Effect of elevated temperatures on tensile properties of concrete

Alireza Javadian

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EFFECT OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF CONCRETE

ALIREZA JAVADIAN

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Master of Engineering

2010

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TENSILE PROPERTIES OF CONCRETE**

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**SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY**

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Abstract

Fire is known to cause spalling in concrete structures. The Structural integrity of the building will be affected as the reinforcement steels will be weakened when exposed to heat directly in the absence of concrete cover. Fire resistance of concrete structural elements is often predicted based on the assumption that spalling does not occur. Researches show that spalling is more susceptible in high strength concrete and concrete of low water/cement ratio. The fundamental cause of spalling is still not addressed.

One of the key factors in behavior of concrete at high temperatures is the mechanical properties of concrete, especially tensile strength of concrete. Organized experiments to show the effect of temperature on Flexural and Tensile Splitting strength of High Strength Concrete were done. Both Splitting tensile test and flexural strength test were conducted at high temperature and for the residual behavior, with two kinds of fibres, Polypropylene and steel fibre at different ratios.

Results of hot and residual tests show that for temperatures up to 100°C there is practically no significant loss of strength. However, at temperatures above 100°C, the loss in strength follows a linear trend for both flexural strength (modulus of rupture) and splitting tensile strength. At 650°C, the modulus of rupture reduces to only about 10-20% of that at room temperature. For the tensile splitting strength, at 650°C the value drops to 15 – 30% of that at room temperature. A set of formulas to estimate the values of modulus of rupture and tensile splitting strength as functions of heating temperatures are proposed.

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LIST OF SYMBOLS

A	Cross sectional area
b	Average width of the specimen as oriented for testing
d	Average depth of the specimen as oriented for testing
T	Temperature
f_{cu}^T	Residual compressive strength of HPC at T
f_{cu}^{20}	Compressive strength of HPC at 20 °C
P	Pore pressure
d_p	Pore diameter
γ	Surface tension
φ	Contact angle
T_0	Initial room temperature
t	Time
f'_c	Compressive strength of the specimens
F	Load
r	Loading rate
S	Rate of increase in maximum stress on the tension face
L	Span length
R	Modulus of rupture
p	Load
f_r	Flexural Strength
f_{rT_0}	Flexural Strength at room temperature

f_{sp} Tensile Splitting Strength

f_{spT_0} Tensile Splitting Strength at room temperature

Chapter one: Introduction

1.1 Background

Nowadays, concrete structures are the basis of building construction all over the world. However the structural performance of concrete deteriorates in the presence of elevated temperatures. Elevated temperature can exist in various forms from extreme heat in a nuclear reactor to an industrial fire. Generally, this type of structures has very good fire behaviour when compared to structures made of other types of materials. However, severe fires, with heavy fire loads and specific environmental conditions, can lead to critical destruction states of the structures and sometimes to a high number of casualties.

The heating effects during the course of a fire can cause not only immediately danger to occupants but also significant damage to the structural elements of buildings, which may subsequently jeopardize evacuation and endanger rescue personnel. Therefore, structural elements should remain stable for a period to allow the occupants to evacuate, and to allow the fire fighters to fight the fire safely and to carry out rescues effectively. Furthermore, if the building is well designed, fire damage will be small and the cost of repair will be reduced

It is well established that fire was the main reason in bringing down both of the WTC towers during the tragic event in September 2001 in New York, USA. That has led to increase the importance of the fire resistance of building materials among designers in particular and the building industry in general.

Also some other catastrophes such as the case of the Mont Blanc tunnel, and in buildings, such as the case of the building of CESP, in S. Paulo, Brazil, the Military Personnel Record Center, in Overland, USA, the Windsor Tower, in Madrid, Spain, and others, touched the public opinion for its consequences and for the extension of the damages that a fire can have.

One of the main damages due to rapid heating of concrete during fires is spalling. Spalling of concrete is a phenomenon whereby pieces of concrete break off from the surface of concrete element. There are many concerns with the integrity of reinforced concrete elements concerning the occurrence of spalling.

Combining the effective stresses due to pore pressure and thermal stresses caused by material expansion, thermally induced spalling has become more likely for higher performance concrete.

Two theories have evolved to explain the causes of spalling in concrete under severe thermal loading. One theory assumes that thermal gradients in the concrete cause differential expansion and thus differential thermal stresses that exceed the strength limits of the material (Bazant 1997).

Other studies (Ali et al. 2001; Ichikawa and England 2004; Kalifa et al. 2000; Qian et al. 2005; Tenchev et al. 2001; van der Heijden et al. 2007) have supported the theory that pore pressure buildup associated with moisture clogging may also play an important role in initiating the spalling of concrete. Essentially, this theory states that in low permeability, porous materials, the flow of water and steam that occurs during heating is restricted and consequently vapor pressures increase in the pore structure to a point that the

resulting skeleton stresses exceed the material strength.

In addition to spalling phenomenon, there is a significant loss in mechanical properties of concrete due to high temperature. Compressive strength, tensile strength and modulus of elasticity are the main mechanical properties of concrete, which are of interest during and after fires. Researchers made use of mechanical properties of concrete to quantify spalling.

However, there is not a distinct relation between mechanical properties of concrete and spalling. Nevertheless, according to the theories, which are used to explain spalling at high temperatures, tensile properties of concrete are more likely to have effects on this phenomenon. At such high temperatures, internal cracking usually leads to failure of structural concrete. Internal cracking is known to be caused by vapor pressures in the pore structure. Therefore, for high strength concrete with low permeability is more prone to this kind of failure. To postpone spalling at high temperatures or even to prevent it, higher tensile strength is advantageous, since it can reduce the danger of internal explosion. Other factors such as gas permeability, water permeability and porosity also have important influences on concrete behaviour at high temperatures, which can affect spalling behaviour of concrete.

Efforts were also made to reduce the occurrence of spalling. Design guides gave recommendation on the reduction on the risk of spalling. For instance, design guides (BS 8110: Part 2: Section 4.1.6, 1985; FIP/CEB Report, 1978) mentioned that concrete with moisture content less than 2% would have a significant reduction in the risk of explosive spalling.

The latest draft of Eurocode also mentioned the use of polypropylene fibres (minimum of 2.0 kg/m^3) to reduce the occurrence of spalling. Many researchers (Bentz 2000; Bian et al. 2006; Connolly 1995; Gai-Fei Peng et al. 2006; Han et al. 2005a; Han et al. 2005b; Zeiml et al. 2006) have investigated the effect of polypropylene fibres on concrete behaviour at high temperatures. They concluded that by adding around 0.2% polypropylene fibres to the mix design the risk of spalling would be reduced considerably.

Most of researchers (Arioz 2007; Behnood and Ziari 2008; Carette et al. 1982; Chan et al. 1999; Faiyadh and Al-Ausi 1989b; Ju and Zhang 2006; Noumowe 2005; Peng et al. 2008; Peng et al. 2006a; Saad et al. 1996; Sakr and El-Hakim 2005; Tanyildizi and Coskun; Tanyildizi and Coskun) have measured the residual mechanical properties of concrete, specially tensile and compressive strength after exposing the specimen to high temperature, which are usually called residual properties.

Figure 1.1: Residual Split-Tensile Strength of Concrete (Carette et al. 1982)

Unfortunately, there is not enough evidence to support the clause that hot properties, during which the specimen is heating and being tested, and residual properties of concrete, after exposure to heat and being cooled to room temperature, especially tensile strength of concrete are the same or near to each other.

As we know during fires, hot properties of concrete are more important than the residual properties. Also based on the mentioned mechanisms for spalling, tensile properties of concrete at high temperatures could give us some useful reasons to scrutinize spalling behaviour of concrete.

To summarize, this dissertation is concerned about hot and residual properties of concrete. The scope of the investigation is found in the next section.

1.2 Objective and Scope of Research

The objective of the research is to investigate the effects of elevated temperature on the mechanical properties of concrete, namely tensile strength and compressive strength. Both residual and hot properties will be considered. A new approach for measuring hot tensile strength of concrete is introduced which has not been mentioned in previous researches. In addition, a relationship between fire exposure and tensile strength of concrete will be developed. Since high strength concrete is more prone to spalling, this dissertation is mainly investigating the properties of high strength concrete. In addition, a comparison will be provided between different type of high strength concrete with different percentage of steel and polypropylene fibres.

The scopes of the research are as follows:

1. To study the effects of high temperature on splitting tensile strength of concrete; hot and residual strength
2. To study the effects of high temperature on flexural strength of concrete; hot and residual strength
3. To investigate the effect of polypropylene and steel fibres on mechanical properties of concrete at high temperature
4. To find a relationship between hot and residual properties of high strength concrete with temperature

Three types of high strength concrete with 0 to 0.2% polypropylene and steel fibres were used to identify the mentioned properties.

Cylinders with 150 mm diameters and 300mm length were used to measure splitting tensile strength and 150x150x500mm beams were used to investigate the flexural strength of concrete.

1.3 Organization of Report

This thesis consists of six chapters.

Chapter 2 presents a literature review on the mechanical properties and behaviour of concrete at elevated temperatures followed by spalling behaviour of concrete at high temperatures. Mechanisms of spalling and parameters affecting spalling are also discussed in this chapter. The significance of the tensile properties of concrete is also provided in this chapter.

Chapter 3 describes the experimental program including methodology, casting and testing of various types of specimens. Flexural strength, Tensile Splitting Test is also described in this chapter.

Chapter 4 presents the test results obtained from experiments.

Chapter 5 discusses the results obtained from the experiments. Comparison between Hot and Residual Strength is provided. This chapter also provides the experimental models for prediction of flexural and tensile splitting strength at high temperatures

Chapter 6 summarizes the main findings of this research. Recommendations for future work are also included.

Appendix A shows the reported strength after subjecting to elevated temperature. The data which were used to verify the proposed models to predict strength subjected to elevated temperature are also included.

Chapter 2: Literature Review

2.1 Overview

The approach of this research is to identify the effect of elevated temperatures on the hot and residual tensile strength of concrete. Two methods for measuring tensile strength of concrete, splitting tensile strength and flexural strength test will be conducted.

Also, pore structure of high strength and normal strength concrete after exposure to elevated temperatures will be measured.

In this chapter, a literature review of previous works on the mechanism of spalling, the mechanical properties of concrete subjected to elevated temperatures, the pore structure of heated concrete and experimental investigations for tensile properties of concrete will be provided.

2.2 Spalling

Currently, there are two mechanisms concerning the occurrence of spalling. One group of researchers believes that the pore pressure build up causes spalling in the cement matrix while the other believes that spalling is caused by thermal and mechanical stresses. Much debate has been going on and the criterion of spalling is still in the hypothesis stage.

Anderberg (Anderberg 1997) gave an account on spalling caused by vapour pressure. The mechanism is believed to be the same for both High Performance Concrete (HPC) and Normal Strength Concrete (NSC). He

defined three zones as illustrated in Figure 2.1 for a 1-D heating scenario: 1) dry zone, 2) vapour zone and 3) partially saturated zone. The water at the heated face starts to vaporize when temperature reaches 100 °C. A dry zone is created at the boundary of the heated face and the thickness of this layer increases rapidly in NSC than HPC. The temperature gradient rises sharply in this zone as water, being high in specific heat capacity, is vaporized and no longer exists to absorb the heat energy. Gas diffusivity is also believed to increase rapidly with temperature.

Figure 2.1: Schematic Illustration of the 3 Zones (Anderberg 1997)

A vapour zone immediately follows behind the dry zone. It is a zone where vapour and free water coexist together. Moisture content within the vapour zone rises and obstructs the vapour to migrate into the direction of the unheated face. This phenomenon is known as “moisture clog”. Vapour pressure starts to build up within the concrete even though the vapour continues to migrate in both directions (towards the heated and unheated face). Condensation is observed in the unheated face.

A possible criterion for spalling could exist when the tensile stress due to vapour pressure exceeds the tensile strength of the concrete (Anderberg 1997; Bazant 1997; Consolazio et al. 1998; Kalifa et al. 2000; Tenchev et al. 2001). Anderberg (Anderberg 1997) also observed that spalling is progressive. Spalling will continue to occur until the tensile stress due to vapour pressure is less than the tensile strength of concrete. Essentially, this theory states that in low permeability porous materials, the flow of water and steam that occurs during heating is restricted and consequently vapor pressures increase in the pore structure to a point that the resulting skeleton stresses exceed the material strength.

Arita (Arita 2002) believes that spalling is caused by thermal stress. He documented the observations made in his experiments. Initially, the sound of crack propagation can be heard during the first 3 to 10 minutes. Small pieces of concrete gets dislodged from the surface.

Explosive spalling occurred at around 11 minute, which corresponds, to approximately 700 °C. Arita made a hypothesis on the mechanism of spalling due to thermal stress from the observations made in his experiment. Two factors are identified that lead to spalling: 1) high concrete density and 2) large water content in concrete. High-density concrete has a high initial vapour pressure existing within the pores. The large water content in concrete tends to delay the temperature rise within the concrete resulting in a high thermal gradient across the section. This will lead to an increase in thermal stress as thermal expansion in the heated region of the concrete is restrained from expanding. When the thermal stress exceeds a threshold, a crack-split buckling effect will cause spalling.

From both spalling mechanisms mentioned above, water (either evaporable or non-evaporable) does have a role to play in spalling. In addition, it seems that tensile strength of concrete has an important effect on spalling behaviour of concrete based on spalling mechanism mentioned above.

The mechanism of spalling can be classified into 2 main areas (thermal stress and pore pressure) based on the research by (Anderberg 1997) and (Arita 2002). The factors that influence spalling due to pore pressure can further be broken down into environmental and material dependent factors as shown in Figure 2.2 namely.

Figure 2.2: Summary of Factors Affecting Spalling

2.3 Methods to Reduce Spalling

Various methods have been proposed to reduce the occurrence such as limit

the maximum percentage of cement replaced by Silica-Fume (SF) at 15% (Khoury 1992b) or to include polypropylene fibres into the concrete mix. The use of polypropylene fibres probably received the most attention as experimental investigations (Bentz 2000; Han et al. 2005a; Kodur et al. 2003) show the effectiveness of polypropylene fibres. When polypropylene fibres melt at 170 °C, it is partially absorbed by the cement matrix and leaves behind a path for outward migration of gas, which results in the reduction of pore pressure (Kalifa et al. 2000). Migration of gas can only occur outward is because the temperature in the inner depths of concrete are cooler than the exposed surface and the temperature is not sufficiently high enough to melt the polypropylene fibres. No pathway is formed on the cooler face to facilitate migration of gas inwards and hence, migration of gas can only occur outwards.

Researchers also investigated the effect of various dosages of polypropylene fibres on temperature and pressure development in concrete (Bilodeau et al. 2004; Gai-Fei Peng et al. 2006; Zeiml et al. 2006). An increase in the fibre dosage was found to lower the maximum pressure, temperature at maximum pressure and pressure gradient. A fibre dosage of 0.9 kg/m³ appeared to prevent spalling. The latest draft of Eurocode 2 mentioned the use of polypropylene fibres (minimum of 2.0 kg/m³) to reduce the occurrence of spalling.

There is also a lack of investigation on the hot and residual compressive strength of concrete with polypropylene fibres. Luo et al. commented that the use of 1.82 kg/m³ of fibre did not cause significant reduction in residual strength when compared with the case when it was not added (Luo et al. 2000). The gel/space ratio decreases due to the increases in voids in the

cement matrix when the fibre melts. This should lead to a reduction in compressive strength and tensile strength of concrete and may affect the integrity of the building during fire. In the next section, previous works on mechanical properties of concrete at elevated temperatures will be covered.

2.4 Mechanical Properties at Elevated Temperatures

2.4.1 Compressive Strength at elevated temperatures

At present, high-strength concrete (HSC) is widely used in load-bearing members of structures. However, once a fire disaster occurs, the properties of the HSC (especially its compressive strength) will dramatically decrease, and the HSC will lose the capability of load bearing and bring great threats to the safety of the fire-damaged structures.

In general, changes in the compressive strength of HSC at elevated temperatures can be divided into three stages. In the first stage, the HSC strength usually decreases due to the significant losses in free water in the open pores and physically bound water in the hydrate phase (C-S-H mainly). However, in the second stage, the HSC strength tends to be constant even appears to recover and increase, and also may reach a maximum value about 10% higher than the original strength. In the third stage, the HSC strength shows an approximately linear decrease and at 800°C reaches a value of about 30% of its original strength.

The effects of high temperature on the mechanical properties of concrete have been investigated by many researchers (Bian et al. 2006; Chen and Liu 2004; Gai-Fei Peng et al. 2006; Hertz 1992; Hertz 2005; Husem 2006a; Khoury

1992a; Kodur et al. 2003; Luo et al. 2000; Peng et al. 2006b; Phan and Carino 2002; Poon et al. 2004; Savva et al. 2005).

Luo et al. observed that when temperature was elevated to 800°C, the residual strength percentage of the HPC was 26-34% for gradual cooling and 22-28% for rapid cooling. Also they observed that when the peak temperature was 1100°C, the residual strength percentage of HPC was 8-12% for gradual cooling and 8-10% for rapid cooling (Luo et al. 2000).

Works done by Gai-Fei Peng et al. on high strength concrete with fibres (Gai-Fei Peng et al. 2006) indicated that high temperatures can be divided into two ranges in terms of effect on concrete strength loss, namely 20–400 °C and 400–800 °C. In the range 20–400 °C, some types of concrete maintained their original strength. In the range 400–800 °C, these types of concretes lost most of their original strength, especially at temperature above 600 °C. Thus, they concluded that the range 400–800 °C might also be regarded as the critical temperature range for the strength loss of fibre concrete, which is similar to that of plain concrete without any fibers. Xiao and Falkner (Xiao and Falkner 2006b) concluded that residual compressive strength of HPC with Polypropylene (PP) fibres was slightly greater than that of HPC without PP fibres because PP fibres melt under high temperatures and form new channels to release the thermally induced pressures and, therefore, avoid excessive loss of compressive strength. They also proposed an equation for residual compressive strength and exposure temperature based on their results as follows:

$$\begin{aligned} f_{cu}^T / f_{cu}^{20} &= 1.011 - (T / 1900), & T \leq 400^\circ \text{C}, \\ f_{cu}^T / f_{cu}^{20} &= 1.440 - (T / 625), & 400^\circ \text{C} \leq T \leq 900^\circ \text{C}, \end{aligned} \quad (2.1)$$

Where T is the exposure temperature ($^{\circ}\text{C}$), f_{cu}^T is the residual compressive strength of HPC at T and f_{cu}^{20} is the compressive strength of HPC at 20°C .

Husem showed that the compressive strength of high-performance concrete exposed to high temperature and cooled in air and water decreases until 200°C , an increase between 200°C and 400°C and a continuous decrease after 400°C (Husem 2006a).

However, many works have been done on compressive strength of concrete at elevated temperatures especially residual compressive strength. There is a lack of measuring compressive strength when the specimen is hot. This report aims to fulfill this lack by a new approach, which will be discussed later.

2.4.2 Tensile Strength at elevated temperatures

As mentioned earlier tensile strength of concrete is pertaining to be one of the reasons for spalling behaviour based on the mechanisms that indicated before. When internal pressure goes beyond the strength of material, concrete tends to crumble and spalls.

Tensile stresses are typically measured indirectly by one of two means: a splitting tension test or a flexural strength test. Splitting tension test consists of applying a diametric compressive force along the length of a cylindrical concrete specimen at a rate that is within a prescribed range until failure occurs (ASTM C 496-04: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens).

Fig 2.3: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C 496-04)

Flexural strength is the other measure of the tensile strength of concrete. It is a measure of a concrete beam or slab to resist failure in bending. It is measured by loading 150 x 150 mm or 100 x 100 mm concrete beams with a span length at least three times the depth. The flexural strength is expressed as Modulus of Rupture in psi or MPa and is determined by standard test methods ASTM C78-07 or ASTM C293-07.

Unfortunately, there is not a distinct method to verify both splitting tensile and flexural strength of concrete at high temperatures. Many works have been done on measuring residual tensile strength of concrete rather than hot measuring of tensile strength of concrete (Arioz 2007; Balendran and Martin-Buades 2000; Behnood and Ziari 2008; Chan et al. 1999; Faiyadh and Al-Ausi 1989b; Kim et al. 2002; Lau and Anson 2006; Li et al. 2004; Noumowe 2005; Peng et al. 2006a; Saad et al. 1996; Tanyildizi and Coskun).

Fig 2.4: Standard test method for flexural strength of concrete

to enhance the behaviour of high strength concrete at high temperatures, researchers usually use polypropylene fibres to release the vapor inside the pores so that spalling will be prevented. While steel fibred concrete has various excellent properties as a composite material; for instance, flexural, tensile and shear strength, toughness, impact resistance, crack resistance and resistance to frost damage can be improved by the use of steel fibres.

Many researchers have used both types of fibres to compare their effects at elevated temperatures (Aydin et al.; Bian et al. 2006; Chen and Liu 2004; Gai-Fei Peng et al. 2006; Kodur et al. 2003; Lau and Anson 2006; Naaman and Hammoud 1998; Peng et al.; Poon et al. 2004; Suhaendi and Horiguchi 2006).

Lau and Anson concluded that incorporating steel fibre remains beneficial to

concrete, which has been exposed to high temperatures up to 1200 °C confirming that at 1%, steel fibre content has no deleterious effect on heated concrete. Also, the inclusion of steel fibre in the concrete mix leads to an improvement in mechanical properties and a better resistance to heating effects (Lau and Anson 2006).

Suhaendi and Horiguchi made use of Hybrid fibres, which are combination of steel and polypropylene fibres. They also concluded that inclusion of steel fibres will improve tensile strength property of heated HSC (Suhaendi and Horiguchi 2006). This may indicate the effectiveness of steel fibres in bridging cracks induced upon tensile loading, as they do not melt after heat exposition. They found that degradation trend in compressive strength of heated high strength concrete with polypropylene fibres, steel fibres, and hybrid fibres is found to be quite similar while tensile strength of high strength concrete with polypropylene fibres degrades in a more rapid way compared with high strength concrete with steel fibres. For high strength concrete with hybrid fibres, degradation in tensile strength is related to proportioning combination of its fibres constituent.

In spite of the previous works that mentioned above, few works have been done by some researchers in hot state. Kaplan and Roux indicated that for specimen tested in hot state, the test values were lower than when they were tested after cooling down (Kaplan and Roux 1972). Also Faiyadh and Al-Ausi reached the same point as Kaplan and Roux. They tested normal strength concrete with glass and steel fibres. They concluded that the tensile strength was sensibly independent of fibre content at exposed temperatures higher than 350°C and 600°C for glass and steel fibre reinforced concrete respectively (Faiyadh and Al-Ausi 1989a). However, a study by Sullivan and Poucher

mentioned that there was no significant difference in the Flexural strength between those tested in hot state, and those tested after cooling (Sullivan and Poucher 1973).

Balendran et al compared the result of splitting tensile test and flexural strength test at elevated temperature for high strength concrete. They concluded that Flexural Strength suffered sharp loss at low temperatures (at or around 100 °C), but it became gradual later at high temperatures. The loss in splitting tensile strength was observed to be gradual but sharper than that of Flexural Strength. At 600°C, both strengths lost around 80% of their unheated values. (Balendran et al. 2003)

Fig 2.5: Comparison of Residual Flexural Strength and Splitting Cylinder strength loss at different elevated temperatures under slow and quick cooling (Balendran et al. 2003)

In this report, a new approach for measuring splitting tensile and flexural strength of concrete in hot state is introduced which will be discussed later. In addition, a good comparison between splitting tensile and flexural strength, for both residual and hot state, will be provided.

2.5 Pore structure

As mentioned before, it has been commonly thought that the susceptibility for spalling of concrete during fires was directly related to strength (Cui and Cahyadi 2001; Lam et al. 2000; Neville 1996; Poon et al. 2001; Taylor 1990). Moreover, this is due to the notion that permeability rapidly decreases with strength and thus provides a greater restriction to moisture movement (Breysse and Gerard 1997; Hossain 2006; Hossain and Lachemi 2007; Kim et al. 2007). However, a decrease in porosity, which also accompanies an increase in concrete strength, affects both the potential for higher initial amount of water within the pore structure and the stress factor (for conversion of pore pressure to stress).

Porosity is commonly measured using Mercury Intrusion Porosimetry (MIP). The principle behind the test is to measure the volume of mercury injected into the specimens. Equation (3.1) is the well-known Washburn equation that is used to relate the pressure (P) with pore diameter (d). γ and ϕ are surface tension taken as 485 dyne/cm at 20 °C and contact angle taken as 130° respectively.

$$d = -\left(\frac{1}{p}\right)4\gamma \cos\phi \quad (2.2)$$

The key limitation of the Washburn equation is the assumption that all pores are cylindrical in geometry.

Many researchers have investigated the theory that pore pressure build up associated with moisture clogging may also play an important role in

initiating the spalling of concrete. For finding the concomitant change of pore structure with temperature a few works have been done (Ahmed and Hurst 1999; Bazant 1997; Chan et al. 1999; Consolazio et al. 1998; Gardner et al. 2005; Gawin et al. 2005; Ichikawa and England 2004; Janotka and Bagel 2002; Kalifa et al. 2000; Pont et al. 2005; Suhaendi and Horiguchi 2006).

Luo et al have investigated the effect of high temperatures on pore volume of normal strength and high performance of concrete by means of Mercury Intrusion Porosimetry. They have concluded that the pore volume of the HPC increased at a larger rate than that of the NSC after being subjected to the same high temperatures so this coarsening effect in pore structure is responsible for the more severe deterioration in mechanical properties of HPC when compared with NSC (Luo et al. 2000).

Work done by Noumowe has shown that there is a significant difference between the porosity of polypropylene fibres high strength concrete and the reference high strength concrete, which he used to compare the results, after exposure at 200 °C. He concluded that this difference may result in lower vapour pressure in the polypropylene fibres high strength concrete in the early stage of heat exposure and lower risk of concrete spalling in case of accident (Noumowe 2005).

2.6 Summary

A unique and significant outcome of this study is determining the effect of high temperatures on hot and residual tensile strength of concrete.

This chapter presented the effect of elevated temperatures on mechanical

properties and pore structure of heated concrete. Both splitting tensile strength and flexural strength were mentioned. The link between tensile strength of concrete and spalling behaviour of concrete was also mentioned. It was also indicated that previous works were based on residual mechanical properties rather than the hot ones. It will be shown later in this report that the difference between hot properties and residual ones, for both splitting and flexural strength, may change the contemporary theories about spalling concerning tensile properties of concrete. To demonstrate this difference, an experimental program was initiated and two different furnaces designed for the first time to measure the tensile properties at high temperatures. Further works relating to comparison between hot and residual properties will be extended from this chapter.

Since there is not a specified code for hot state testing of tensile properties of concrete, the new method is used and will be explained in next chapter. The review of the works done by other researchers in this chapter will help in establishing experimental methodology required to complete the investigation of the behaviour of tensile properties subjected to elevated temperature

Chapter 3: Experimental Investigations

3.1 Overview

This chapter describes the details of the experiments for heating procedures, tensile splitting strength test and flexural strength test. The objective of the experimental investigations is to determine the tensile properties of concrete specimens exposed to elevated temperatures. Listed below are the top-level tasks that constitute the research program.

**Fig 3.1 Flowchart of research program for behaviour of concrete
Exposed to elevated Temperatures**

3.2 Experimental Methodology

3.2.1 Mix Proportions

To investigate the effect of high temperatures on tensile properties of heated concrete, four sets of mixtures have been produced. One set high strength concrete without any fibre and three sets with fibres. which let us to compare the result between HSC with fibres and without fibres.

Table 3.1: Mix proportions

	HSC0	HSCP08	HSCP14	HSCP20	HSCS08	HSCS14	HSCS20
Cement (Kg/m ³)	540	540	540	540	540	540	540
Sand (Kg/m ³)	820	820	820	820	820	820	820
Silica Fume (Kg/m ³)	60	60	60	60	60	60	60
Aggregate (Kg/m ³)	820	820	820	820	820	820	820
water (Kg/m ³)	162	162	162	162	162	162	162
W/C	0.3	0.3	0.3	0.3	0.3	0.3	0.3
W/B	0.27	0.27	0.27	0.27	0.27	0.27	0.27
PP Fibres (Kg/m ³)	-	0.73	1.27	1.82	-	-	-
Steel Fibres (Kg/m ³)	-	-	-	-	6.24	10.92	15.6
SP (% of cement weight)	2	2	2	2	2	2	2

In the above table, Sp= Superplasticizer and PP= Polypropylene fibre.

As mentioned in chapter one, to enhance the behaviour of high strength

concrete at elevated temperatures, researchers have used polypropylene and steel fibres (Anderberg 1997; Aydin et al.; Bayasi and Al Dhaheri 2002; Bian et al. 2006; Chen and Liu 2004; Gai-Fei Peng et al. 2006; Han et al. 2005b; Peng et al. 2008; Zeiml et al. 2006). Extending their work, two types of fibre were used in mix proportions. Details on the mix proportions of specimens are given in Table 3.1.

The ratio of water to cement and water to binder for high strength concrete was chosen based on the findings of various researchers (Anderberg 1997; Bayasi and Al Dhaheri 2002; Khoury 1992b). Since aggregates are stable at elevated temperatures up to 700 °C (Yan et al. 2007), the same aggregates were used for all mixes and the maximum size of aggregates was 10 mm. The grading of aggregates was in accordance with ASTM C 33-07 Standard Specification for Concrete Aggregates. Portland cement type two was used for sample preparation.

The Silica Fume used for mix design, was Elkem Microsilica Grade 920 Undensified with a typical bulk density of 200-350 kg/m³. Other properties of this Silica Fume are in accordance with ASTM C1240-03 Standard Specification for Silica Fume Used in Cementitious Mixtures.

For higher workability of high strength concrete, Grace ADVA 181 Superplasticizer was used. ADVA 181 is a high range retarding water-reducing superplasticizing admixture based on the latest comb polymer technology and is specially formulated for high strength concrete with design strengths above 60 MPa.

The polypropylene fibres were monofilament type. The melting point for this

kind of fibre is usually around 160-170 °C. The PP Fibres used had the following properties.

Table 3.2: Properties of PP Fibres

	Diameter (mm)	Length (mm)	Density (g/cm ³)	Aspect ratio	Tensile Strength (MPa)	Elastic Modulus (Gpa)
PP Fibres	0.018	40	0.91	2222	460	3500

One of the important issues about PP Fibres is stirring during mixing. Cement, aggregate, additive and fibres were put together, and then were stirred after adding enough water. Stirring can be prolonged for 2-3 minutes in order to make the compound mix completely.

The steel fibres had enlarged end anchorage, which can provide an efficient mechanical bond and optimum interlock between the fibres and concrete. Other properties are as follows.

Table 3.3: Properties of Steel Fibres

	Diameter (mm)	Length (mm)	Density (g/cm ³)	Aspect ratio	Tensile Strength (MPa)	Elastic Modulus (GPa)
Steel Fibres	1	18	7.8	18	780	200

3.2.2 Heating Program

The specimens must be uniformly heated before testing can be conducted.

Heat is transferred from hotter to cooler regions. The process takes time before the specimen reaches thermal equilibrium. The time between the end of ramp heating and thermal equilibrium is termed as holding period. During this period, programmed temperature at the end of ramp heating is maintained. The duration of the holding period is dependent on the rate of heating, thermal conductivity, specific heat capacity and size of specimen. Specimens with thermal gradient during testing would make quantification of thermal effects on material behaviour difficult. Hence, thermal equilibrium was considered throughout the research.

3.2.2.1 Heating Regime

The heating program used by researchers varies greatly. The condition of thermal equilibrium is often not reported. No existing standards or recommendations were made regarding the heating program except the ISO 834 and parametric fire curve, which described transient heating condition. The expression for ISO 834 fire curve is given in Equation (3.1).

$$T = T_0 + 345 \log_{10} \left(\frac{8t}{60} + 1 \right) \quad (3.1)$$

Where, T , T_0 and t refer to temperature (°C), initial room temperature (°C) and time (s) respectively. Most researchers used the ISO 834 fire curve for the heating program for spalling test. However, due to the excessive high heating rate in the beginning of the heating phase, most electric furnaces are unable to supply the heat in such a short time. Test fires such as those provided in the ASTM E119 Standard Test Methods for Fire Tests of Building Construction

and Materials and ASTM E1529 Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies are used to evaluate concrete durability during fire exposure.

Since the main purpose is to evaluate mechanical properties of concrete at high temperatures, the specimens must be heated uniformly. It means that they need to be heated in such a way that ensures the inside and outside equilibrium for the entire heated specimen whether residual or hot state.

For hot state testing all specimens were heated in the Nabertherm Electric Furnace first. After reaching equilibrium, each specimen was transferred to the other furnace, which was located under the actuator and already was set to maintain the temperature of the specimen at the target temperature, which will be discussed later. One issue here is that however, due to the limitation of the heating elements and volume of space enclosed by an electric furnace, the gas temperature in the furnace may be lower than the specified temperature calculated using Equation (3.1). An electric furnace heating test was conducted to determine the accuracy of the actual and programmed heating rate by (NG.L.P 2007). Figure 3.2 shows the electric furnace and digital controller used in the investigation.

Figure 3.2: Nabertherm Electric Furnace (Left) and Digital Controller (Right)

The temperature step in the controller was set to follow the ISO 834 fire curve at 5-minute interval. Temperature readings were taken at 1-minute interval using a data logger. A scenario described in Figure 3.3 was obtained from the furnace test. Both time and temperature lag were observed. This is undesirable, as researchers tend to compare experimental results using the same heating rate. They may not have considered the difference in the actual heating rate provided by the gas in electric furnace and the ISO 834 fire curve. The rate of heating experienced in the furnace is approximately 30 °C/min. This rate also represents the maximum heating rate achievable by the electric furnace. The gas and targeted temperature calculated using Equation (3.1) coincides after 30 minutes of heating.

Figure 3.3: Difference between Targeted and Gas Temperature

In this research, the heating rate was selected as low as $2.5^{\circ}\text{C}/\text{min}$. In addition, to reach a state of equilibrium the holding period for each target temperature was selected around 45 minutes.

The target temperatures, selected to investigate their effects on mechanical properties, were room temperature, 250°C , 350°C and 550°C . In addition to prevent explosive spalling, all the specimens were dried at 105°C first to decrease the moisture content of concrete to a lower degree (Gai-Fei Peng et al. 2006). After heating up 105°C , the temperature was maintained for 8 hours then the heating program ran to the target temperature with the rate of $2.5^{\circ}\text{C}/\text{min}$. However; during the first test all the specimens inside the furnace exploded. To make sure that enough samples have been provided for the splitting test, the heating program was modified to reduce the risk of spalling. For this purpose the modified heating program for maximum

temperature in this study has been measured and illustrated in figure 3.4.

Figure 3.4: Time-Temperature curve

3.2.2.2 Furnace Design

Furnace designs were developed that could properly deliver transient temperatures. Both furnaces, splitting tensile strength and flexural strength, which called half-shell furnace and chamber furnace respectively are described in the following section.

Chamber Furnace for Flexural Test

The designed furnace is shown below. All units are in millimeters.

Figure 3.5: Chamber Furnace

The Flexural Test based on ASTM C78-07 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), requires the beam specimen must have a span length within 2 % of being three times its depth as tested. For this purpose, molds with 100×100 mm cross sections and length of 500 mm were selected. To maintain the temperature within the middle of the specimen after being transferred to this furnace, the length of the furnace was selected as 240 mm. Since the bottom rollers can not resist the high temperatures, in design the furnace these rollers should not encounter with effect of temperatures. For this reason, the length of the furnace was fixed as 240 mm, to provide enough gap between the rollers and the furnace, which is shown in figures 3.6 and 3.7.

Figure 3.6: Chamber Furnace setup (Side View)

Figure 3.7: Chamber Furnace setup (3-dimensin view)

The furnace is supplied with 12 Molybdenum discilide heating elements, which are enclosed in a stainless steel case. The programmable temperature controller, which is shown in figure 3.8.

Figure 3.8: Chamber Furnace Controller

To measure the temperature inside the furnace a type K thermocouple was used which is embedded inside the furnace. The furnace is supported by a concrete block, which is stable enough to be assumed as a rigid support. The furnace is fixed under the actuator. The setup is shown in figure 3.9.

Figure 3.9: Chamber Furnace Setup under the actuator

Half-Shell Furnace for Splitting Tensile Test

The designed furnace for the splitting tensile test is shown in figure 3.10.

Figure 3.10: Half-Shell Furnace Sketch

Figure 3.11: Half-Shell Furnace 3D Sketch - Top and Front View

To make sure that the specimen will be at the center line during loading, four steel rods were designed to keep the specimen at the center as shown in figure 3.11. ASTM C496-04 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens was designed for room temperature test but

not a hot test, due to this fact a wood strip at the bottom of the specimens could not be used during hot test. To make sure that the load will be distributed along the length of the cylinder a strip of High-Temperature resistant fabric was used.

Figure 3.12: Specimen (left) and the Half-Shell furnace (right) under the actuator

3.2.3 Sample Preparation

Three different molds were used. For flexural strength tests beams 100 x 100 x 500 mm were used. For splitting tensile tests, cylinders of 150 mm diameter and length of 300 mm were used. In addition, to determine the compressive strength of each batch cubes of 100 x 100 x 100 mm cubes were used.

For mixing the material a Viking Drum Mixer with capacity of 7 ft³ was used. All drum mixers have a container with blades attached to the inside of the movable drum. Their main purpose is to lift the materials as the drum rotates. In each rotation, the lifted material drops back into the mixer at the bottom of the drum and the cycle starts again. The blades have a spiral arrangement to obtain the desired effect for discharge and mixing. Sample preparation was

done at Protective Engineering Laboratory. The mixer is shown in figure 3.13.

Figure 3.13: Drum Mixer

The cement and silica fume were placed first and dry-mixed for about 2 min. PP fibers or steel fibers were utilized; they were added thereafter and strewed into the rotating mixer to avoid any fibre balling. After 5 min of mixing, water was added, followed by another 2 min of mixing. The fine and coarse aggregates and superplasticizer were then finally mixed and stirred for 3–5 min. A slump test was done to determine the concrete workability, and the mean slump of the freshly mixed concrete was found to be more than 150 mm. The slump test has been shown in figure 3.14.

The series of batches were, respectively, cast in three parallel 100x100x100mm³ cubic steel molds, three parallel 100x100x500 mm prism steel molds and three parallel 150(D) mm x 300(H)mm cylinder steel molds.

The steel molds were half-filled with fresh concrete. The steel molds were then vibrated for a minute to remove the air bubbles trapped in the fresh concrete.

Figure 3.14: Slump Test

In the second stage, the steel molds were completely filled with fresh concrete and were vibrated for a further minute before being left to cure. The molds were sealed with plastic sheet to prevent the loss of water through evaporation. The molds were removed after 24 hours from casting and the specimens were stored in water tank with an average temperature of 25 °C inside the lab.

Figure 3.15: Mixer

Figure 3.16: Fresh Concrete

All specimens were water cured for 28 days and then air-dried until the time of the test in the laboratory.

Figure 3.17: Vibration table

Figure 3.18: Molds with fresh concrete

Cubes of 100x100 mm were tested at the age of 7-days, 21-days and 56-days. The results for compression test were shown in table 3.4.

3.2.4 Mechanical Properties

Compressive and flexural strength of the specimens were measured. Splitting tensile strength will be measured later on.

3.2.4.1 Compressive Strength Test

The compressive strength is calculated from the failure load divided by the cross-sectioned area resisting the load and reported in units of pound-force per square inch (psi) in US Customary units or megapascals (MPa) in SI units. Concrete compressive strength requirements can vary from 2500 psi (17 MPa) for residential concrete to 4000 psi (28 MPa) and higher in commercial structures. Higher strength up to and exceeding 10000 psi (70 MPa) are specified for certain applications.

This test was done for each batch to find out the compressive strength of the specimens, f'_c .

Compressive loads were applied to the specimens using a compressive strength testing machine, which is shown in figure 3.19.

Figure 3.19: Compressive Strength Testing Machine

The test was done for 100x100x100 mm cubes with a loading rate of 150 kN/min which conforms to BS EN 12390-3:2001. The compressive strength of the specimen (σ_c) was calculated by taking the load (F) over cross sectional area (A) as given in Equation (3.2).

$$\sigma = \frac{F}{A} \quad (3.2)$$

Compressive strength of the specimens was measured after 28-day water-

curing. Table 3.4 summarizes the result of compression test.

Table 3.4: Compressive Strength of Specimens

Average Compressive Strength (Mpa)	HSC0	HSCP08 PP fibres	HSCP14 PP fibres	HSCP20 PP fibres	HSCS08 Steel fibres	HSCS14 Steel fibres	HSCS20 Steel fibres
7 days	21	20	23	22	24	25	25
28 days	68	70	72	72	75	74	76
56 days	88	89	90	91	92	93	94

As can be found from the table, by adding steel fibres to the mix design, the compressive strength of the specimens is increased compare to the specimens without steel fibres. However, the average compressive strength of the specimens is 90 MPa which is defined by ACI 363R American Concrete Institute, as the strength required for specimens to be recognized as HSC. Nevertheless, as the development has continued, the definition of high-strength concrete has changed. In the 1950s, concrete with a compressive strength of 5000 psi (34 MPa) was considered high strength. In the 1960s, concrete with 6000 and 7500 psi (41 and 52 MPa) compressive strengths were used commercially. In the early 1970s, 9000 psi (62 MPa) concrete was being produced. More recently, compressive strengths approaching 20,000 psi (138 MPa) have been used in cast-in-place buildings.

3.2.3.2 Flexural Strength Test

Flexural strength test was done on concrete beams with 100x100 mm cross sections and span lengths of 500 mm. Since there is not a specified code or requirement for hot state measuring the tensile strength of specimens, a 100-

ton Instron Actuator was selected for loading. The rate of loading conformed to ASTM C78-07 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). According to this code the load must be applied at a rate that constantly increases the maximum stress on the tension face between 125 and 175 psi/min (0.86 and 1.21 MPa/min) until rupture occurs. The loading rate is calculated using the equation (3.3):

$$r = \frac{Sbd^2}{L} \quad (3.3)$$

Where:

r = loading rate, lb/min (N/min),

S = rate of increase in maximum stress on the tension face, psi/min (MPa/min),

b = average width of the specimen as oriented for testing, in. (mm),

d = average depth of the specimen as oriented for testing, in. (mm), and

L = span length, in (mm).

The stress on the tension face was assumed to be 1.035 MPa and the loading rate is calculated as 3.45 kN/min. Also ASTM C78-07 recommends that results of two properly conducted tests by the same operator on beams made from the same batch sample should not differ from each other by more than 16 %.

The rollers for top and bottom were made in Construction Laboratory and in accordance with the requirements of ASTM C78-07 for rollers. The top rollers were mounted to a plate then the plate mounted firmly to the actuator, which is shown in figure 3.20.

Figure 3.20: Mounted Rollers for Flexural Test

The Instron Actuator is shown in figure 3.21.

Figure 3.21: Instron 100-Ton Actuator

Figure 3.22: Outside roller

Each specimen has been heated first to the target temperature in the big furnace. Then the heated specimen was transferred to the above furnace while was hot. The above furnace was already switched on and maintained the target temperature at least in the one-third of the span length.

While specimen was hot, the actuator was run by the technician at the specified loading rate. The load must be applied continuously and without shock until failure. The tension cracks should be within the middle third of the span length based on the ASTM C78-07. After failure the Flexural Strength or Modulus of Rupture was calculated by equation (3.4):

$$R = \frac{pL}{bd^2} \quad (3.4)$$

Where:

R = modulus of rupture, psi, or MPa,

P = maximum applied load indicated by the testing machine, lbf, or N,

L = span length, in., or mm,

b = average width of specimen, in., or mm, at the fracture, and

d = average depth of specimen, in., or mm, at the fracture.

After each test, the hot specimen was quenched in water to prevent any danger in the laboratory. The specimen during the test is shown in figure 3.23.

Figure 3.23: Testing Under progress

The results and discussion will be provided in next chapter.

3.2.3.3 Splitting Tensile Strength

Splitting Tensile strength test was done on concrete cylinders 150 mm in diameter and length of 300 mm. The same actuator was used for both flexural

strength test and the splitting tensile test. The rate of loading conformed the ASTM C496-07 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. According to this code the load must be applied continuously without shock, at a constant rate within the range 100 to 200 psi/min [0.7 to 1.4 MPa/min] splitting tensile stress until failure of the specimen. In this study the rate of loading was selected 1.05 MPa/min.

It should be mentioned here again that to make sure that the load will be distributed along the length of the cylinder two bearing strips of high-temperature resistant material was used. The bearing strips shall be placed between the specimen and both the upper and lower bearing blocks of the testing machine or between the specimen and supplemental bars or plates.

The test procedure is the same as flexural test; each specimen was heated first to the target temperature in the big furnace and then transferred to the furnace under the actuator. After failure, the failure load was calculated by equation (3.5):

$$T = \frac{2P}{\pi ld} \quad (3.5)$$

Where:

T = splitting tensile strength, psi or MPa,

P = maximum applied load indicated by the testing machine, lbf or N,

l = length, in. or mm, and

d = diameter, in. or mm.

After each test, the hot specimen was quenched in water to prevent any danger in laboratory. The specimen during the test is shown in figure 3.24.

Figure 3.24: Specimen under actuator after testing

3.4 Summary

The experimental methodology has been discussed in this chapter. The condition of thermal equilibrium was maintained throughout the experiments. The heating regime is been described. The new method to investigate the flexural strength at hot state was indicated. The results and discussion will be given in next chapter.

Chapter 4: Results and Discussion

4.1 Overview

This chapter presents the results from Flexural Strength and Splitting Tensile strength test of heated specimens. Both Residual and Hot measured Strengths are included in this chapter. Material properties that can be derived from experimental data obtained in this research are also discussed. As expected, at higher temperatures the Hot Flexural Strength and Splitting Tensile Strength differed from residual test values for both types of fibres, PP and steel fibres.

4.2 Test Results

4.2.1 Flexural Strength Test

4.2.1.1 Residual Flexural Strength

For each temperature, 3 specimens were selected and heated in the Furnace. The rate of heating was 2.5°C/min. After reaching the target temperature, the temperature was kept constant for 2 hours to reach an equilibrium state. After holding period, the furnace was turned off and the specimens were let to cool down to room temperature. Many surface cracks appeared on the surface of the specimens. At higher temperatures, the change of surface color was more severe.

The results of Flexural Strength at different temperatures have been shown in table 4.1.

Table 4.1: Residual Flexural Strength Results (MPa)

T(°C)	HSC0	HSCP08	HSCP14	HSCP20	HSCS08	HSCS14	HSCS20
29	6.94	7.36	7.97	8.18	8.60	8.89	9.33
250	6.26	6.40	7.25	7.79	7.60	7.91	8.19
350	5.06	5.54	6.59	7.05	5.77	6.05	6.50
550	1.58	1.81	2.42	2.50	2.58	3.31	3.97

Figure 4.1: Flexural Strength at Room Temperature

Figure 4.2: Residual Flexural Strength after heating to 250°C

Figure 4.3: Residual Flexural Strength after heating to 350°C

Figure 4.4: Residual Flexural Strength after heating to 550°C

4.2.1.2 Hot Flexural Strength

The procedure has been described before. The important part of this section is loading. The load was applied with 100-Ton Instron Actuator. Since the results were ranged between 3 to 35 kN, so the accuracy of the results seemed to us not satisfactory since 100-Ton actuator can apply loads as high as 1000 kN, so based on the maximum load capacity of the actuator the reading was very small and needed to be verified. For this reason a 5-Ton load cell was used to calibrate the Actuator. The result of calibration was in accordance with 100-ton actuator.

The results at different temperatures are shown in figure 4.5. For each temperature 3 specimens were put inside the big furnace, and then at the target temperature they were transferred to the designed furnace under the actuator by using a long clamping arm.

The temperature was measured after the specimen transferred to the testing machine. For measuring the surface temperature type K thermocouple was used. It is shown in figure 4.5.

Figure 4.5: Type K Thermocouple and its controller

The results at different temperature are as follows.

Table 4.2: Hot Flexural Strength Results(MPa)

T(°C)	HSC0	HSCP08	HSCP14	HSCP20	HSCS08	HSCS14	HSCS20
29	6.94	7.36	7.97	8.18	8.60	8.89	9.33
250	3.11	3.25	3.50	3.91	4.64	4.34	3.90
350	4.67	5.52	5.22	4.20	5.63	5.29	5.83
550	1.87	1.87	2.07	1.54	2.26	2.16	2.58

Figure 4.6: Hot Flexural Strength at 250°C for all samples

Figure 4.7: Hot Flexural Strength at 350°C for all samples

Figure 4.8: Hot Flexural Strength at 550°C for all samples

4.2.2 Splitting Tensile Strength Test

4.2.2.1 Residual Splitting tensile Strength

For each temperature, 3 specimens were selected and heated in the Furnace. The rate of heating was 2.5°C/min. After reaching the target temperature, the temperature was kept constant for 2 hours to reach an equilibrium state. After holding period, the furnace was turned off and the specimens were let to cool down to room temperature. The results of Splitting Tensile Strength at different temperatures have been shown in table 4.3.

Table 4.3: Residual Splitting Tensile Strength Results(MPa)

T(°C)	HSC0	HSCP08	HSCP14	HSCP20	HSCS08	HSCS14	HSCS20
29	5.41	5.74	5.79	6.01	6.03	6.16	6.64
250	4.23	4.33	4.66	4.81	4.86	5.15	5.48
350	3.35	3.01	3.50	3.63	3.45	3.85	4.22
550	2.17	1.80	1.96	2.41	2.44	2.49	2.97

Figure 4.9: Splitting Tensile Strength at Room Temperature

Figure 4.10: Residual Splitting Tensile Strength after heating to 250°C

Figure 4.11: Residual Splitting Tensile Strength after heating to 350°C

Figure 4.12: Residual Splitting Tensile Strength after heating to 550°C

4.2.2.2 Hot Splitting Tensile Strength

The results at different temperatures are shown in table 4.4. For each temperature 3 specimens were put inside the big furnace, and then at the target temperature they were transferred to the designed furnace under the Actuator by using a long clamping arm.

Table 4.4: Hot Splitting Tensile Strength Results(MPa)

T(°C)	HSC0	HSCP08	HSCP14	HSCP20	HSCS08	HSCS14	HSCS20
29	5.41	5.74	5.79	6.01	6.03	6.16	6.64
250	3.68	3.30	3.46	3.91	3.68	3.86	4.10
350	3.16	2.63	2.81	3.40	3.23	3.49	3.65
550	1.97	1.83	1.89	2.46	2.31	2.59	2.91

Figure 4.13: Splitting Tensile Strength at 250°C for all samples

Figure 4.14: Splitting Tensile Strength at 350°C for all samples

Figure 4.15: Splitting Tensile Strength at 550°C for all samples

4.3 Discussion

4.3.1 Flexural Strength

For better comparison, the Residual results and Hot results were depicted in the same figure. The comparisons at target temperatures can be found in the following figures.

The first two columns are the room temperature results but depicted in different colors to compare with other temperature results.

Figure 4.16: Comparison the Hot and Residual Flexural Strength for HSC0

Figure 4.17: Comparison the Hot and Residual Flexural Strength for HSCP08

Figure 4.18: Comparison the Hot and Residual Flexural Strength for HSCP14

Figure 4.19: Comparison the Hot and Residual Flexural Strength for HSCP20

It is obvious that at higher temperatures the Flexural Strength is lower than room temperature.

The results for High Strength Concrete with steel fibres can be seen in following figures.

Figure 4.20: Comparison the Hot and Residual Flexural Strength for HSCS08

Figure 4.21: Comparison the Hot and Residual Flexural Strength for HSCS14

Figure 4.22: Comparison the Hot and Residual Flexural Strength for HSCS20

It can be seen that at high temperatures up to 550 °C for both types of fibres, Hot result is lower than Residual one. At 550 °C, the results for HSCS are slightly higher than HSCP.

For all Residual tests the failure crack happened at the middle part of the beam. Although for Hot tests, the failure crack tended to form near the top rollers, which is because of the heat transfer during the loading and failure time. The middle part was continuously heated but the parts near the bottom rollers were not heated directly so the temperature difference between these parts led to formation of cracks near top rollers. The crack after hot test is shown in figure 4.23.

Figure 4.23: hot test Failure

As it can be seen for all of the hot test results at 250 °C due to the explosive failure the result is lower than 350 °C. The other fact which can be realized from the above figures is the effect of low percentage of fibres; as it can be seen for HSCS08 and HSCP08 the effect of fibres on residual and hot test is similar. However by adding more fibres the difference between hot and residual test is more considerable. Nevertheless, at 550 °C for both types of fibres, Residual strength and Hot Strength are quite low. For HSC with steel fibres the difference between the result of hot test and residual test is more

considerable compared to HSC with PP fibres. This behavior is due the fact that PP fibres will melt around 160 °C and steel fibres can remain effective until 700-800 °C.

4.3.2 Splitting Tensile Strength

The comparisons between the results of residual and hot test are shown in following figures.

Figure 4.24: Comparison the Hot and Residual Splitting Tensile Strength for HSC0

Figure 4.25: Comparison the Hot and Residual Splitting Tensile Strength for HSCP08

Figure 4.26: Comparison the Hot and Residual Splitting Tensile Strength for HSCP14

Figure 4.27: Comparison the Hot and Residual Splitting Tensile Strength for HSCP20

Figure 4.28: Comparison the Hot and Residual Splitting Tensile Strength for HSCS08

Figure 4.29: Comparison the Hot and Residual Splitting Tensile Strength for HSCS14

Figure 4.30: Comparison the Hot and Residual Splitting Tensile Strength for HSCS20

The Splitting Tensile strength for all HSCSs is higher than HSCPs which is reasonable due to the load-bearing capability of steel fibres and the effectiveness of steel fibres in bridging cracks induced upon tensile loading, as these fibres do not melt after heat exposition. Besides vaporization of free water at 100°C and loss of hydrates crystalline that take place in all series, HSCPs also underwent the melting of its fibres at 160–170°C and vaporization of fibres at approximately 340°C. This mechanism, which is preferable during heating exposure, is found to be the cause for significant reduction in properties of HSCPs.

The unusual behavior observed for flexural strength test at 250°C was not observed for tensile splitting strength. However the failure at 250 °C for both types of fibres was explosive and by increasing the test temperature the failure was less explosive. The specimen tested after hot test can be seen in figure 4.31.

Figure 4.31: Tested specimen after hot test

4.4 Summary

4.4.1 Summary of the results

Results for splitting tensile strength and flexural strength are summarized in tables 4.5 to 4.7.

Table 4.5: Results of all tests at 250°C

	250°C				
Mix	Flexural		Tensile splitting		
	Residual	Hot	Residual	Hot	
HSC0	6.26	3.11	4.23	3.68	No fibres
HSCP08	6.4	3.25	4.33	3.3	Polypropylene fibres
HSCP14	7.25	3.5	4.66	3.46	
HSCP20	7.79	3.91	4.81	3.91	
HSCS08	7.6	4.64	4.86	3.68	Steel fibres
HSCS14	7.91	4.34	5.15	3.86	
HSCS20	8.19	3.9	5.48	4.1	

Table 4.6: Results of all test at 350°C

	350°C				
Mix	Flexural		Tensile splitting		
	Residual	Hot	Residual	Hot	
HSC0	5.06	4.67	3.35	3.16	No fibres
HSCP08	5.54	5.52	3.01	2.63	Polypropylene fibres
HSCP14	6.59	5.22	3.5	2.81	
HSCP20	7.05	4.2	3.63	3.4	
HSCS08	5.77	5.63	3.45	3.23	Steel fibres
HSCS14	6.05	5.29	3.85	3.49	
HSCS20	6.5	5.83	4.22	3.65	

Table 4.7: Results of all test at 550°C

	550°C				
Mix	Flexural		Tensile splitting		
	Residual	Hot	Residual	Hot	
HSC0	1.58	1.87	2.17	1.97	No fibres
HSCP08	1.81	1.87	1.8	1.83	Polypropylene fibres
HSCP14	2.42	2.07	1.96	1.89	
HSCP20	2.5	1.54	2.41	2.46	
HSCS08	2.58	2.26	2.44	2.31	Steel fibres
HSCS14	3.31	2.16	2.49	2.59	
HSCS20	3.97	2.58	2.97	2.91	

Experimental tests on Flexural Strength and Tensile Splitting Strength of both types of fibres has shown that the Hot test result and Residual test result up to 350°C, which researchers found spalling would happen around this temperature, will differ and cannot be assumed the same especially in heat and mass transfer programs to investigate the spalling behaviour of high strength concrete. In addition, it was found that failure behavior at high temperature is not brittle and due to the limited design of the actuator it cannot be detected easily. At normal temperature, the failure behavior is brittle and actuator could easily detect the onset of cracking. This brittle failure was the main cause of explosive behaviors of samples during hot tests..

Chapter 5: Relationship between Temperature and Tensile Strength

5.1 Flexural Strength Relationship with Temperature

5.1.1 Residual Strength Relationship

The works done by researchers on residual Flexural Strength of concrete have been summarized in figures 5.1 to 5.3 with the results obtained in this study (Lau and Anson 2006; Li et al. 2004; Purkiss 1984; Sakr and El-Hakim 2005; Tanyildizi and Coskun 2008a; Xiao and Falkner 2006a). The figures show tensile strength for each series of specimens. Many factors affect the result for both types of fibres, such as different heating rates, different aggregates, type of cement and type of fibres used. For most cases at temperature around 800°C, tensile strength is only 10% of the strength at room temperature. The relationships obtained between residual Flexural strength of high strength concrete with and without fibres, based on the previous results and those obtained in this study, are expressed in following equations. Since the effect of temperature on Flexural strength up to 100°C is not considerable based on the result of this study and previous studies, the Flexural strength has been assumed same as room temperature strength up to 100°C which is the boiling point for water. After 100°C, the following linear formulas can be used to find the strength at higher temperatures up to 800°C after which the strength is only 10% of the strength at room temperature.

$$f_r = f_{rT_0} (-0.0012T + 1.12) \quad \text{HSC without fibres} \quad (5.1)$$

$$f_r = f_{rT_0} (-0.001414T + 1.1414) \quad \text{For HSC with PP fibres} \quad (5.2)$$

$$f_r = f_{rT_0} (-0.001186 T + 1.1186)$$

For HSC with Steel fibres (5.3)

Where

f_r = Flexural Strength, MPa

f_{rT_0} = Flexural Strength at room temperature, MPa

T = Temperature, Celsius

It should be noted that the above formulas are appropriate for temperature range of 100-800°C and fibre percentages of not less than 0.08% and not exceeding 0.20% of concrete volume. For temperatures above 800°C the strength is only 10% of the strength at room temperature.

Figure 5.1: Proposed equation with experimental data for Residual HSC without fibres

Figure 5.2: Proposed equation with experimental data for Residual HSC with PP fibres

Figure 5.3: Proposed equation with experimental data for Residual HSC with steel fibres

5.1.2 Hot Flexural Strength Relationship

One of the main objectives of this study was to perform hot state tests and compare the results with residual flexural strength result. Due to the limited works done on hot properties of concrete, there is no specific relationship between temperature and tensile strength. In this study relationships were obtained for different temperatures with or without fibres. Those relationships for High Strength Concrete with or without fibres are expressed in following equations. For hot test also the formulas can be used up to 800°C and after that the strength is only 10% of the strength at room temperature.

$$f_r = f_{rT_0} (-0.001276 T + 1.1276) \quad \text{HSC without fibres} \quad (5.4)$$

$$f_r = f_{rT_0} (-0.001312 T + 1.1312) \quad \text{For HSC with Steel fibres} \quad (5.5)$$

$$f_r = f_{rT_0} (-0.001359 T + 1.1359) \quad \text{For HSC with PP fibres} \quad (5.6)$$

Where

f_r = Flexural Strength, MPa

f_{rT_0} = Flexural Strength at room temperature, MPa

T = Temperature, Celsius

The proposed equations with all the results can be seen in figures 5.4 to 5.6. It can be seen that the regression lines from above equations showed a relatively good relationship between hot Flexural strength and temperature. However it must be considered that the proposed equations in this investigation for HSC with and without fibres are given only as a function of the temperature and Flexural strength, using a relatively small number of experimental data.

Figure 5.4: Proposed equation with experimental data for Hot HSC without fibres

Figure 5.5: Proposed equation with experimental data for hot HSC with steel fibres

Figure 5.6: Proposed equation with experimental data for hot HSC with PP fibres

5.2 Tensile Splitting Strength Relationship with Temperature

5.2.1 Residual Tensile Splitting Strength Relationship

The works done by researchers (Chan et al. 1999; Li et al. 2004; Peng et al. 2008; Saad et al. 1996; Sakr and El-Hakim 2005; Suhaendi and Horiguchi 2006; Tanyildizi and Coskun 2008b) on residual Splitting Tensile Strength of concrete have been summarized in figures 5.7 to 5.9. The results for high strength concrete are also depicted those figures. The figures show tensile strength for each series of specimens. Many factors affect the result for both types of fibres, such as different heating rate, different aggregates, type of cement and type of fibres used. For most cases at temperature around 600°C, Tensile strength is only 10%-15% of the strength at room temperature. The

relationships obtained between residual tensile splitting strength of high strength concrete with and without any fibres, based on the previous results and those obtained in this study, are expressed in following equations. Since the effect of temperature on tensile splitting strength up to 100°C is not considerable based on the result of this study and previous studies, the tensile splitting strength has been assumed same as room temperature strength up to 100°C which is the boiling point for water. After 100°C the following linear formulas can be used to find the strength at higher temperatures up to 650°C after which the strength is only 10%-15% of the strength at room temperature.

$$f_{sp} = f_{spT_0} (-0.00133T + 1.133) \quad \text{HSC without fibres} \quad (5.7)$$

$$f_{sp} = f_{spT_0} (-0.0015T + 1.15) \quad \text{For HSC with PP fibres} \quad (5.8)$$

$$f_{sp} = f_{spT_0} (-0.00125T + 1.125) \quad \text{For HSC with Steel fibres} \quad (5.9)$$

Where

f_{sp} = Tensile Splitting Strength, MPa

f_{spT_0} = Tensile Splitting Strength at room temperature, MPa

T = Temperature, Celsius

It should be noted that the above formulas are appropriate for temperature range of 100-650°C and fibre percentage between 0.08-0.20% of concrete volume. For temperatures above 650°C the strength is only 10% of the strength at room temperature. The results from this study with the above formulas are depicted in figures 5.7 to 5.9.

Figure 5.7: Proposed equation with experimental data for HSC without fibres

Figure 5.8: Proposed equation with experimental data for HSC with PP fibres

Figure 5.9: Proposed equation with experimental data for HSC with Steel fibres

5.2.2 Hot Tensile Splitting Strength Relationship

It is important to know the behavior of high strength concrete during hot test compare to residual test. Because there is no research available in the area of Hot test for tensile splitting strength, in this study the relationship obtained for Hot test is based on the results of this study. Those relationships for High Strength Concrete with or without fibres are expressed in following equations. For Hot test the formulas can be used up to 650°C and after that the strength is only 10%-15% of the strength at room temperature.

$$f_{sp} = f_{spT_0} (-0.00155T + 1.155) \quad \text{HSC without fibres} \quad (5.10)$$

$$f_{sp} = f_{spT_0} (-0.00165T + 1.165) \quad \text{For HSC with Steel fibres} \quad (5.11)$$

$$f_{sp} = f_{spT_0} (-0.0016T + 1.160) \quad \text{For HSC with PP fibres} \quad (5.12)$$

Where

f_{sp} = Tensile Splitting Strength, MPa

f_{spT_0} = Tensile Splitting Strength at room temperature, MPa

T = Temperature, Celsius.

The above formulas with the data form this study have been depicted in following figures. Since there are no Hot test results available, the above formulas are depicted together with the results of this study only.

It should be noted here again that above formulas are applicable for high strength concrete with and without fibres up to 650°C. For higher temperature for design purpose 10%-15% of the strength at room temperature can be used.

Figure 5.10: Proposed equation with experimental data for HSC without fibres

Figure 5.11: Proposed equation with experimental data for HSC with steel fibres

Figure 5.12: Proposed equation with experimental data for HSC with PP fibres

It can be seen that the regression lines from above equations showed a relatively good relationship between the residual and hot splitting tensile

strength with temperature.

5.3 Summary

Various experiments were conducted to determine the behavior of HSC with various types of fibres subjected to elevated temperature. Experimental results were used to verify the proposed models for hot and residual flexural strength and tensile splitting strength. Hot and residual tensile strength can be predicted by proposed models if the strength at room temperature is known. The design curve for both types of fibres, and for both flexural strength and tensile splitting strength will be presented in next chapter.

Chapter 6: Conclusions and Recommendations

6.1 Summary and Conclusions

The flexural strength and splitting tensile Strength of concrete exposed to high temperature were investigated. Methods were used to measure the strength at high temperatures. The significance of this research is the difference between hot and residual results. In analysis for heat and mass transfer, the tensile strength of concrete is required to model the spalling behaviour of concrete. The behaviour of split cylinder tensile strength of concrete subjected to elevated temperature was derived from the works by Carette et al. (Carette et al. 1982). They conducted experiments to determine the residual compressive and tensile strength of concrete subjected to various elevated temperature. Tensile splitting strength was observed to increase when heated to temperatures less than 200°C and decrease at temperatures beyond 200°C. The w/c of test specimens used by Carette et al. (Carette et al. 1982) was 0.45 and 0.60.

Many researchers have shown that tensile strength of concrete at heated and residual state is same. From experimental investigations on the heated and residual compressive strength of concrete, researchers generally observed that the cracks formed during cooling lowers the residual compressive strength. From this observation they deduced that the residual tensile strength of concrete must be lower than hot tensile strength. Nevertheless, this report shows that the result of Hot and Residual tensile Strength is not same. However the difference between the results at higher temperatures is not significant. Based on the results of this study and results from other literature

two design curves were developed for prediction of flexural strength and tensile splitting strength at different temperatures. The normalized design curves can be seen in following figures.

Figure 6.1: Normalized Design curves for Flexural Strength at different temperatures

Figure 6.2: Normalized Design curves for Tensile Splitting strength at different temperatures

However, the results at 250°C due to explosive behaviour of the test were neglected. Further verification for this temperature is necessary. The use of bi-linear model for prediction of tensile properties at high temperatures is based on the fact that heating the concrete to constant mass at 105°C, as much as 60% of the mixing water is lost while the remaining 40% of the mixing water remains as non-evaporable water (England and Khoylou 1993). Based on this fact and also the observations during the experimental program the bi-linear models were used to evaluate the tensile properties at high temperatures.

The following lists the major conclusions made from this research.

1. Experimental tests on Flexural and Tensile splitting Strength of High Strength Concrete has shown that the Hot test result and Residual test result up to 550 °C, will differ and can not be assumed the same especially in heat and mass transfer programs used to investigate the spalling behavior of high strength concrete. However the difficulties in hot test procedure have enforced researchers to perform the residual test rather than hot test. But a comparison for residual and hot test results was needed which initiated this research..
2. The effect of low percentage of fibres on flexural strength of concrete is not significant. The results show the effect of 0.08% of PP or steel fibres at different temperatures is not considerable, except at 250°C. At this temperature the explosive failure was the main cause for the loss in strength for flexural strength. However this behavior was not seen for tensile splitting test.
3. The effect of high temperatures on the tensile properties of concrete was

more significant for concrete mixtures produced by steel fibres compare to Polypropylene fibres.

4. The mixture with steel fibres shows higher strength than the mixture without any Fibres. At high temperatures, the difference between the results is not significant. This can be attributed to the fact that steel will be soft at high temperatures, so effect of steel on Flexural and Tensile Splitting Strength and prevention of crack opening is not significant.

5. The models proposed for estimating the hot and residual Flexural and Tensile Splitting Strength of concrete can be used for high strength concrete and also in heat and mass transfer for prediction of spalling.

6.2 Recommendations for Future Research

The following recommendations for future research are made based on the findings of this research.

1. The proposed models to predict flexural and tensile splitting strength of high strength concrete require more experimental verification. Studies should be done to consider other parameters such as exposure time to heat and different heating rates that are related to flexural and tensile splitting strength at high temperatures.
2. Flexural and tensile splitting strength tests involving mix proportion of different volume of sand and aggregate but constant w/c should be conducted to verify the changes of strength with aggregate and sand.
3. The study on the effects of microstructure on tensile properties of concrete should be conducted to improve the accuracy of the proposed models.

4. Different types of steel and polypropylene fibres should be used for different mix proportions to verify the effect of shape and dimension of the fibres on tensile properties.

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Appendix A

Summary of Reported Flexural Strength can be seen in following tables.

Table A.1: Hot HSC0 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	23.71	7.11
	22.36	6.71
	23.32	7.00
250	12.00	3.60
	9.60	2.88
	9.50	2.85
350	19.00	5.70
	16.50	4.95
	11.30	3.39
550	6.81	2.04
	6.30	1.89
	5.62	1.69

Table A.2: Residual HSC0 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	23.71	7.11
	22.36	6.71
	23.32	7.00
250	22.21	6.66
	19.40	5.82
	21.00	6.30
350	17.10	5.13
	18.00	5.40
	15.50	4.65
550	7.60	2.28
	7.50	2.25
	9.10	2.73

Table A.3: Hot HSCP08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	22.41	6.72
	24.70	7.41
	26.45	7.94
250	11.00	3.30
	10.30	3.09
	11.20	3.36
350	18.70	5.61
	17.90	5.37
	19.40	5.82
550	6.74	2.02
	5.73	1.72
	6.69	2.01

Table A.4: Residual HSCP08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	22.41	6.72
	24.70	7.41
	26.45	7.94
250	19.80	5.94
	20.65	6.20
	23.65	7.10
350	17.60	5.28
	18.90	5.67
	19.10	5.73
550	6.00	1.80
	6.10	1.83
	6.00	1.80

Table A.5: Hot HSCP14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	26.25	7.88
	28.41	8.52
	25.00	7.50
250	12.22	3.67
	11.10	3.33
	11.66	3.50
350	17.20	5.16
	17.90	5.37
	17.00	5.10
550	6.78	2.03
	7.30	2.19
	6.66	2.00

Table A.6: Residual HSCP14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	26.25	7.88
	28.41	8.52
	25.00	7.50
250	26.85	8.06
	25.50	7.65
	20.20	6.06
350	21.00	6.30
	22.00	6.60
	22.86	6.86
550	8.97	2.69
	7.50	2.25
	7.70	2.31

Table A.7: Hot HSCP20 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	27.11	8.13
	28.16	8.45
	26.51	7.95
250	12.80	3.84
	14.40	4.32
	12.66	3.80
350	13.40	4.02
	13.10	3.93
	15.53	4.66
550	5.50	1.65
	5.13	1.54
	4.74	1.42

Table A.8: Residual HSCP20 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	27.11	8.13
	28.16	8.45
	26.51	7.95
250	24.20	7.26
	26.50	7.95
	26.80	8.04
350	22.20	6.66
	24.20	7.26
	23.80	7.14
550	8.71	2.61
	8.83	2.65
	7.50	2.25

Table A.9: Hot HSCS08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	28.70	8.61
	29.00	8.70
	28.32	8.50
250	15.20	4.56
	14.90	4.47
	16.20	4.86
350	20.10	6.03
	17.00	5.10
	19.20	5.76
550	6.90	2.07
	7.70	2.31
	8.00	2.40

Table A.10: Residual HSCS08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	28.70	8.61
	29.00	8.70
	28.32	8.50
250	26.40	7.92
	25.20	7.56
	24.70	7.41
350	20.00	6.00
	19.50	5.85
	18.20	5.46
550	7.30	2.19
	9.84	2.95
	7.34	2.20

Table A.11: Hot HSCS14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	29.70	8.91
	29.50	8.85
	29.80	8.94
250	13.30	3.99
	14.22	4.27
	15.83	4.75
350	17.58	5.27
	18.10	5.43
	17.20	5.16
550	6.90	2.07
	7.00	2.10
	7.70	2.31

Table A.12: Residual HSCS14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	29.70	8.91
	29.50	8.85
	29.80	8.94
250	25.35	7.61
	26.76	8.03
	27.02	8.11
350	20.17	6.05
	20.84	6.25
	19.50	5.85
550	11.12	3.34
	11.17	3.35
	10.85	3.26

Table A.13: Hot HSCS20 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	31.28	9.38
	31.78	9.53
	30.21	9.06
250	13.00	3.90
	13.10	3.93
	12.80	3.84
350	20.30	6.09
	18.30	5.49
	19.80	5.94
550	9.40	2.82
	8.35	2.51
	8.00	2.40

Table A.14: Residual HSCS20 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	31.28	9.38
	31.78	9.53
	30.21	9.06
250	28.30	8.49
	27.10	8.13
	26.50	7.95
350	20.30	6.09
	21.90	6.57
	22.70	6.81
550	15.00	4.50
	13.00	3.90
	11.70	3.51

Summary of Reported Splitting Tensile Strength can be seen in following tables.

Table A.15: Hot HSC0 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	409	5.79
	347	4.91
	390	5.52
250	270	3.82
	250	3.54
	255	3.61
350	237	3.35
	223	3.15
	211	2.99
550	127	1.80
	140	1.98
	150	2.12

Table A.16: Residual HSC0 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	409	5.79
	347	4.91
	390	5.52
250	275.5	3.90
	298.3	4.22
	323.6	4.58
350	232	3.28
	243	3.44
	236	3.34
550	153	2.16
	154	2.18
	148	2.09

Table A.17: Hot HSCP08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	413	5.84
	406	5.74
	399	5.64
250	221.1	3.13
	224.5	3.18
	254	3.59
350	191.4	2.71
	180	2.55
	178	2.52
550	110.8	1.57
	149	2.11
	128.6	1.82

Table A.18: Residual HSCP08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	413	5.84
	406	5.74
	399	5.64
250	310	4.39
	309.1	4.37
	299.8	4.24
350	223.8	3.17
	201.1	2.84
	198	2.80
550	132	1.87
	146	2.07
	103.6	1.47

Table A.19: Hot HSCP14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	422.2	5.97
	398	5.63
	407.5	5.76
250	255	3.61
	245	3.47
	234.6	3.32
350	189	2.67
	190	2.69
	217.4	3.08
550	119.3	1.69
	118.8	1.68
	162.8	2.30

Table A.20: Residual HSCP14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	422.2	5.97
	398	5.63
	407.5	5.76
250	287	4.06
	411	5.81
	290	4.10
350	259	3.66
	238	3.37
	246	3.48
550	132	1.87
	145	2.05
	138	1.95

Table A.21: Hot HSCP20 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	434	6.14
	420	5.94
	421	5.96
250	250	3.54
	290	4.10
	289	4.09
350	241	3.41
	235	3.32
	245	3.47
550	166	2.35
	190	2.69
	165	2.33

Table A.22: Residual HSCP20 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	434	6.14
	420	5.94
	421	5.96
250	350	4.95
	330	4.67
	340	4.81
350	256	3.62
	256	3.62
	258	3.65
550	162	2.29
	160	2.26
	188	2.66

Table A.23: Hot HSCS08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	419.2	5.93
	449.8	6.36
	410.5	5.81
250	265	3.75
	240	3.40
	276	3.90
350	220	3.11
	225	3.18
	231	3.27
550	179.1	2.53
	170	2.41
	140	1.98

Table A.24: Residual HSCS08 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	419.2	5.93
	449.8	6.36
	410.5	5.81
250	349.7	4.95
	346.8	4.91
	333.9	4.72
350	250	3.54
	240	3.40
	242	3.42
550	188	2.66
	189	2.67
	140	1.98

Table A.25: Hot HSCS14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	496	7.02
	408	5.77
	402	5.69
250	260	3.68
	280	3.96
	278.6	3.94
350	269	3.81
	233	3.30
	238	3.37
550	195	2.76
	175	2.48
	180	2.55

Table A.26: Residual HSCS14 Results

Temperature°C	Load(kN)	Tensile Splittting Strength(MPa)
29	496	7.02
	408	5.77
	402	5.69
250	368.6	5.21
	335	4.74
	387.7	5.48
350	270	3.82
	274	3.88
	268	3.79
550	171	2.42
	179	2.53
	178	2.52

Table A.27: Hot HSCS20 Results

Temperature°C	Load(kN)	Tensile Splitting Strength(MPa)
29	483.9	6.85
	446.9	6.32
	476.8	6.75
250	280	3.96
	300	4.24
	286	4.05
350	256	3.62
	260	3.68
	261	3.69
550	220	3.11
	199	2.82
	199	2.82

Table A.28: Residual HSCS20 Results

Temperature°C	Load(kN)	Tensile Splitting Strength(MPa)
29	483.9	6.85
	446.9	6.32
	476.8	6.75
250	387	5.47
	398	5.63
	378	5.35
350	310	4.39
	287	4.06
	294	4.16
550	215	3.04
	205	2.90
	209	2.96

Summary of results obtained from models for Flexural and Tensile Splitting Strength are presented in following tables.

Table A.29: Results obtained from Normalized models for Residual Flexural Strength

	HSC0-Residual	HSCS-Residual	HSCP-Residual
T _C			
25	1	1	1
40	1	1	1
50	1	1	1
60	1	1	1
70	1	1	1
80	1	1	1
90	1	1	1
100	1	1	1
100	1	1	1
110	0.99	0.99	0.99
130	0.96	0.96	0.96
150	0.94	0.94	0.93
170	0.92	0.92	0.90
190	0.89	0.89	0.87
210	0.87	0.87	0.84
230	0.84	0.85	0.82
250	0.82	0.82	0.79
270	0.80	0.80	0.76
290	0.77	0.77	0.73
310	0.75	0.75	0.70
330	0.72	0.73	0.67
350	0.70	0.70	0.65
370	0.68	0.68	0.62
390	0.65	0.66	0.59
410	0.63	0.63	0.56
430	0.60	0.61	0.53
450	0.58	0.58	0.51
470	0.56	0.56	0.48

T _C	HSC0-Residual	HSCS-Residual	HSCP-Residual
490	0.53	0.54	0.45
510	0.51	0.51	0.42
530	0.48	0.49	0.39
550	0.46	0.47	0.36
570	0.44	0.44	0.34
590	0.41	0.42	0.31
610	0.39	0.40	0.28
630	0.36	0.37	0.25
650	0.34	0.35	0.22
670	0.32	0.32	0.19
690	0.29	0.30	0.17
700	0.28	0.29	0.15
710	0.27	0.28	0.14
730	0.24	0.25	0.11
750	0.22	0.23	0.08
770	0.20	0.21	0.05
790	0.17	0.18	0.02
800	0.16	0.17	0.01

Table A.30: Results obtained from Normalized models for Hot Flexural Strength

	HSC0-Hot	HSCS-Hot	HSCP-Hot
T _C			
25	1	1	1
40	1	1	1
50	1	1	1
60	1	1	1
70	1	1	1
80	1	1	1
90	1	1	1
100	1	1	1
100	1	1	1
110	0.99	0.99	0.99
130	0.96	0.96	0.96

T ₀	HSC0-Hot	HSCS-Hot	HSCP-Hot
150	0.94	0.93	0.93
170	0.91	0.91	0.90
190	0.89	0.88	0.88
210	0.86	0.86	0.85
230	0.83	0.83	0.82
250	0.81	0.80	0.80
270	0.78	0.78	0.77
290	0.76	0.75	0.74
310	0.73	0.72	0.71
330	0.71	0.70	0.69
350	0.68	0.67	0.66
370	0.66	0.65	0.63
390	0.63	0.62	0.61
410	0.60	0.59	0.58
430	0.58	0.57	0.55
450	0.55	0.54	0.52
470	0.53	0.51	0.50
490	0.50	0.49	0.47
510	0.48	0.46	0.44
530	0.45	0.44	0.42
550	0.43	0.41	0.39
570	0.40	0.38	0.36
590	0.37	0.36	0.33
610	0.35	0.33	0.31
630	0.32	0.30	0.28
650	0.30	0.28	0.25
670	0.27	0.25	0.23
690	0.25	0.23	0.20
700	0.23	0.21	0.18
710	0.22	0.20	0.17
730	0.20	0.17	0.14
750	0.17	0.15	0.12
770	0.15	0.12	0.09
790	0.12	0.09	0.06
800	0.11	0.08	0.05

Table A.31: Results obtained from Normalized models for Residual Splitting Tensile Strength

	HSC0-Residual	HSCS-Residual	HSCP-Residual
T ₀			
10	1	1	1
20	1	1	1
30	1	1	1
40	1	1	1
50	1	1	1
60	1	1	1
70	1	1	1
80	1	1	1
90	1	1	1
100	1	1	1
101	1	1	1
125	0.96	0.97	0.96
150	0.93	0.94	0.93
175	0.90	0.91	0.89
200	0.86	0.88	0.85
225	0.83	0.84	0.81
250	0.80	0.81	0.78
275	0.76	0.78	0.74
300	0.73	0.75	0.70
325	0.70	0.72	0.66
350	0.66	0.69	0.63
375	0.63	0.66	0.59
400	0.60	0.63	0.55
425	0.56	0.59	0.51
450	0.53	0.56	0.48
475	0.50	0.53	0.44
500	0.47	0.50	0.40
525	0.43	0.47	0.36
550	0.40	0.44	0.33
575	0.37	0.41	0.29
600	0.33	0.38	0.25
625	0.30	0.34	0.21
650	0.27	0.31	0.18

Table A.32: Results obtained from Normalized models for Hot Splitting Tensile Strength

	HSC0-Hot	HSCS-Hot	HSCP-Hot
T°C			
10	1	1	1
20	1	1	1
30	1	1	1
40	1	1	1
50	1	1	1
60	1	1	1
70	1	1	1
80	1	1	1
90	1	1	1
100	1	1	1
101	1	1	1
125	0.96	0.96	0.96
150	0.92	0.92	0.92
175	0.88	0.88	0.88
200	0.85	0.84	0.84
225	0.81	0.79	0.80
250	0.77	0.75	0.76
275	0.73	0.71	0.72
300	0.69	0.67	0.68
325	0.65	0.63	0.64
350	0.61	0.59	0.60
375	0.57	0.55	0.56
400	0.54	0.51	0.52
425	0.50	0.46	0.48
450	0.46	0.42	0.44
475	0.42	0.38	0.40
500	0.38	0.34	0.36
525	0.34	0.30	0.32
550	0.30	0.26	0.28
575	0.26	0.22	0.24
600	0.23	0.18	0.20
625	0.19	0.13	0.16
650	0.15	0.09	0.12