalisation was investigated. Findings revealed that the realkalisation treatment recovered the compressive strength and its effect extent depends upon exposure temperature, current density, treatment time and concentration of electrolyte. The comparison with ambient temperature results showed that the residual compressive strengths of tested specimens of cube compressive strength of 71.2 MPa exposed to temperature from 300°C to 700°C for two hours to three hours ranging from 80.3% to 39.7%. The recovered specimens had residual strengths of 89.6% to 61.4% after 7 days of treatment. Compared with obtained experimental results of fire-damaged tested specimens of cubic compressive strength of 50.2 MPa, the effect of recovered residual strengths was better for a lower compression strength of compression cube.

Nazari and Riahi [95] tested compressive, flexural, and split tensile strengths together with coefficient of water absorption of self-compacting HSC containing different amount of SiO2 nanoparticles. Strength and water permeability of the specimens were enhanced by adding SiO_2 nanoparticles in the cement paste up to 4.0 wt%. SiO_2 nanoparticles accelerated the C–S–H gel formation as a result of increased crystalline $Ca(OH)_2$ amount especially at the early age of hydration, and increasing the strength of the specimens and improving the compressive strength of concrete.

It can be said that a considerable strength loss in HSC occurs above 350°C to 400°C and it reaches up to 75% loss at 800°C [7]. Below 200°C, the strength losses are below 10%, however, these losses are greater as compared to NSC when exposed to fire [96]. The addition of steel fibers may reduce strength loss and increase ductility [79].

3.2. Effect of Temperature on Stress–Strain Relationship

The SSR of concrete under compression and subjected to elevated temperatures is determined by three different recognized types of tests. In the first type, initially no stress is generated and a load is applied until failure. This test is known as the 'un-stressed' test method. The stressed test method gives better results for the elevated temperature testing of compression members such as column. In the second method, a load equivalent to a fractional value of maximum compressive strength recorded at ambient temperature (normally ranging between 20% and 40% of the compressive strength) is applied and kept constant giving a rise in temperature until the temperature reaches the desired value. This is known as the 'stressed' test method. In the third method, only temperature is first applied.Then the specimens are cooled to ambient temperature and mechanical load is applied until specimen failure. This method is referred to as an 'unstressed residual' test method.

Since modern design approaches give significant importance to performance-based design of concrete structures, and temperature-dependent calculations are considered essential to fulfill the fire safety requirements, researchers have investigated the general stress–strain relationship (SSR) for various types of concretes. The effects of fire on compressive strength of concrete have been extensively discussed [24, 97–99]. Several studies are available on the stress–strain behavior of NSC at elevated temperatures and HSC at ambient temperature [60, 100–114].

Hertz [115] and Purkiss and Li [98] reported that a concrete preloaded with compressive stress may minimize fire influence on both the compressive strength and absolute strain. Initial compressive stress before heating also generated supplementary strains known as transient creep strains [116–118]. The rate of heating, mixture proportions, and amount of preloaded stress directly influence the values of transient creep strains. Youssef and Moftah [119] reviewed the general characteristics of SSR concrete under fire. They presented the available formulations for estimating the concrete compressive strength, concrete tensile strength, concrete compressive strain at peak stress, initial modulus of elasticity of concrete, transient creep strain, thermal strain, and yield stress and bond strength of reinforcing bars for unconfined and confined concrete. The relationships proposed by Youssef and Moftah [119] were compared to already existing ones and to available experimental data. The formulations were able to capture changes in the mechanical properties of concrete resulting from temperature and confinement and provided better results compared to the available ones [119]. Hsu et al. [79] investigated the SSR of steel-fiber HSC. The 3 × 6-in. cylinder specimens were tested in a uniaxial compression in a material testing system (MTS), consisting of a servo-controlled, closed-loop machine, with a maximum load capacity of I 00 kips. In order to derive a complete stress–strain curve, a slow strain rate of 1.67 × I 0-5 strain/s was employed. The axial deformations were measured by two clip-on gages which were mounted on the specimen. The experimental setup was capable of incorporating the entire SSR for steel-fiber HSC with or without tie confinements was employed. The volume fractions of steel fiber in the concrete were 0, 0.5, 0.75, and 1%. Theoretical formulas were presented for HSC with compressive strength exceeding 70 MPa.

Mansur et al. [120] also identified the SSR of fiber HSC using prismatic and cylindrical samples. The compressive strength of samples ranged between 70 MPa and 120 MPa. Emphasis was given to measuring the influence of proportion of fibers and casting direction corresponding to the axis of loading. Fibers enhanced both strength and strain at maximum stress level; however, the initial tangent modulus was reduced for the fibers embedded vertically. Prismatic samples showed a higher post-peak ductile behavior than cylindrical specimens. Chin et al.

[108] investigated the influence of the geometry and casting direction on the SSR of cylindrical and prismatic samples of HSC of up to 120 MPa strength. Findings indicated that the effect of specimen size vanishes below a certain size and that the effects of the shape and casting direction of specimens were significant, particularly when the slope of the stress–strain curve became lower. A mathematical model was proposed and the differences between the behavior of prismatic and cylindrical samples were tested. Prismatic specimens were found to be more ductile than cylinders. Candappa et al. [121] tested the axial-stress–axial-strain and axial-stress–lateral-strain behavior of HSC concrete under active lateral confinement. Axial strain at peak stress was shown to have a strong linear relationship with the level of confinement.

Despite the high volume of research on the SSR of NSC at elevated temperatures and HSC at ambient temperature, the SSR of HSC exposed to fire has not been comprehensively reported in the literature. Such a relationship is valuable to investigators keen to model the fire behavior of HSC.

Decades ago, researchers encountered problems understanding the behavior of the ingredients of HSC under fire [122]. The calculation of elastic strain in concrete was considered unable to include the differential strain generated due to the aggregate expansion and shrinkage of mortar. This problem was resolved by the 'transient creep' (TP) phenomenon. TP grows only during the first heating under mechanical loading and not develops during cooling. TP results in a strain quite higher than elastic strain supporting considerable relaxation and redistribution of thermal stresses in concrete under elevated temperatures [122]. The effect of transient heating on the stress–strain relationship of HSC was determined by Castillo [51]. The primary variables of this study were temperature, concrete compressive strength, and type of loading. The specimens were heated to 800°C. The specimens were tested under displacement control to allow monitoring of the descending branch of the curve. The influence of elevated temperatures on the elastic modulus of both the HSC and the NSC was very similar. In the temperature range of 100°C to 400°C, as capillary and adsorbed water was expelled and concrete became more compressible, the modulus of elasticity decreased slightly. At temperatures above 400°C, the enhanced dehydration loosens the bond between materials resulting to reduce the elastic modulus by 20% to 25% compared to control concrete in ambient temperature. Between 600°C and 700°C, temperature travel within the specimen was retarded due to absorption of heat by the endothermic reaction of calcination of the limestone and therefore, there was no significant change in the modulus of elasticity of concrete.

While testing the HSC columns in their studies, Kodur et al. [9, 48] pointed out the differences in the behavior of NSC and HSC when exposed to fire. The HSC columns showed less contraction and low deformation. This may be because HSC becomes brittle when subjected to fire and lower strain occurs at any stress point as compared to that which occurs in the case of NSC. Kodur et al. [123] also modeled the SSR of HSC columns subjected to fire. The fire performance of HSC columns was numerically calculated by modeling the calculation of the resulting deformations and strength, including analysis of stress and strain distribution.

Based on their experimental data, Phan and Carino [34] reported that for unstressed tests, there were no significant differences in the modulus of elasticity-temperature relationships for HSC contained NWA and LWA. For the unstressed residual-strength tests, the difference in elastic modulus between NWA-HSC and LWA-NSC was also less than 10%. However, the data used from Hertz [71] for LWA-HSC revealed significantly different profiles of the modulus-temperature relationship versus that of NWA-HSC.

Gawin et al. [124] modeled the deformation behavior of HSC subjected to fire. In their constitutive model the free thermal strains, which are the concrete strains during first heating, were decomposed with three main contributions: thermal dilatation strains, shrinkage strains, and thermo-chemical strains of the concrete. Thermodynamic relationships via capillary pressure and area fraction coefficients were used to evaluate shrinkage strains, whereas thermo-chemical strains were related to thermo-chemical damage. Pore pressure and thermal strains are the key parameters responsible for the spalling of HSC, as also indicated by Kodur [125].

Cheng et al. [7] examined the influence of high temperatures on the compressive strength and SSR of HSC. The temperatures used for testing were 20, 100, 200, 400, 600, and 800°C for four types of HSC. The strength of specimens was between 75 MPa and 84 MPa. The parameters used for experiments were strength of concrete, aggregate characteristics and involvement of steel reinforcement. Findings revealed that up to 600°C, plain HSC behaves in a brittle manner while it shows a ductile behavior above 600°C. Reinforced HSC showed ductile behavior above 400°C. The fire caused a one-fourth room temperature compressive strength degradation when HSC was exposed to the temperatures between 100°C and 400°C. The rise in temperature continuously reduced the compressive strength and 75% loss was observed in the original compressive strength at 800°C. The strain at peak stress increased with temperature, from 0.003 at room temperature to 0.02 at 800°C. Siliceous aggregate HSC showed higher rate of increase for strains as compared to carbonate aggregate HSC.

Aslani and Bastami [126] developed constitutive relationships for NSC and HSC exposed to fire to offer effective modeling and stipulated fire-performance criteria for NSC and HSC. The relationships took into account compressive and tensile strengths, SSR and elastic modulus at high temperatures. To model the SSR of HSC in tension, a linear branch until reaching cracking stress was suggested. Thereafter, a tension softening model was introduced which was capable of the incorporation the tensile strength degradation. The proposed tensile SSR showed a satisfactory agreement with existing test data on HSC under fire.

4. Comparison of Design Approaches and Studies

Despite the availability of proper guidelines for the preparation and behavior of NSC in the design standards, rare design approaches are available on the behavior of HSC especially when subjected to fire. There is a lack of information in recent standards on the alteration in material properties of HSC under fire conditions [8, 127–130].

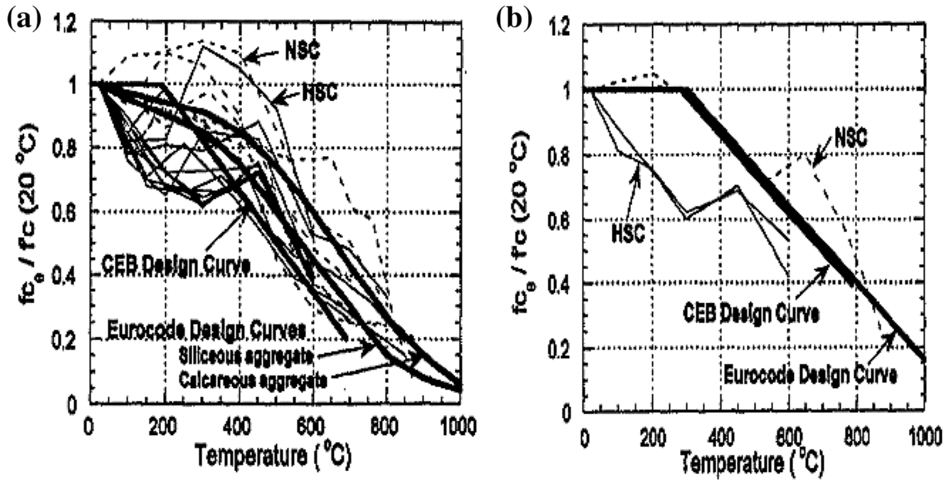

Figure 2. Comparison of recommended design curves for compressive strength of: (a) NWA concretes; (b) LWA concretes and results of unstressed tests [34].

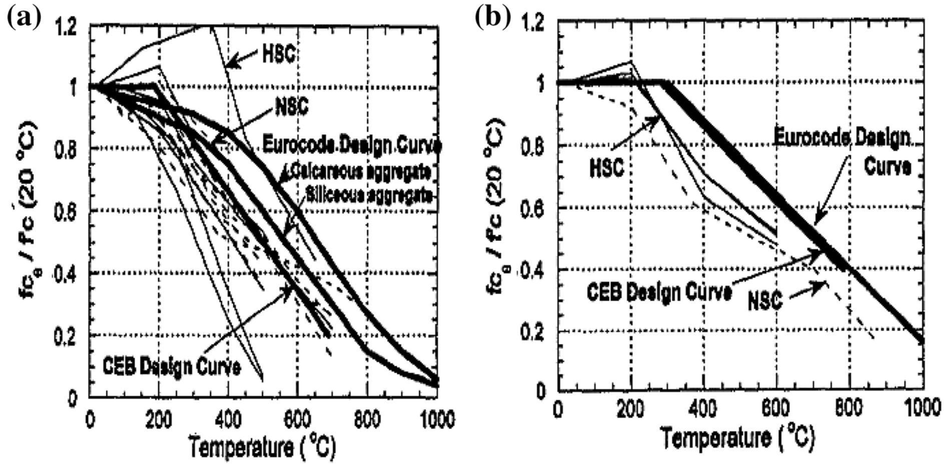

Figure 3. Comparison of recommended design curves for compressive strength of: (a) NWA concrete; (b) LWA concrete and results of unstressed residual-strength tests [34].

Phan and Carino [34] performed experimental testing on HSC exposed to fire using stressed, unstressed, and unstressed residual test methods. Two types of aggregate, LWA and NWA, were used to produce HSC. They compared their results with Eurocode [131] and CEB [132] for evaluating the compressive strength

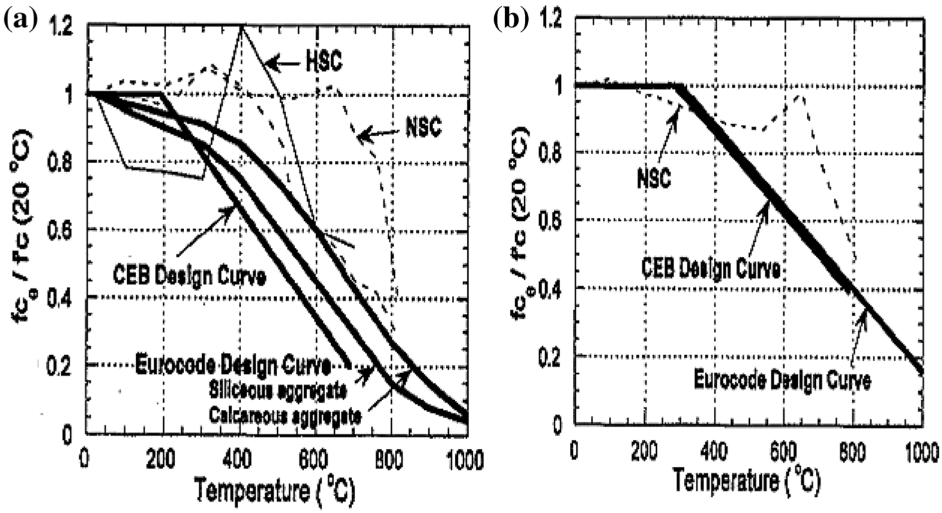

Figure 4. Comparison of recommended design curves for compressive strength of: (a) NWA concretes; (b) LWA concretes and results of stressed tests [34].

and modulus of elasticity. The comparatives curves for compressive strength are presented in Figs. 2, 3 and 4. They declared that the current design recommendations for compressive strength and modulus of elasticity of fire-exposed concretes are more relevant to NSC than HSC. The Eurocode and CEB design curves were found to have questionable application to HSC.

As can be seen in Figs. 2, 3 and 4, the design curves recommended with Eurocode and CEM to predict compressive strength of normal weight and lightweight HSC give conservative and conservative prediction in different testing conditions which is strongly depend on temperature. For example, in unstressed condition (Fig. 2), both of these codes had unconservative prediction for normal weight HSC (Fig. 2a) in the temperature ranging between room temperature and a temperature up to 200°C. While, for lightweight HSC (Fig. 2b), predictions are conservative for all high temperature levels (available data is up to 600°C).

Figure 2 shows that the standard design curves can have acceptable prediction for normal weight HSC but not for lightweight HSC. However, for normal weight NSC, predictions are acceptable and conservative up to 800°C. While, for lightweight NSC, the predicted results are conservative just in high temperatures ranging from 600°C to 800°C.

Under stressed residual-strength test condition (Fig. 3), generally, these cods could have conservation prediction for normal weight HSC for for a high temperature up to 400°C. While, for normal weight NSC and lightweight NSC and HSC, predictions are unconservative.

It can be seen in Fig. 4 that under stressed tests condition, HSC shows different behaviour in different temperatures. Based on the test results, HSC showed significantly lower compressive strength under a temperature up to 300°C compared to the predicted compressive strength of the CEB and Eurocode. While, it is clear that both of these codes could have conservative estimation for normal weight NSC up to a high temperature of 800°C.

In another study by Phan and Carino [8], a comparison of existing test data available from their previous experimental studies and their own was compared with the existing design specifications. In total, five different recent standards: Eurocode 2, [13], Eurocode 4 [131] ACI 216 R [133], CEB [132], and RakMK B4 [87] were compared. It was declared that Eurocode 2, Eurocode 4 and CEB codes make no distinction between HSC and NSC in their fire design provisions. Therefore, the applicability still needs to be validated. Further, though the ACI 216 R provides strength test data obtained by Abrams but did not prescribe a strength-temperature relationship for concrete. Recommendations were given to improve the design standards. In 1998, the Technical Activities Committee and its subcommittee on high-performance concrete developed and approved an official ACI definition. Henry [5] presented a commentary of that definition. However, the document was also lacking the information about any fire resistance approach of HSC.

Husem [30] compared the results of experiments performed on NSC and HSC exposed to fire with Eurocode, CEB, and Finnish code. The CEN Eurocode and the CEB's design curves for properties of fire-exposed concrete were found not applicable to HSC. The Finnish Code was more suitable for HSC especially until 400°C temperature. The comparative curve achieved by Husem [30] is presented in Fig. 5.

5. Spalling of HSC Under Fire

The literature shows that spalling is the dominant failure mode of HSC when exposed to fire. This fact is vital in understanding the phenomena of spalling of concrete subjected to fire. Spalling is simply referred to as the crumbling of concrete surfaces when exposed to rapid fires, for instance with a rate of 20°C/min to 30°C/min. There are four major types of spalling: (a) aggregate spalling; (b) explosive spalling; (c) surface spalling; and (d) corner/sloughing-off spalling [122]. Explosive spalling is an intense form of spalling. Surface spalling is considered as a sub-class of explosive spalling [122]. Regarding the time period, there are three stages of spalling; (a) early spalling; (b) intermediate spalling; and (c) late spalling [36]. Except the last one, all three types of spalling occur within 30 min to 45 min of exposure to standard fire [36].

A number of factors govern the reasons of concrete spalling. These include permeability, saturation level, aggregate size and type, presence of cracking and reinforcement, section shape and size, heating rate and profile and loading. The mechanisms proposed to explain the explosive spalling of concrete fall under three categories including; pore pressure spalling, thermal stress spalling and combined pore pressure and thermal stress spalling [122]. The spalling of a HSC beam

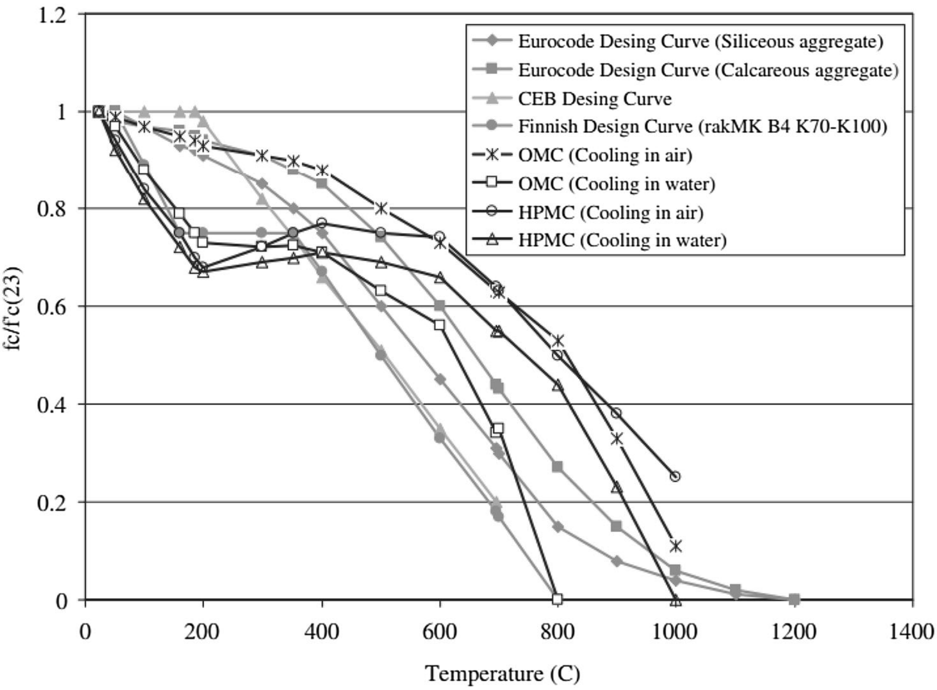

Figure 5. Comparison of design curves and experimental loss of strength curves [30].

Figure 6. Spalling of HSC beam exposed to long fire [36].

exposed to Long duration furnace fire by Dwaikat and Kodur [36] is presented in Fig. 6.

6. Conclusion and Future Recommendations

HSC is a rapidly increasing and popular application in structural engineering. The fire behavior of HSC is not yet fully understood. Several differences in studies exist regarding the behavioral comparison of NSC and HSC, the critical temperature range of compressive strength loss, and the consequences of admixtures used for the production of HSC. This study has presented a review of studies performed into the behavior of HSC at elevated temperatures. The effect of fire on the performance of HSC were also evaluated.

Comparing the fire behavior of NSC and HSC presented in the literature, it was found that the failure behavior of NSC and HSC at elevated temperatures differ. The major failure mode of HSC when exposed to fire is explosive spalling. In plain HSC, spalling may be minimized by using recycled particles of crumbed used truck tires, whereas use of fiber reinforced polymers could minimize the spalling if used as reinforcement in HSC. The use of a suitable amount of SF also found to be beneficial to minimize the effect of explosive spalling. Differences were found between the strength loss behavior of NSC and HSC exposed to fire. HSC loses compressive strength at a higher rate as compared to NSC above 400°C. However, the residual strength of HSC is better than NSC after exposure to fire. Also, the strength recovery stage of HSC occurs at higher temperatures than NSC. The resulting expansion in concrete may lead to a rapid loss of compressive strength. The design recommendations provided in the codes of practice for the fire design of NSC were found to be ill-suited to the fire design of HSC.

A significant degradation was revealed in the strength of HSC occurs at 350°C and above. Below this range, strength loss is not significant. At about 800°C, HSC loose almost half of its original strength. A comparison of NSC and HSC above 350°C showed a higher strength loss in HSC. Above 800°C, the effect of water content on compressive strength of HSC is negligible. A temperature of 350°C marks the beginning of higher rate of decrease in modulus of elasticity for HSC. The behavior of HSC becomes brittle after 600°C. HSC exhibits a more considerable reduction in permeability-related durability than compressive strength after 600°C.

A review of the studies discussing the effects of replacing the conventional ingredients with waste materials used in HSC exposed to fire revealed that good performance at elevated temperatures was shown by the HSCs containing 30% fly ash and 15% to 30% of slags as a cement replacement.

The literature review showed that the elastic modulus of HSC exposed to fire may not improved much with the use of steel fibers, but may be more influenced by the selection of aggregate type due to their noticeable impact on the ultimate strain.

The effect of specimen size is also influential on the overall performance of HSC under fire. It was found that enlarging the size of specimen may result in comparatively lesser rate of strength loss. Prismatic specimens provide a higher post-peak ductile behavior than cylindrical specimens. Moreover, the aggregate characteristics, porosity, loading, distance between ties influence the performance of HSC.

A review of existing literature showed that there are several aspects of fire behavior of HSC which need further investigations. A few of them are more important and the authors recommend that the future research should focus on those few aspects of fire behavior of HSC. For example, spalling was shown as the most influencing factor hampering the accuracy of fire safety design approaches of HSC structures. It is therefore important to: (a) better understand the fundamental mechanisms responsible for explosive spalling of concrete; (b) develop a realistic predictive model; and (c) optimise (in terms of cost and effectiveness) the methods for eliminating explosive spalling in practice. However, the methods should be different for existing and new HSC.

A very few number of studies are available on the use of waste materials as aggregates in the HSC exposed to fire. The waste materials may show a good performance regarding the rate of strength loss. Local recycled waste materials available can be used and tested to obtain a better performing HSC.

Most studies have shown unsatisfactory agreement between their test results and the provisions provided in the test standards. There is a need to quantify the applicability of standards' recommendations for HSC exposed to fire. Modifications should be incorporated if possible.

The data available into the behavior of HSC exposed to fire is insufficient in light of the number of parameters which should be investigated. There are several factors such as concrete strength, aggregate types, test conditions, specimen size, concrete density, concrete permeability, concrete porosity, heating rate and loading rates among others. These factors should be considered in terms of both the behavior and design of HSC subjected to elevated temperatures. In addition, available test methods should be adopted simultaneously to discuss all possible parameters in one study.Publisher's NoteSpringer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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