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***Review Article***

# AN OVERVIEW OF HIGH PERFORMANCE CONCRETE AT ELEVATED TEMPERATURES

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## ABSTRACT

High Performance Concrete (HPC) has been used more widely in recent years for the construction of important concrete structures and high rise buildings. Fire accidents, sabotages or natural hazards are the situations where HPC is likely to get exposed to elevated temperatures. As a consequence, it undergoes change in its chemical composition, physical structures and there is deterioration in its mechanical properties. This paper presents an overview of the HPC performance when exposed to elevated temperatures as regards to use of concrete mix materials, fire characteristics, and available mathematical models for the performance assessment.

***Key Words:*** *High Performance Concrete, Elevated Temperature, Physical and Mechanical Properties, Assessment Models.*

## INTRODUCTION

Reinforced concrete is the most commonly used construction material worldwide. High performance concrete (HPC) is a novel construction material with improved properties like higher strength, longer durability, and higher workability etc. than conventional concretes (Aitcin 1998). The need for high compressive strength concrete and increased service life of reinforced concrete structures, has led to the development of HPC in the past decades.

Fire poses as one of the most severe risks to buildings and structures (Lau and Anson 2006). With development in materials and application of HPC, understanding of its behavior when subjected to fire is needed to guarantee its safe application. HPC exhibits inferior thermal behavior with its dense and complex microstructure, which yet has been not been fully understood. This is a threat to HPCs application in many types of engineering structures such as high rise buildings, bridges, tunnels, offshore platforms, nuclear reactor, power industries, other forms of infrastructures etc. and risk to the human society (Chan *et al.* 1999, Peng *et al.* 2006). As HPC is exposed to elevated temperatures in an accidental building fire, sabotages, or a natural hazard, its mechanical properties such as concrete strength and modulus of elasticity may decrease with increasing temperature remarkably, crack developments result in undesirable fractures and explosive spalling seems to increase with decreased permeability, increased moisture content compared with conventional concrete when exposed to same heating condition (Husem 2006, Phan and Carino 1998).

The behaviour of HPC in fire depends on factors like the type of aggregate, pozzolonic material, fiber used in its composition, the temperature and duration of the fire, type of cooling, sizes of structural members, and presence of moisture in concrete. The HPC behavior at elevated temperature plays a vital role in design of concrete structures for fire resistance and to ensure the serviceability at elevated temperatures. This paper presents an overview of the performance of HPC when exposed to elevated temperatures in the context of use of concrete mix materials, fire characteristics, and available mathematical models for performance prediction.

### *Physical Properties of Hpc at Elevated Temperature*

Although concrete is generally believed to be an excellent fireproofing material, many recent studies have shown extensive damage or even catastrophic failure at high temperatures, particularly in high strength concrete (HSC). The dominant process for unsealed concrete relates to the loss of the various forms of water (free, adsorbed and chemically bound), while the dominant process in sealed concrete relates to hydrothermal chemical reactions which could result in much weaker or stronger gel, depending upon the CaO/SiO$_2$ ratio (C/S ratio). The C/S ratio is influenced by the use of cement replacements such as slag, pulverized fly ash (PFA), or silica fume in the mix (Khoury 2000).

The slight increase in concrete strength associated with a further increase in temperature (between 100-200$^0$C) is attributed to the general stiffening of the cement gel, or the increase in surface forces between gel particles, due to the removal of absorbed moisture (Cheng et al. 2004). At 400$^0$C gel-like hydration products are decomposed. At 600$^0$C, Ca(OH)$_2$ is dehydroxylated and CaCO$_3$ dissociation to CaO and CO$_2$ accompanied with the re-crystallisation of non-binding phases from hydrated cement under re-combustion are dominant processes between 600$^0$C and 800$^0$C. This stage of concrete is characterized by the collapse of its structural integrity, and loss in compressive strength.

***Colour Change:*** As temperature increases colour of concrete changes, at 300$^0$C the concrete colour doesn't change noticeably. When temperatures are increased up to 400$^0$C – 600$^0$C concrete colour slightly changes to dust colour or brownish/ yellowish grey. Beyond 600$^0$C, concrete colour observed is straw yellow to pinkish yellow/pinkish red (Xiao and Falkner 2006). Certain colours correspond with specific temperature ranges, this is an important indicator of the maximum temperature, and the structure is exposed to.

***Spalling:*** Spalling is a damage where concrete surface scales and falls off from the concrete along with explosion at high temperature. High strength concrete appears to be more prone to spalling in a fire than normal strength concrete (Sanjayan and Stocks 1993). For high performance concrete the spalling will start when temperature is reached to 600$^0$C (Lau and Anson 2006, Sideris *et al*. 2009). This has two effects: a physical effect due to reduced Van der Waals' forces as water expands upon heating, and a chemical effect whereby detrimental transformations can take place under hydrothermal conditions. Spalling can be grouped into four categories:

(i) Aggregate spalling (ii) Explosive spalling
(iii) Surface spalling (iv) Corner/sloughing-off spalling

The first three occur during the first 20–30 minutes of a fire and are influenced by the heating rate, while the fourth occurs after 30–60 minutes of fire and is influenced by the maximum temperature (Khoury 2000). Explosive spalling is a particularly dangerous type of failure and may affect the integrity and stability of a concrete structure.

**Table 1 Characteristics of the different forms of spalling (Khoury 2000)**

| Spalling | Time of occurrence (minutes) | Nature | Sound | Influence | Main Influences |
|---|---|---|---|---|---|
| Aggregate | 7-30 | Splitting | Popping | Superficial | H, A, S, D, W |
| Corner | 30-90 | Non-violent | None | Can be serious | T, A, Ft, R |
| Surface | 7-30 | Violent | Cracking | Can be serious | H, W, P, Ft |
| Explosive | 7-30 | Violent | Loud bang | serious | H, A, S, Fs, G, L, O, P, Q, R, S, W, Z |

A- aggregate thermal expansion, D- aggregate thermal diffusivity, Fs-shear strength of concrete, Ft-tensile strength of concrete, G- age of concrete, H- heating rate, L- loading/restraint, O-heating profile, P-permeability, Q- section shape, R- reinforcement, S- aggregate size, T- maximum temperature, W-moisture content, Z- section size.

The internal vapour pressure may be the leading reason of concrete spalling (Chan *et al.* 2000, Peng *et al.* 2008, Dong *et al.* 2008). This is mainly attributed to the dense, low permeability structure of the paste which does not readily allow moisture to escape from the heated concrete, thus resulting in high pore pressures and the development of microcracks (Sanjayan and Stocks 1993). Many material (e.g. aggregate size and type, permeability, saturation level, presence of pozzolonic material, fibers used presence of cracking and reinforcement), geometric (e.g. section shape and size) and environmental (e.g. heating rate, heating profile, load level) factors have been identified from experiments as influencing spalling of concrete in fire (Lau and Anson 2006, Phan and Carino 1998, Khoury 2000, Kalifa *et al.* 2001). The risk of explosion seems to increase with decreased permeability and tensile strength, increased moisture content and heating rate (Lau and Anson 2006, Chan *et al.* 1999, Phan and Carino 1998).

The potential spalling increased in HPC with lower w/c and silica fume (Phan *et al.* 2001). The addition of silica fume gives highly densified pore structure for concrete, which can result in explosive spalling owing to the build-up of pore pressure by steam, and thus the rates of strength loss are significantly higher in silica fume concrete than Ordinary Portland Cement (OPC) concrete when exposed to high temperature. Significant spalling cannot be observed if the concrete is not densified by particles smaller than the cement grains such as micro silica and if the moisture content is less than 3% by weight (Sideries *et al.* 2009). Figure 1 shows the explosive spalling of HPC when heated to 700$^0$C.

Spalling tendency of HPC under fire conditions is a reason for inhibiting its use in buildings, bridges and tunneling, as several safety considerations are raised (Sideries *et al.* 2009). Maximum cover to reinforcement is recommended to reduce the potential for spalling, but a minimum thickness is required for thermal insulation. Therefore, the actual thickness should be between these two limits (Khoury 2000).

**Figure 1 Explosive spalling of HPC when heated to 700 $^0$C (Sideries *et al.* 2009)**

***Crack Behavior:*** The concrete cracking observation revels that the consequence of rapid heating are quite different from those of slow heating. For slow heating at a rate of 0.5$^0$C / min, HPC suffered no obvious cracking below 600$^0$C even if it had high moisture content. Rapid heating such as firing could cause considerable internal cracking. Microcracks cause attributed to the development of difference in thermal expansion coefficients between components and by calcium hydroxide decomposition, such cracks are more observed in high strength concrete (Noumowe *et al.* 1996).

***Permeability:*** For HPC permeability is very low at ambient temperature. Permeability of concretes increases drastically with the increase in the temperature. The increase in permeability is directly related to the maximum temperature reached. Poon *et al.* (2001, 2003), Noumowe *et al.* (2009), reported loss of impermeability (2000–10,700 %) and it may be due to the internal cracking and pore structure coarsening of the concrete at high temperatures. Janotka and Bagel (2003), presented permeability coefficient on the basis of the measured pore sizes which is suitable for evaluation of concrete quality when exposed to temperature.

***Porosity and compressive strength:*** More pore volume is observed for HPC than ordinary concrete, which is an important factor deemed to be responsible for the more severe strength deterioration. The porosity of the concrete varies with saturation level and with maximum temperature of exposure. As the type of cooling varies the porosity of HPC observed a significant change (Luo *et al.* 2000 a). The porosity of concrete can be positively correlated with residual strength of concrete (Lau and Anson 2006, Luo *et al.* 2000 b). Luo *et al.* (2000 a), developed model by optimizing and considering the effect of cooling regime the parameters in the Ryshkewitch model for HPC at elevated temperature. Figure 2 showing the relationship model for porosity and the strength of concrete. Author's data is for Normal Strength Concrete (NSC) based on the experiments, which lies in between the old models.

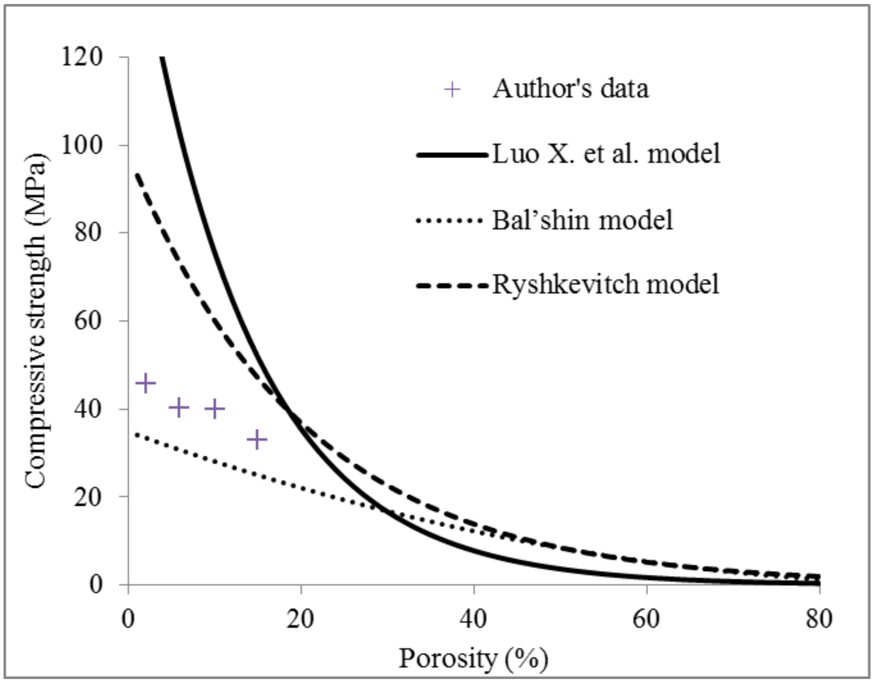

**Figure 2 Relation between compressive strength and porosity (Luo *et al.* 2000 a).**

## MATERIAL USED

### *Type of aggregate*

Type of aggregate has significant influence on thermal properties of high strength concrete. Concrete made by gravel aggregate degrades faster than concrete made by basalt aggregate as reported by Nilsen and Bieanic (2003). The HPC with siliceous aggregate has lower residual compressive strength behaviour than the HPC made by silico-calcareous as well as calcareous aggregate. The linear thermal expansion coefficient for siliceous aggregate seems to dilate a little more than calcareous aggregate (Robert and Colina 2009). This is due to calcine-carbon dioxide driven off from the calcareous aggregate and calcium oxide remains during the fire exposure. Since calcining required heat, this reaction absorbs some of the fire heat. Thus reaction begins the fire exposed surface and slowly progress towards the opposite face. Extent of spalling is found to be much greater when lightweight aggregate is used. This is mainly because the lightweight aggregate contains more free moisture, which creates higher vapour pressure under fire exposures (Kodur and Phan 2007). The presence of carbonate aggregate in HSC increases fire resistance (Kodur and Sultan 2003).

***Pozzolonic material***

The addition of pozzolanic or supplementary cementing materials as partial replacements is one effective method of preparing high-performance concrete (HPC). High performance concrete is typically a concrete prepared with pozzolanic admixtures, such as silica fume, fly ash, slag, etc. and a low water to binder ratio. Addition of silica fume and fly ash resulted to the formation of denser microstructure and shifted the threshold temperature to lower values (Sideries *et al.* 2009).

***Silica fume (SF):*** Sarshar, and Khoury, (1993), have found that the residual strength of the concrete containing SF appeared to be worse than the concrete made with OPC. The fire behavior of HPC with silica fume at various moisture content, shows that the moisture content has dominant influence on spalling (Chan, et al. 1999, Sanjayan, and Stocks 1993, Phan, et al. 2001, Hertz, 1992). Use of more than 5% to 10% silica fume in concrete creates high risk of explosive spalling (Poon, et al. 2003, Sarshar, and Khoury, 1993).

***Fly ash (FA):*** HSC containing FA shows better performance in residual mechanical and fracture properties for higher temperatures over the concrete with OPC (Teng and Lo 2008). Increase in strength is observed up to $200^0$C for concrete containing FA is due to the formation of tobermorite (a product of lime and Pulverized Fly Ash (PFA) at high pressure and temperature), which is reported to be two to three times stronger than the Calcium-Silicate-Hydrate (CSH) gel (Poon *et al.* 2003). Relative residual compressive strength is 88% at $450^0$C and 73% at $600^0$C for 30 % PFA, which is almost, double than the residual strength shown by pure OPC pastes as observed by Sarshar and Khoury (1993). Cement replacement by 30 % of fly ash in HSC found to be optimal to retain maximum strength and durability after high temperatures.

***Ground granulated blast furnace slag (GGBFS):*** The GGBS concrete showed the best performance followed by Pulverised Fly Ash (PFA) and Condensed silica fume concretes as reported by Hosam, et al. (2011). Up to $600^0$C PFA and GGBS shows better performance due to the reduced amount of $Ca(OH)_2$. GGBS is beneficial to retain residual compressive and flexural strengths of HPCs with and without polypropylene fibres after fire exposure, compared to silica fume (Xiao, and Falkner, 2006). Cement replacement by 40% of blast furnace slag in HSC is found to be optimal to retain maximum strength and durability after high temperatures (Poon, et al. 2003). Xiao, and Falkner, (2006), found that the relative residual cube compressive strength of HPC-blast furnace slag is close to the referenced normal strength concrete by Comites Euro-International Du Beton.

***Metakaolin (MK):*** Poon *et al*. (2004), have studied the Compressive behavior of fiber reinforced high-performance concrete with and without MK and SF subjected to elevated temperatures. The spalling frequency increases with the higher MK content, because of its dense pore-structure seems to be the reason for such spalling. The MK concrete with 5% cement replacement shows better performance against elevated temperatures (Noumowe *et al.* 2009).

***Use of Fibers and confinements***

***Steel and Polypropylene fibers:*** The use of fiber in HPC exhibits different behavior when subjected to elevated temperature. The inclusion of steel fibers in concrete cannot reduce the risk of spalling, but they can affect the spread of cracking, and potentially improve the performance of concrete, after exposure to high temperatures. The HPC with high steel fibers content is most likely to explode (Lau and Anson 2006, Sideris *et al*. 2009, Kodur and Sultan 2003, Hertz 1992). Steel-fiber-reinforced concrete also showed the highest energy absorption capacity after the high-temperature exposure, although they suffered a quick loss of this capacity after exposure to $800^0$C (Poon *et al.* 2004). 1% steel fiber in concrete has shown improvement in fire resistance and crack. Inclusion of steel fiber in the concrete mix leads to an improvement in mechanical properties and a better resistance to heating effects.

Polypropylene (PP) fibers are very useful in preventing HPC from spalling. PP fibers melt and vaporize due to their lower melting point (about 165$^0$C), which results in many micro-channels in HPC, which maybe the reason for no explosive spalling in HPC with PP fibers (Sideris *et al*. 2009, Dong *et al*. 2008, Poon *et al*. 2004, Kodur *et al*. 2003, Phan 2008, Kalifa *et al*. 2001). However they have negative effect on concrete's residual mechanical properties, since they significantly decreased the residual mechanical properties of concrete and increased residual peak strain (Sideris *et al*. 2009). The presence of PP fibers is more effective for compressive strength than splitting tensile strength above 200 $^0$C (Behnood and Ghandehari 2009). High performance concrete containing 0.2% polyprolene fiber by volume or 2% by mass shows good resistance against spalling (Poon *et al*. 2001).

The use of polypropylene fibers can control the spalling of concrete while the steel fibers provide high ductility for the concrete post-cracking behaviour (Rodrigues *et al*. 2010). Incorporating hybrid fiber seems to be a promising way to enhance resistance of concrete to explosive spalling and improvement in mechanical properties, which may provide necessary safe guarantee for the rescue work and structure repair after fire disaster (Peng et al. 2006, Dong et al. 2008, Poon et al. 2004).

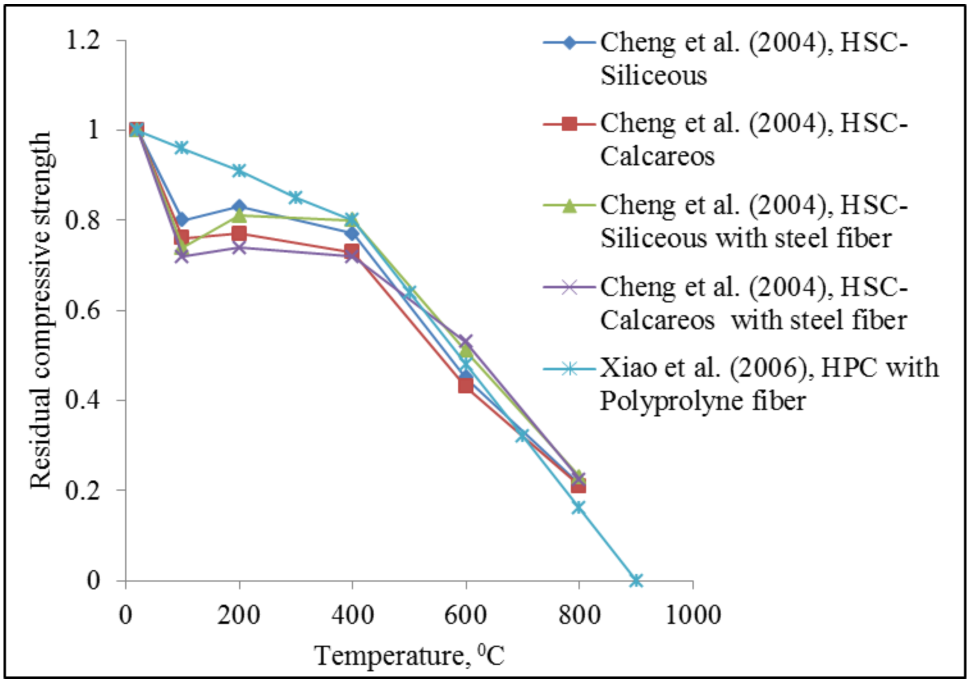

**Figure 3: Residual compressive strength of HSC as a function of temperature**

From fig 3., the HSC without steel fiber has a slightly higher compressive strength below 400°C for both aggregate types. However, the ductility of HSC with steel fibers increases at temperatures above 400°C (Cheng *et al*. 2004). Steel fiber reinforced HPC mixture with silica fume and fly ash decreased loss of compressive strength, splitting tensile strength and modulus of elasticity at low temperatures (Sideris *et al*. 2009). Xiao and Falkner (2006), proposed a simplified model for HPC with PP fibers at elevated temperatures as shown in fig. 3. The strength decrease is found to be continuous up to 400$^0$C and then the similar trend is followed as HPC with steel fiber.

***Confinement used:*** Combined usage of PP fiber and metal fabric in reinforced concrete column exhibited favorable spalling protection, showed effective residual compressive strength and a ductile behavior (Hana *et al*. 2009). HPC is resistance against spalling with incorporating PP fibers and fabric or lateral confinement with sheet material when subjected to fire (Hana *et al*. 2009). Specimen containing metal fabric is good in spalling resistance; it is due to lateral confinement pressure which is higher than internal vapour pressure. Glass or carbon fabrics do not show similar kind of performance, because of its bonding effect (Hana *et al.* 2005). Confinement has the effect of stitching the cracks caused by the thermal gradients in the material during heating and makes stronger concrete specimens at all temperatures provided that the steel ties remain integral. Confinement also has the effect of increasing the ductility of the concrete specimens. Terro and Hamoush (1997), observed an improvement in the compressive strength of around 20 to 30% for confined concrete specimens especially at temperatures above $400^0$C.

From the available research it is suggested that combination of Steel and polyprolene fiber prevent the spalling of concrete. It is possible to use PP fiber and Metal Fabric as lateral confinement measures to control the spalling of HPC when subject to fire.

### *Temperature Build-Up And Cooling Regimes*

***Rate of heating:*** The explosion of concrete is for a very slow heating rate of only $1^0$C/min, whereas heating rate of 10-20 $^0$C/min is normal for fire-exposed concrete surface as observed by Hertz (1992). Similar kind of observation made by Yan *et al*. (2007), when heating rate is as per standard fire exposure test (BS 476 curve). Higher thermal gradient caused by high heating rate might cause micro cracks to develop early, thereby allowing pore pressure to escape and resulting in lower maximum pore pressure (Phan 2008, Belkacem *et al.* 2008). HPC specimens are prone to explosive spalling even when heated with relatively slow heating rate, ($\leq 5^0$C/min) as compared with ordinary concrete. This is due to the fact that HPC contains fewer pores so the thermal conductivity is more (Husem 2006).

***Type of cooling:*** The various ways of cooling the structure affects the mechanical strength of HPC. The effect of cooling regimes on mechanical properties of concrete is of great concern. Thermal shock produced by water cooling or quenching produces a more deterioration in strength than in the case of furnace cooling (Husem 2006, Chan *et al.* 2000, Luo *et al.* 2000 a). Quenching of concrete specimens could cause internal cracks, due to stresses that developed when temperature difference between the core and the surface of a specimen (Chan *et al.* 2000, Luo *et al.* 2000 a, Lin and Lin 1996). Cracking in concrete originated from the pores inside concrete (Chan *et al.* 1999). Water spraying for duration of 30 min or more is in consistency with quenching in water which has a same effect as a water curing (Peng *et al.* 2008).

Fire resistance of the aggregate is generally high. However, having a non-uniform high temperature effect of aggregate or cooling the heated aggregate using water spray causes the internal pressure in the aggregates. Under thermal shock hybrid fiber (steel fiber and polypropylene fiber) can enhance residual strength and fracture energy of concrete subjected to high temperatures up to $800^0$C (Peng *et al.* 2008). High strength concrete containing fly ash shows better performance under quick cooling regimes (Teng and Lo 2008).

The Finnish Code is more suitable than the other codes for high-performance concrete (except cooled in water) until $400^0$C (fig. 4). CEB and the Finnish code are more suitable than Euro code for ordinary and HPC between 400 and $600^0$C. After $600^0$C, Euro code design curves are the most suitable ones except for ordinary concrete cooled in water (Husem 2006).

### *Performance of Structural Elements Subjected To Elevated Temperatures*

Failure of a structural member could occur from loss of bending or tensile strength, loss of bond strength, loss of shear or torsional strength, loss of compressive strength and spalling of the concrete. The fire resistance of a structural member is dependent on the geometry, the materials used in construction, the load intensity and the characteristics of the fire exposure itself. While there is a limited fire test data of concrete and data on fire-exposed HPC structural elements are scarce. High strength concrete members at high temperatures are significantly different from that of Normal Strength Concrete (Kodur and Phan 2007). Concrete strength, detailing of ties, type of aggregate, and materials incorporated influence the fire performance of HSC columns. The fire endurance of HSC columns with higher silica fume content is

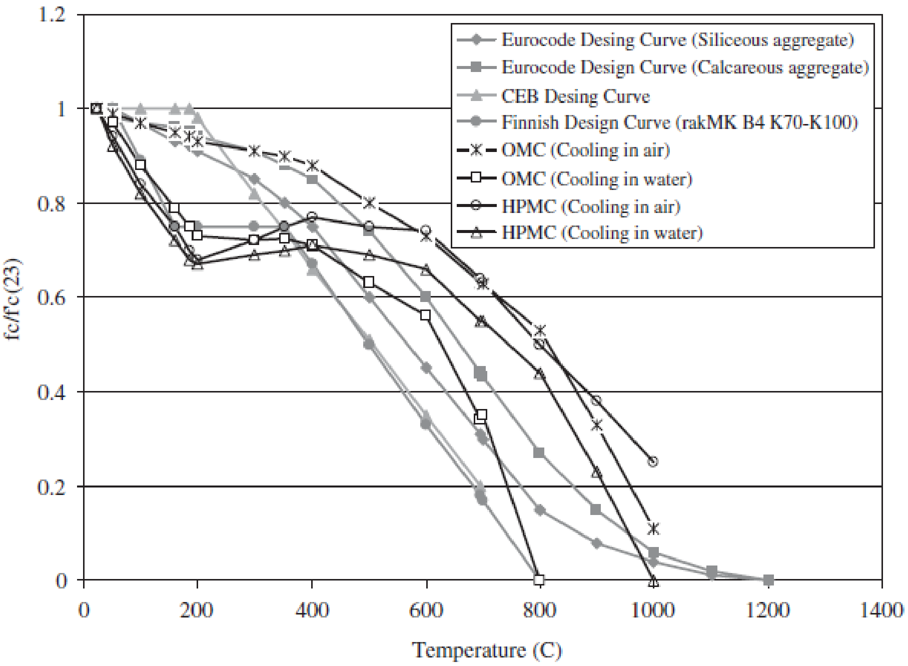

**Figure 4 Comparison of design curves and experimental loss of strength curves (Husem 2006)**

lower than that of HSC columns with lower levels of silica fume. The reduced tie spacing and the provision of cross-ties is beneficial in minimizing the spalling in HSC (Kodur and McGrath 2006). The presence of steel fibers increases the ultimate strain and improves the ductility of a fiber-reinforced concrete member (Kodur *et al.* 2003). Kodur *et al.* (2004), carried out a full scale fire resistance test on HPC columns and developed a computer program which gives the time to reach failure of column depending on any significant parameters such as load, section dimension, column length, concrete strength, aggregate type, fiber reinforcement.

### *Mathematical Models For The Assessment Of Hsc Performance At Elevated Temperatures*

Based on test experimental results researchers have proposed various mathematical models by considering the effect of type of aggregate, use of fiber, type of cooling, type of test (Stressed, Unstressed, Unstressed residual) and concrete strength. So with the consideration of the entire respective model it is suitable to assess the residual strength of High performance concrete.

Figure 5 presents the concrete compressive strength loss model as proposed by American Society of Civil Engineers (ASCE) for Normal strength concrete which has not differentiated test type and aggregate type. Eurocode model and Comite Euro-International du Beton (CEB) models considered the type of aggregate but not the type of test. ACI 216.1 model considered the effect of test type and type of aggregate. All these models are un-conservative for estimating mechanical properties of HSC at elevated temperatures and do not specify a strength limit for their prescribed compressive strength-temperature curves. The Finnish Code (RakMK B4) which prescribes a design curve specifically for HSC. Yaragal *et al.* (2010), carried out experiments with considering the wide range of concrete strengths and proposed a model for unstressed residual test type and siliceous type of aggregate. This model estimating less than 3% error in the relative strength of concrete at elevated temperatures.

Figure 6 showing the comparison of design curve for the NSC and HSC behavior at elevated temperature. Proposed model by Kodur *et al.* 2004, do not differentiate the test type and aggregate type. The behavior of HSC is different than the NSC. Yaragal *et al.* (2010), model showing the sudden drop in the residual compressive strength which is due to change in behavior of concrete after 500$^0$C. All the models following similar trend after the 600$^0$C.

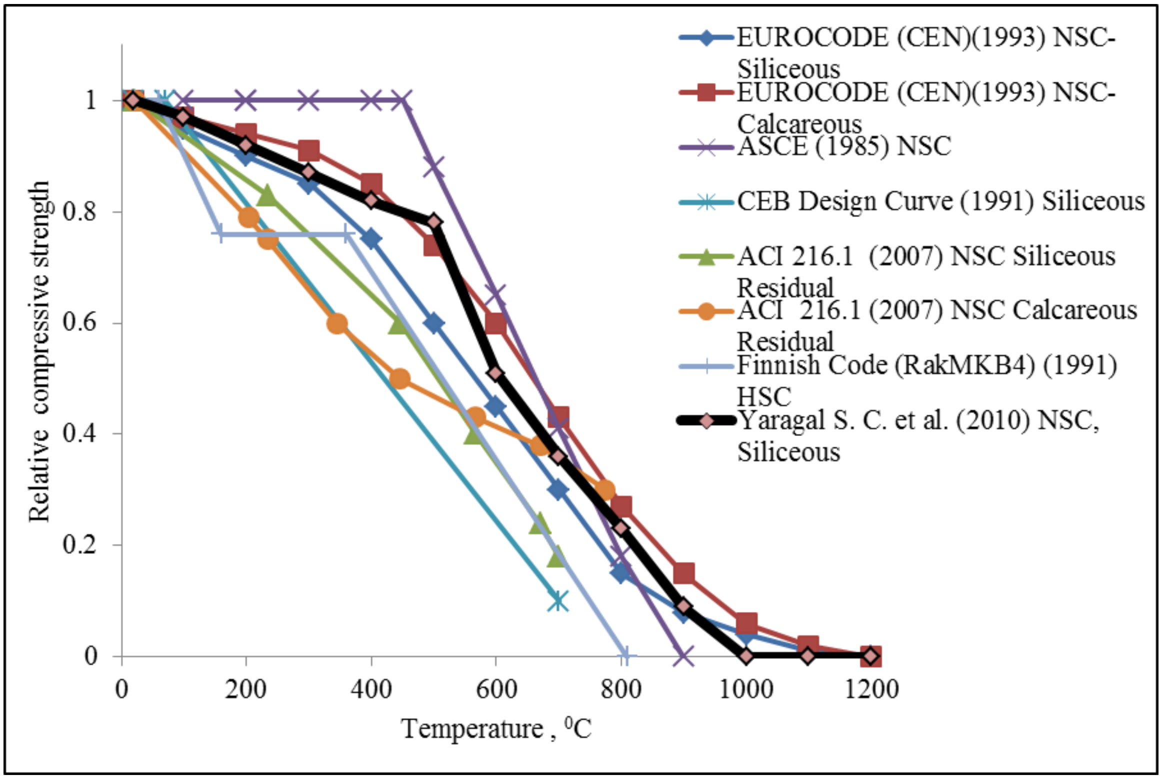

**Figure 5 Concrete compressive strength loss models**

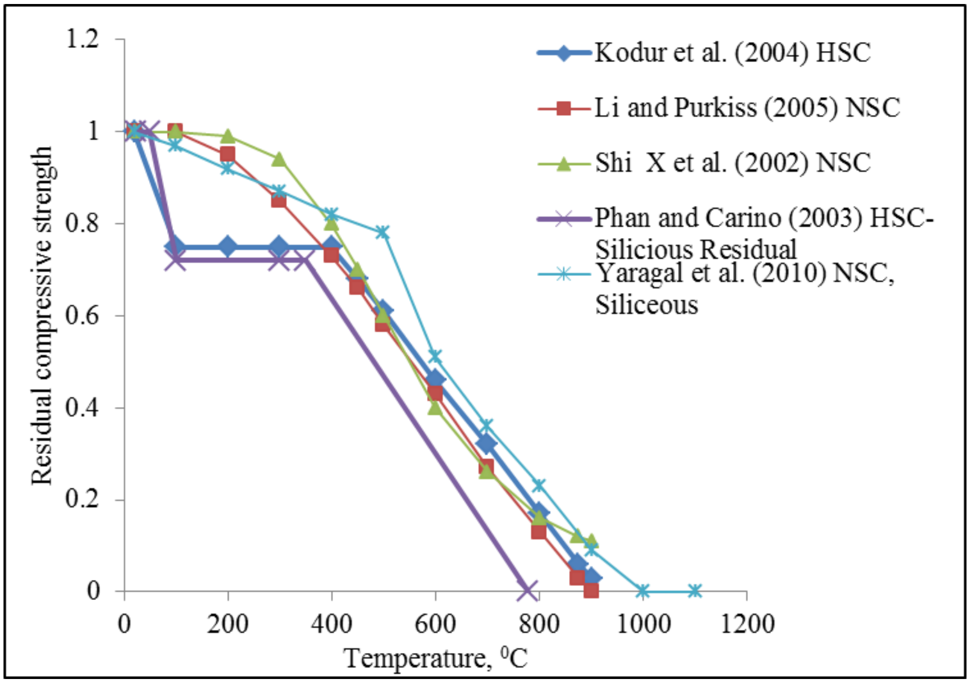

**Figure 6 Comparison of design curves for compressive strength with other researchers**

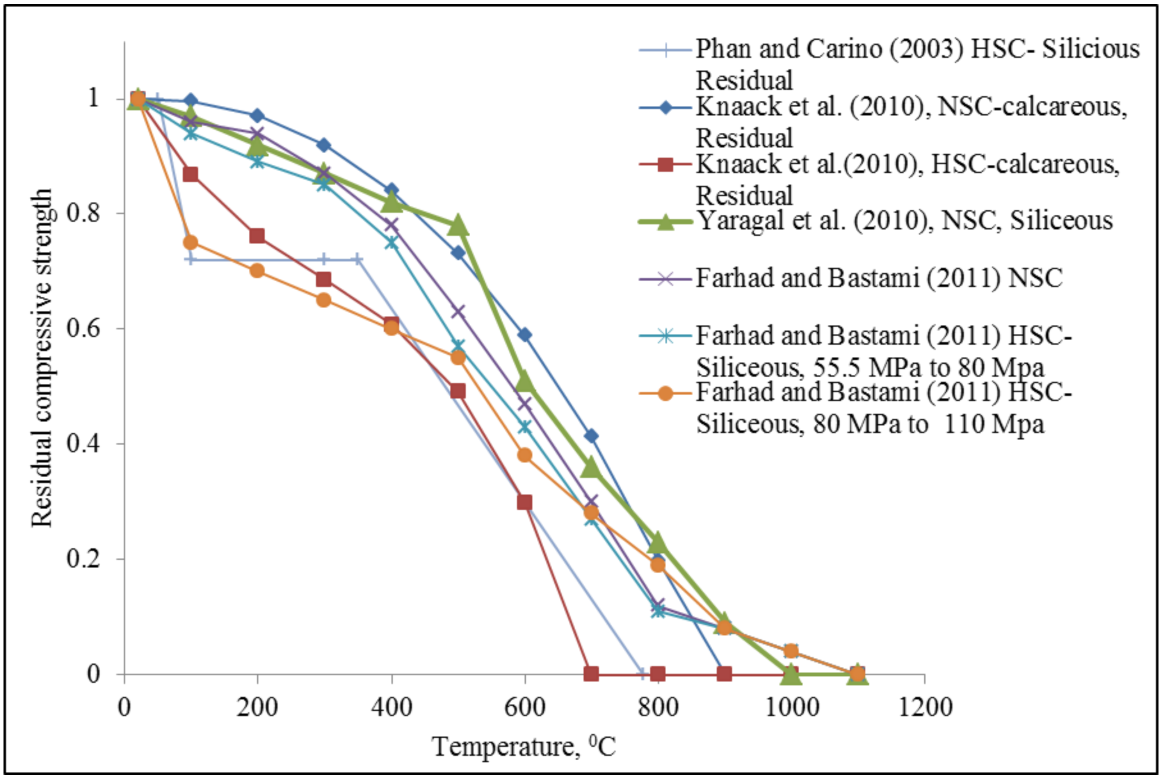

**Figure 7 Proposed models by researchers based on comprehensive multiple regression analysis**

Figure 6 and 7 showing high strength temperature relationship developed by Phan and Carino (2003), which consists of four temperature ranges: 23 to 50, 50 to 100, 100 to 350$^0$C (intermediate temperature range); and above 350$^0$C is superposed over the compiled test data. These relationships differ from the existing provisions of the National Building Code of Finland's Finnish code (Rak MKB4) in two areas: (1) the proposed relationships consider the differences caused by preload and the effect on concrete strength "at" elevated temperatures or at room temperature "after" elevated temperature exposure, whereas the RakMKB4 only considers the effect of preload for NSC; (2) the proposed relationship extends the intermediate temperature range for HSC with and without preload to between 100 to 350$^0$C thereby eliminating the un-conservativeness of the RakMK B4 in this intermediate temperature Range (Phan and Carino 2003). Knaack *et al.* (2010) proposed relationships is based on a comprehensive multiple regression analysis of the existing experimental data on North American concrete. Similar kind of work carried by Aslani and Bastami (2011), and proposed a constitutive relationship for compressive strength and temperatures for NSC, HSC (Siliceous Aggregate), and Calcareous aggregate as shown in fig. 7.

Researchers have carried out experiments with different concrete composites, test facilities and varied retention times resulting in a large set of heterogeneous data, difficult compare. It is required to perform convincing fire tests on concrete, because the fire resistance has to be considered at two levels: the level of the material itself and the level of the structural element in which concrete is used in conjunction with steel. An extensive research work is further needed to investigate the heat resistive properties of concrete mixes containing ternary or tertiary blends of pozzolanic materials. To homogenize the test results it is better to use standard time temperature curves as suggested by codes of practice. Residual mechanical strength assessment curve is required to be refined with the concrete mix, moisture condition, materials used, heating rate, and load during heating, cooling regimes.

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