# FIRE-DAMAGED NORMAL CONCRETE PROPERTIES AND BOND STRENGTH EVALUATION OF ULTRA HIGH PERFORMANCE FIBRE REINFORCED CONCRETE AS A REPAIR MATERIAL

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By

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| | |
|---|---|
| ACI | American Concrete Institute |
| AD | Air Dry |
| ASTM | American Standard Test Method |
| $CaCO_3$ | Calcium Carbonate |
| $Ca(OH)_2$ | Calcium hydroxide |
| $CaSO_4$ | Calcium Sulphate |
| CFRP | Carbon Fibre Reinforced Polymer |
| $C_2S$ | Di-calcium Silicate |
| COV | Coefficient Of Variation |
| CSH | Calcium Silicate Hydrate |
| FDNC | Fire-damaged Normal Concrete |
| FRP | Fibre Reinforced Polymer |
| GFRP | Glass Fibre Reinforced Polymer |
| HPFRCC | High Performance Fibre Reinforced Cementitiuous Composite |
| HSC | High Strength Concrete |
| ITZ | Interfacial Zone |
| ISAT | Initial Surface Absorption Test |
| LAC | Left As Cast |
| MSST | Modified Slant Shear Test |
| NC | Normal Concrete |
| NSC | Normal Strength Concrete |
| OPC | Ordinary Portland Cement |
| RC | Reinforced Concrete |

| | |
|---|---|
| SCC | Self-Compacting Concrete |
| SCT | Splitting Cylinder Test |
| SEM | Scanning Electron Microscopy |
| SHB | Shot Blasting |
| SHSC | Super High Strength Concrete |
| SSD | Saturated Surface Dry |
| SST | Slant Shear Test |
| TR | Technical Report |
| UHPFRC | Ultra-High Performance Fibre Reinforced Concrete |
| UHSC | Ultra-High Strength Concrete |
| UPV | Ultrasonic Pulse Velocity |
| VHSC | Very High Strength Concrete |
| WT | Wet |
| WB | Wire Brushing |

# LIST OF SYMBOLS

| | |
|---|---|
| $Y$ | Percentage of loose in column strength |
| $X$ | Fire duration in hours. |
| $t$ | Test point time period in seconds |
| $D$ | Number of scale divisions during the period |
| $f$ | Flow in millimetre / meter$^2$ / second |
| $W_{\mathrm{d}}$ | Dry weight |
| $W_{\mathrm{ssd}}$ | Weighted in air |
| $W_{\mathrm{s}}$ | Weight in water |
| $P$ | Maximum load applied |
| $A$ | Total area of the bonded |
| $T$ | Splitting tensile strength |
| $S$ | Slant shear strength |
| $S_{po}$ | Pull-off strength |

**SIFAT- SIFAT KONKRIT NORMAL SELEPAS DIBAKAR DAN PENILAIAN KEKUATAN IKATAN KONKRIT GENTIAN BERTETULANG PRESTASI TINGGI SEBAGAI BAHAN BAIK PULIH**

## ABSTRAK

Umum mengetahui bahawa sifat mekanikal struktur konkrit merosot selepas terdedah kepada api. Kerja-kerja pembaikkan dan pengukuhan adalah penting bagi meningkatkan ketahanan struktur ini. Oleh yang demikian, Konkrit Gentian Bertetulang Prestasi Tinggi(UHPFRC) telah digunakan sebagai bahan pembaikkan berikutan kekuatannya yang sesuai. Kajian ini menilai sifat-sifat mekanikal dan fizikal substrat konkrit biasa tertakluk kepada tempoh pemanasan yang berbeza, mengenal pasti keadaan kelembapan permukaan substrat yang paling sesuai dalam membaiki konkrit yang terdedah kepada suhu yang tinggi dan untuk mengkaji kesan jangka masa pemanasan substrat terhadap kekuatan ikatan dan jenis kegagalan berlaku. Sebagai permulaan, pada usia 28 hari spesimen konkrit normal akan didedahkan kepada suhu 600°C selama 30, 60, 90, 120 dan 150 minit. Perubahan sifat konkrit yang telah dibakar (FDNC) dari segi kualiti, jisim, kekuatan mampatan dan warna akan diteliti. Antara ujian untuk menilai sifat-sifat konkrit selepas terbakar yang telah dilaksanakan adalah Ujian Kekuatan Mampatan, Ujian Lantunan Tukul (*Rebound Hammer Test*), Ujian Halaju Gelombang Denyut Ultrasonic (*Ultrasonic Pulse Velocity Test*), Ujian Penyerapan Awalan Pemukaan (*Initial Surface Absorption Test*), Ujian Keliangan dan Penyerapan Air. Seterusnya, konkrit yang telah terdedah kepada suhu yang tinggi itu dibaiki dengan menggunakan UHPFRC. Permukaan substrat adalah dalam keadaan letupan pasir (*sandblasted*) dan dibasahkan secara tiga kaedah iaitu kering (AD), permukaan kering tepu (SSD) dan

basah (WT). Dari peringkat ini, keadaan lembapan optimum yang memberikan kekuatan ikatan tertinggi akan digunakan dalam langkah seterusnya. Kemudian, ujian untuk menguji kekuatan ikatan seperti Ujian Tegangan Silinder (*splitting cylinder test*), Ujian Lereng Ricih (*slant shear test*) dan *Pull off test* akan dijalankan. Hasil kajian telah menunjukkan bahawa keadaan kelembapan substrat mempengaruhi FDNC kekuatan ikatan dengan UHPFRC. Berdasarkan ujian yang dijalankan, keadaan SSD adalah digalakkan dan permukaan substrat tidak seharusnya dalam keadaan kering. Dalam suhu yang sama, jangka masa pemanasan menyebabkan darjah kerosakan yang berbeza ke atas konkrit. Jika konkrit normal dibakar dalam tempoh masa yang lama, kehilangan kekuatan mampatan, kekuatan tegangan, ketegangan dan keretakkan akan berlaku. Konkrit tersebut juga menjadi semakin tidak berkualiti. Tempoh pemanasan substrat, juga memberi kesan kepada kekuatan ikatan mereka dengan UHPFRC. Kerosakan substrat ini pasti memberi kesan negatif kepada kekuatan ikatan mereka dengan UHPFRC. Kebanyakan mod kegagalan berlaku adalah melalui substrat FDNC. Ia menunjukkan bahawa, kekuatan substrat sebenarnya adalah lebih rendah daripada kekuatan ikatan.

# FIRE-DAMAGED NORMAL CONCRETE PROPERTIES AND BOND STRENGTH EVALUATION OF ULTRA HIGH PERFORMANCE FIBRE REINFORCED CONCRETE AS A REPAIR MATERIAL

## ABSTRACT

It is well known that the mechanical properties of concrete structure deteriorate after exposure to fire. Repair and strengthening in order to improve the performance of the affected structure has become critical. Ultra High Performance Fibre Reinforced Concrete (UHPFRC) has been used as repair material due to its superior properties. The aim of this study is to evaluate mechanical and physical characteristic of normal concrete substrate subjected to different heating duration, to identify the most suitable substrate surface moisture condition in repairing fire-damaged concrete and to investigate the effect of substrate heating duration subjected to the bond strength and type of failure occur. Firstly, at the age of 28 days all normal concrete specimens were heated up. The temperatures are 600°C for 30, 60, 90, 120 and 150 minutes. The changes of Fire-damaged Normal Concrete (FDNC) in term of quality, mass, compressive strength and colour were examined. Several tests conducted to evaluate the properties of concrete after fires were Compressive Test, Rebound Hammer Test, Ultra-sonic Pulse Velocity Test, Initial Surface Absorption Test, Porosity and Water Absorption Test. Next, all the fire-damaged samples repaired with using UHPFRC. The substrate surface was sand blasted and moistened by three methods which are Air Dry (AD), Saturated Surface Dry (SSD) and Wet (WT). From this stage, the optimum moisture condition which gives highest bond strength was used in the next step. Then, the test to verify their bond strength namely Splitting Tensile Test, Slant Shear Test and Pull Off Test conducted. The result indicates that the substrate moisture condition influences FDNC bonding strength with UHPFRC. Based on the

tests conducted, SSD condition is favourable while the substrate surface should not in dry state. With same degree of temperature, the heating durations give various degree of damaged on concrete. As the heating duration increase, normal concrete loss its compressive strength, tensile strength, stiffness and cracking occurred. The quality of concrete also reduced. Heating duration of normal concrete substrate, also affects their bonding strength with UHPFRC. These substrate damages surely give negative effects to their bonding strength with UHPFRC. Most of the failure occurs in the tests are through the FDNC substrate. The most frequent failure mode occurred was the failure at the interface with minor substrate crushing. It is indicated that the substrate strength was lower than the bond strength.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of study

Concrete have been used as construction material since previous era. The first construction using concrete was done by the Romans, who mixed the lime, pozzolan, rubble and water together. In $19^{th}$ century, by doing some changes to the ancient mix, the Portland cement emerges (Gromicko and Shepard, 2015). Nowadays, Portland cement becomes the most widely used as a construction material. This material has excellent durability, readily available and relatively low cost. However, concrete have its poor side too. Concrete is very sensitive to the conditions in which it is mixed and applied. There are many causes and conditions that will make concrete become vulnerable. Concrete deterioration might be caused by chemical attack, aggression by physical element such as high temperature, aggression by mechanical elements (abrasion, impact, erosion and cavitation) and defects (Santhakumar, 2007).

One of the advantages of concrete over other building materials is its inherent fire-resistance properties. However, it is important to design the concrete structures for fire. Structural components need to withstand dead and impose loads without collapse even though there is decrease in strength and modulus of elasticity due to high temperature. In addition, heat will caused structural component expansion. Furthermore, if reinforced concrete (RC) buildings exposed to accidental, their major component such as columns, beams and slabs will crack, spall and loss in the bearing capacity. Figure 1.1 shows the spalling of concrete beam and column.

Figure 1.1 Spalling of concrete to beam and a column caused by fire (Rogerson, 2017)

The rehabilitation techniques appeared as a problem solver in questions related to degradation of concrete structures. Now, the repair material and techniques were developed. It was important to find effective and economic solutions for the problems. Excellent repair works can be achieved by choosing the right repair material. A good repair material should have some special properties which are high performance, high durability but low maintenance. It should be easy to use, increase productivity, reduce construction cycle time, environmental friendly and did not increase load supported by the repaired component. The various useable repair materials are Portland cement based material, micro concrete, resin-based product, polymer modified product, fibre reinforced cement composite, high performance concrete, and Fibre Reinforced Polymer (FRP) composites (Santhakumar, 2007). These repair materials have proved to be effective if chosen and applied properly. Previously works by Tayeh et al. (2013a) stated that the usage of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) as a repair material is accountable. The excellent performance of UHPFRC which have high durability making it suitable for rehabilitation and retrofitting works.

The UHPFRC has more than 150 MPa compressive strength. It also has more than 10 MPa tensile strength and excellent durability. The presence of fibre in concrete helps in increase it resistance to severe condition and also strengthen it. This fibre concrete also has higher strength, and toughness than conventional normal strength concrete. Furthermore, by carrying all this superior properties, UHPFRC is able to be good repair material which can form a super bond with old concrete and able to maintain substrate structural integrity. When mentioning concrete repair in general, one of the common essential aspect that should be taken care is the bond between existing and new concrete. Bond strength eventually determines whether the repair work is successful or not. Good bond strength describe as the ability of these two materials performed monolithic action. The repaired specimen should act as one entity rather than two separate materials (Silfwerbrand et al., 2011). The quality assurance of bond, request for test methods that can assess the bond as well as identify the failure mode.

The research on application of UHPFRC as a repair materials are still in progress. However, the behaviour of UHPFRC as a repair material on old concrete substrate still available (Tayeh et al.,2013a) and (Tayeh et al.,2013b). There is limitation information regarding to the performance of UHPFRC in terms of their bond strength with fire-damaged normal concrete substrate. In this regards, this research aims at studying the properties of normal concrete after fire and their bond strength with UHPFRC. The changes causes by heating duration and substrate moisture condition on bond strength, which has not yet accomplish vastly by previous researcher also being studied.

## 1.2 Problem Statement

Previous researchers such as Al-Rousan et al. (2015), Kai et al. (2011) and Haddad and Almasaeid (2016) used Fibre Reinforced Polymers (FRP) for strengthening fire-damaged concrete. FRP proves to be good repair material for fire-damaged concrete but there is some shortcomings in its application. FRP lacks in shear strength, cannot be used when there is heavy deflection, poor performance when exposed to high temperature, the failure action is brittle, can be ruptured, and not environmental friendly materials (Masuelli, 2013). So, it is challenges to form an efficient repair system that enable fire-damaged structure regain their structural integrity. Cementitious based repair material was preferred as it does provide excellent fire proofing, and more durable. UHPFRC was known as one of the strongest material for concrete structures. UHPFRC can also be an admirable repair material for an old substrate (Tayeh et al., 2013a). But there is no 'universally good' repair material. There were different repair material for different purpose, conditions and environment (Emmons and Vaysburd, 1994).

Until now, the applications of UHPFRC as a repair material especially to the fire-damaged concrete structure are rarely looked into. Fire portrays as one of the most extreme environmental condition which structure can subjected to (Kodur, 2014). The behaviour of concrete due to high temperature is very complex and thorough study should be done in order to understand it. The mechanical and physical property of concrete before and after fire should be evaluated. Levels of concrete damage might be different depends on fire severity and the high temperature levels reached. As in real situation, the fire duration might be varies, depending on the time for fire brigade to come. The extent of concrete damaged and the repair design scheme might be different too. High cost of full replacement, result in need of cost-effective and suitable solution for rehabilitation (Harris et al., 2014).

Previously, the bond strength of UHPFRC with old normal concrete substrate was evaluated. Bond strength of concrete influenced by several factors which are surface roughness, surface moisture conditions, differential stiffness and the type of bonding agent. As substrate exposed to high temperature it's assumed to experience major moisture loss. So, preferable surface moisture conditions, especially to achieve good bond with fire-damaged substrate is needed. However, as concrete can be deteriorated by various factors. It is necessary to prove that UHPFRC can be used as repair material particularly to the fire-damaged concrete structures. This study contributes added value to existing knowledge regards to the behaviour of UHPFRC as a repair material to high temperature. The UHPFRC can also be commercialised as a repair material after fire.

## 1.3 Objectives of study

This study has three main objectives, and outlined as follows:

i. To evaluate mechanical and physical characteristics of normal concrete substrate (FDNC) subjected to different heating durations.

ii. To identify the most suitable substrate surface moisture condition in repairing fire-damaged concrete.

iii. To investigate the effect of substrate heating durations and ages towards bond strength and type of failure occur when repaired with UHPFRC material.

## 1.4 Scope of work

The experimental study involved in the determination of mechanical and physical properties of FDNC substrate before and after fire. The normal concrete was heated up to 600 °C for 30, 60, 90, 120 and 150 minutes. Several tests conducted to evaluate these properties were Compressive Test, Rebound Hammer Test, Ultra-sonic Pulse Velocity Test, Initial Surface Absorption Test, Porosity and Water Absorption Test. The changes of Fire-Damaged Normal Concrete (FDNC) in term of quality, mass, compressive strength and colour were examined. Next, all the fire-damaged samples repaired with using UHPFRC. The surface of FDNC substrate was sand blasted. Steam curing was used to cure the composite FDNC+UHPFRC sample.

Before placing UHPFRC on the FDNC substrate, their surfaces were moistened. The surface of substrate will be prepared as Air Dry (AD), Saturated Surface Dry (SSD) and Wet (WT). The best moisture condition was selected and used in the next step. By using the optimum moisture condition selected in previous step, the effects of substrate heating duration on UHPFRC+FDNC bond strength and failure mode were evaluated. Substrates were heated up to 600 °C for 30, 60, 90, 120 and 150 minutes. Three tests have been conducted in order to verify their bonding strength. The tests conducted were Splitting Cylinder Test, Slant shear Test and pull-off Test. The procedures of tests are referred to:

i. ASTM C496 (1996) (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimen).
ii. ASTM C882 (1999) (Standard Test Method for Bond Strength of Epoxy-Resin System Used With Concrete by Slant Shear).
iii. ASTM-C4541 (1992) Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers.

## 1.5 Dissertation Outline

In Chapter 1, the background of study, objectives, overview of the research, scope of work and the outlined of the dissertation are introduced. In short, this chapter give the general view of the research.

Chapter 2 covers the literature review of past research works related to current study. This chapter reviews about the behaviour of concrete in fire, levels of concrete fire-damaged, effects of heating duration, rehabilitation works on fire-damaged concrete and application of UHPFRC as a repair material. In addition, the different test methods for assessing bond strength were also reviewed. The studies from previous researchers on how substrate roughness and moisture condition affected bond strength were also analysed.

Chapter 3 explain the sequences of the methodology and adopted experimental program. This chapter explains the mixing procedure of UHPFRC and normal concrete. It describes preparation of the FDNC substrate specimens which were exposed to five different heating durations and three different moisture conditions. The surface of substrates was sand blasted. Besides, the test procedures on evaluating mechanical, permeability and bond characteristics of the FDNC and UHPFRC were highlighted in this chapter.

Chapter 4 presents mechanical properties of normal concrete substrate after fire. The changes of FDNC in term of mass, compressive strength and colour were examined. The permeability and mechanical properties of FDNC and UHPFRC are deliberated in this chapter. The most suitable FDNC substrate surface moisture condition was selected and concluded. Discussions on the effect of heating durations of FNDC on bonding strength were presented. Lastly, the results of the bonding strength and failure mode of composite UHPFRC/FDNC were detailed.

Chapter 5 presents the conclusion for this study. Suggestion and recommendation for future improvement are also be pointed out.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Overview

This chapter presents the behaviours of concrete due to fire, concrete changes in term of mechanical strength and physical characteristics when exposed to fire. The effects of heating durations to the residual strength of concrete also were explored. A special attention was given to the procedure and type of test conducted by previous researcher in order to quantify the bond strength. Other than that, this chapter also describes the previous application of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) in rehabilitation works, repair practice of fire-damaged concrete structures and factors affecting bond strength between the two concrete materials.

## 2.2 Properties of concrete at high temperature

The properties of concrete will deteriorated when it was subjected to high temperature. This is due to the changes of physical properties and chemical composition of concrete. Concrete will undergo different type of damages depending on level of temperature. The effects of concrete component due to high temperature include reduction in compressive strength, micro-cracking within the concrete microstructure, colour changes consistent with strength reduction, increase in pore structure, and various degree of spalling. The following sub-section explains the properties of concrete at high temperature.

### 2.2.1 Mechanical strength

There was certain reduction in strength of concrete when it is exposed to high temperature. Based on Ma et al. (2015) residual compressive strength of concrete after being exposed to high temperature occurs in three stages;

1) Room temperature to 300°C, compressive strength keeps constant.
2) 300 to 800°C, compressive strength of concrete drop drastically.
3) More than 800°C, concrete lost its compressive strength.

Moreover, research done by Schneider (1988) and Khoury et al. (2002) highlighted that at high temperatures, concretes component suffer major changes, namely the following;

1) Evaporation of water inside the concrete in temperature of 100°C and above;
2) Loss of cement hydration water between 300°C and 400°C which leads to strength reduction and causes cracks to appear;
3) Thermal expansion of aggregates up to 600°C, causing internal stresses that lead to the concrete breaking down
4) Aggregates decomposition from 800°C, weakening the concrete until it becomes a fragile material

Prior to technical note by Phaedonos (2011), concrete lose its strength up to 30 to 40% once the temperature hit 300°C. This is because of thermal expansion, internal cracking, and weak adhesion between paste and steel reinforcement within the concrete. At 500 to 600 °C, more than 70% of concrete strength reduced.

In previous research by Haddad and Al-Rousan (2016), the mechanical performance of beams after fire was scaled down due to reduction in compressive strength, weak concrete to steel bond and reinforcement steel deteriorated. The load capacity of beam, after heated at 300, 500, and 600°C was reduced to 32%, 79% and 80%.

Up to now, previous study by Park et al. (2015) has established that post fire curing condition surely enhanced the residual properties of fire-damaged concrete. The mass and concrete density gradually decreases after heating (300°C, 500°C and 700°C). In addition, post fire curing also recovers the density, mass and also the concrete tensile strength.

During fires, tensile strength of concrete can be affected severely. Fire can induce the occurrence of spalling that in a concrete structural member (Khaliq and Kodur, 2012). Same as compressive strength, the change of tensile strength of concrete due to fire was dependent on certain factors. Thelandersson (1972) studied the influence of temperature on residual splitting strength of concrete. The authors found that, for 300°C temperature, the concrete tested lose about 20% of its original tensile strength. The concrete approximately lose about 70-80% of its tensile strength while temperature in the range of 300-600°C. Next, for temperature range 600-800°C the concrete practically loses its tensile strength.

The concrete's residual flexural strength also reduces in function of temperature. Li et al. (2004) pointed that, when concrete exposed to 800°C temperature, there was significant reduction of strength. The other author indicated that, the flexural strength of concrete started to loose after temperature hit 200°C. As the temperature increase, the strength loss become smaller and at 1000°C the value become null (Husem, 2006). The high temperature surely gave negative effect to the concrete strength (Dos Santos and Rodrigues, 2016).

### 2.2.2 Physical changes of heated concrete

After exposed to elevated temperature, concrete would experiences the following physical changes. These changes were said to be responsible for the changes of concrete's mechanical properties.

At room temperature, concrete is grey in colour. However, when concrete exposed to 300–600 °C temperature , the colour of the cement matrix changes from grey to red/pink .Whereas at 600–900 °C, it changed to whitish grey and buff at 900–1000 °C (Lee et al., 2010).

At high temperature, the colour of aggregates also changes. However, there are differences of colour changes found between siliceous and calcareous aggregates. At room temperature, siliceous aggregates have a wide spread of colours. When heated they may follow different colour paths relying on their constituent (Annerel and Taerwe, 2008). Despite, most of them turn pink around 250–300 °C due to the oxidation of the present iron ions. On the other hand, the change of some calcareous aggregates only visibly at about 700 °C where from black, they turn white due to de-carbonation. The common colour changes in concrete due to high temperature are shown in Table 2.1 and Figure 2.1.

Table 2.1 Colour and strength loss at different temperature (Arioz, 2007)

| **Temperature** | **Colour of normal concrete** | **Strength loss** |
|---|---|---|
| Under 300 ˚C | Grey | Minimal loss of strength |
| 300 ˚C – 600 ˚C | Pink, red or red-brown | Loss of strength about 30% |
| 600 ˚C – 900 ˚C | Grey-white | 70% strength loss |
| Over 1000 ˚C | Buff | Sintered |

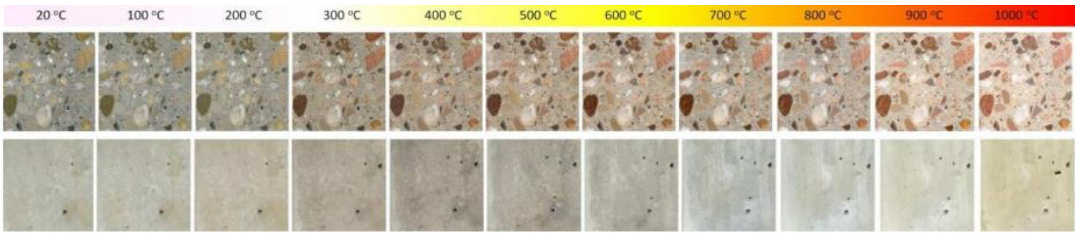



Figure 2.1 Colour change of heated concrete: surface with exposed aggregates and external surface of the concrete specimen (Hager, 2013)

Proximately, any pink/red or discoloured concrete should be remarked as potentially weakened. The colour change of concrete is a vital indication of the effect of fire. Colour changes also provide a good visual guide to estimate temperature range to which concrete has been exposed to (Phaedonos, 2011),

Concrete's colour changes may indicate the exposure to temperatures greater than 550°C. Concrete that subjected to temperatures higher than approximately 570 °C usually turns to pink, associated with chemical changes of the iron-containing compounds in the aggregates and paste matrix. Concrete that has turned pink is considered as damaged and should be replaced and repaired (Marxhausen, 2014). Figure 2.2 shows concrete spall from slab soffit and pink/red discoloration.

Figure 2.2 Concrete spalled from slab soffit showing pink/red discoloration (Rogerson, 2017)

When concrete structure subjected to fire, there were breaking off of the pieces of concrete’s surface and this phenomenon known as spalling. Spalling will greatly reduce mechanical properties of concrete structure and even cause the structure failed (Khoury et al., 2002).

Previously, Sarker et al. (2014) stated that, concrete starts to spall at 800 °C and 1000 °C temperatures. The pieces of concrete spalled without any explosive sound. Spalling occurred cause by the thermal gradient between concrete internal core and its surface. This is due to the temperature of furnace air which accelerated quickly. The image of concrete spalling is shown in Figure 2.3.

Figure 2.3 Concrete spalling on wall (Rogerson,2017)

The high temperature increased the pore pressure in the concrete. Spalling occurs when the tensile stress in surpass the tensile strength of concrete. High tensile stress may cause by this excessive pore pressure. The risk of spalling increases with increasing porosity caused by the increasing amount of water to evaporate during heating (Zhang et al., 2014).

In terms of crack, between 100℃~500℃ no crack was detected with naked eyes. At the temperature above 600℃, cracks started to appear and as the temperature go higher, the cracks became wider from 0.2mm to 1.0mm (Lee et al., 2010). Concrete will crack when exposed to high temperature. Heat will dry up the concrete and cause great thermal gradient between outer and inner layer. The concrete surface is will be in tension and the core in compression. The serviceability of concrete structures can severely reduce by its crack, leads to increase in their permeability and diffusivity. Cracking therefore provokes to a speedy penetration of liquid, gaseous and aggressive agents, which may weaken the durability and the tightness of the structures (René and Boogaard, 1994 and Ding et al., 2012).

According to Hager (2013), the heating of concrete will involve the process of expelling water that is chemically bound with cement hydrates .The evaporation of water will greatly impact the mechanical strength of concrete. As stated by Phaedonos (2011), when temperature reached 250°C free moisture in concrete completely loss and paste volume reduced. High temperature also changes concrete constituent. The free water in pores evaporated at almost 200°C. At almost 180°C, dehydration of chemically combined water in the cement gel occurred. Then, at temperature more than 500°C there is decomposition of hydration product in concrete (Park et al., 2015).

## 2.3 Factors affect post fire concrete properties

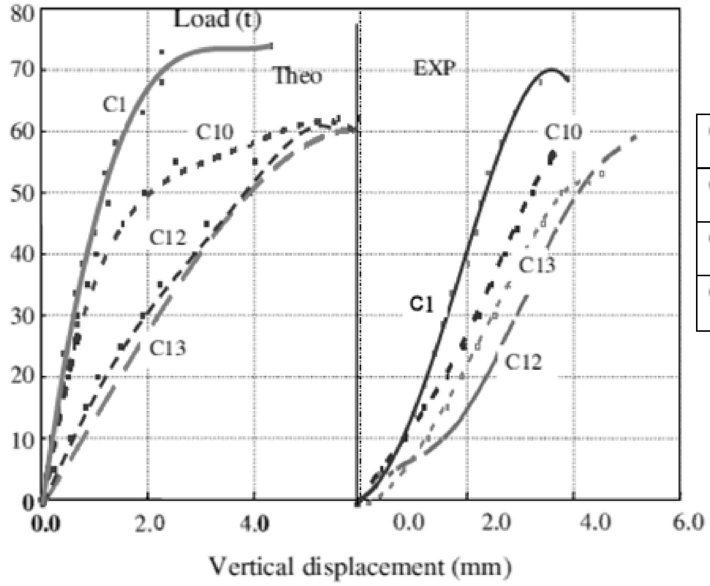
### 2.3.1 Heating Duration

The factors that affect post fire concrete's compressive strength are the rate of heating, the duration of heating, whether the specimen was loaded or not, the type and size of aggregate, the water/cement ratio, and the percentage of cement paste. In general, concrete heated by a building fire always loses some compressive strength and continues to lose it on cooling.

Previous research done by Mazza (2015) stated that concrete damaged zone comes bigger with longer heating duration. Concrete structures that exposed to high temperature for 60 minutes experienced more damaged compared to concrete that heated for 45 minutes.

Bikhiet et al. (2014) compared the experimental and theoretical analysis for column heated at constant 600°C temperature with different durations. The findings stated that, for column sample as the period of fire increased from 10 min to 15 or 20 min, the strain of column increased by 45% and 55%, respectively.

Both experimental and theoretical analysis reported that as the period of fire increases, the column stiffness decreases. The analysis also showed that with increase in the period of fire (10, 15, 20 min), the corresponding column failure load compared with $C_1$ decreased by nearly (12%, 15%, 25%) respectively, as shown in Figure 2.4




| | |
|---|---|
| $C_1$ | 0 min |
| $C_{10}$ | 10 min |
| $C_{12}$ | 15 min |
| $C_{13}$ | 20 min |

Figure 2.4 Experimental and theoretical load-vertical displacement relationship (Bikhiet et al., 2014)

### 2.3.2 Exposure temperature

At elevated temperature, free water in the concrete matrix will firstly be discarded due to moisture evaporation. As the temperature further increases, hydration products will decomposed of and loss of chemically bonded water will take place (Zhao et al., 2014). Table 2.2 list the changes that take places in concrete at high temperature.

Table 2.2 List the changes that take places in concrete at high temperature (Hager, 2013)

| Temperature Range | Changes |
|---|---|
| 20-200°C | Slow capillary water loss and reduction in cohesive force as water expands;<br>80-150°C ettringite dehydration;<br>C-S-H gel dehydration<br>150-170°C gypsum decomposition ($CaSO_4$ $.2H_20$):phyisically bound water loss |
| 300-400°C | Approximate 350°C break up of some siliceous aggregates (flint):<br>374 critical temperature of water; |
| 400-500°C | 460-540°C portlandite decomposition<br>$Ca(OH)_2 \rightarrow CaO + H_2O$ |
| 500-600°C | 573°C quartz phase of the C-S-H decomposition, formation of $\beta$-$C_2S$ |
| 600-800°C | Second phase of the C-S-H decomposition, formation of $\beta$-$C_2S$ |
| 800-1000°C | 840°C dolomite decomposition;<br>930-960°C calcite decomposition<br>$CaCO_3 \rightarrow CaO + CO_2$, carbon dioxide release; ceramic binding initiation which replace hydraulic bonds |

Arioz (2007) studied the effects of elevated temperatures on the properties of concrete. The result revealed that, high temperature gives significant impact to the concrete properties and structure. At 110 ˚C, the dehydration of the calcium silicate hydrate (CSH) becomes significant. At 300 ˚C, the hydration of the calcium silicate occurs. The thermal expansion of the aggregate increase internal stresses and micro cracks also can be seen. At around 530 ˚C, calcium hydroxide, which is one of the most important compounds in cement paste start to dehydrate which then result in concrete shrinkage.

## 2.4 Rehabilitation works on fire-damaged concrete

There are many options available in order to repair fire-damaged concrete. The common method used are strengthening the structural members with fibre reinforced polymer (FRP) and replacement either with shotcrete or in-situ placement concrete (Zaman et al., 2011). The main objective of every method is to enable concrete structures restore their structural integrity and safely fulfil its intended function even after exposed to high temperature.

A while ago, retrofitting work for fire-damaged structures involved normal concrete only. For example, fire-damaged St Elizabeth hospital was repaired with shotcrete and epoxy injection. In April 2011 Dean's Brook Viaduct at London repaired by sprayed concrete reinforced with wire (Wheatley et al., 2014). Figure 2.5 shows before and after repair work of fire-damaged structures.

(a) (b)

Figure 2.5 Before (a) and after (b) photo of Dean's Brook Viaduct repair work (Wheatley et al., 2014)

Recent most innovation in retrofit techniques is the used of FRP. Various researches have been conducted to study the impact of FRP treatment over the strength and overall structure recovery. It was proved that FRP treatment increase both strength compressive and flexural strength. In the case of, 25MPa strength normal concrete, its compressive strength increased up to 67%, 129% and 150% for one, two and three layers of FRP sheet wrapped around the concrete. However, the effectiveness methods of wrapping and types of FRP used might be differ depend its applications on different structural members (Masuelli, 2013).

Previously, Haddad et al. (2011) used ferrocement, fibrous grout layers and Fibre Reinforced Polymer (FRP) sheet as repair materials. These materials were used to repair heat damaged shallow and T- shape beams. The presence of fibre in grout and polymer composite contributed in regaining concrete flexural capacity and rigidity. Yaqub and Bailey (2011) used glass fibre reinforced polymer (GFRP) to repair fire-damaged concrete column. The result indicated an improvement in the mechanical properties of the repaired sample.

Recently, works by Al-Rousan et al. (2015) conclude that thermal shock damaged beams regain its original load carrying capacity after being repaired by advanced composite materials. The composite material used was Carbon Fibre Reinforced Polymer (CFRP) plates and sheet. The load carrying capacity and stiffness restored about 99% and 90 % respectively.

Other methods in fire-damaged concrete rehabilitation work involved the removal of the affected concrete part by using cleaning techniques such as sandblasters, shot blasters and high-pressure water blasters. This step was crucial in favour of removing thin layers of concrete surface (Zaman, 2014). Usually, the removed part then replaced or overlaid with suitable repair material (Phaedonos, 2011). A detailed repair methods can be exploited by referring to VicRoads Technical Note Number 72 (Phaedonos , 2006).

The fire-damaged reinforced concrete column regains its strength after being repaired with fresh concrete. The result showed that, the repaired columns reach their original strength and even higher than unheated column after being repaired (Lin et al., 1996).

## 2.5 Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) as a repair material

UHPFRC is an advanced concrete, which is also characterized by its constituent material make-up of typical fine grained sand, silica fume, basalt aggregate and Portland cement with low water/cement ratio, and mineral admixtures that are selected to increase the bond between the aggregates and the cement paste (Habel et al., 2006). From the strength point of view, the classification of concrete strength may be made as shown in Table 2.3.

Table 2.3 Classification of concrete strength (Habel et al., 2006)

| Type | From (MPa) | To (MPa) |
|---|---|---|
| Normal Strength Concrete (NSC) | - | 40 |
| High Strength Concrete (HSC) | 41 | 79 |
| Very High Strength Concrete (VHSC) | 80 | 119 |
| Ultra-High Strength Concrete (UHSC) | 120 | 200 |
| Super High Strength Concrete (SHSC) | 200 | No limits |

Recent research has proved that UHPFRC was able to become good repair material. The addition of fibre in concrete or mortar increased its strength, toughness and impact resistance in various concrete applications (Nataraja et al., 2005).

According to Tayeh et al. (2013b) UHPFRC shows excellent interlocking with the surface of substrate and give high bonding strength. UHPFRC also has good workability in fresh state, thus lead to easy casting with using normal concreting equipment. It is also has high resistance to overcome severe environmental conditions (Alaee and Karihaloo, 2003).

UHPFRC was first applied for the repair work of existing concrete structures in Europe during the European project called Sustainable and Advanced Materials for Road Infrastructures in 2004.A bridge over the river La Morge in Switzerland was widened and rehabilitated by using UHPFRC of the CEMTEC multiscale® family. The edge of the beam was severely damaged as exposed to chloride ingress. The bridge was widened by using a prefabricated UHPFRC edge beam and a reinforced beam. Then, the removed concrete and damaged edge beam were replaced by a UHPFRC overlay, as shown in Figure 2.6 (SAMARIS-D22, 2005) and (Brühwiler et al., 2005).

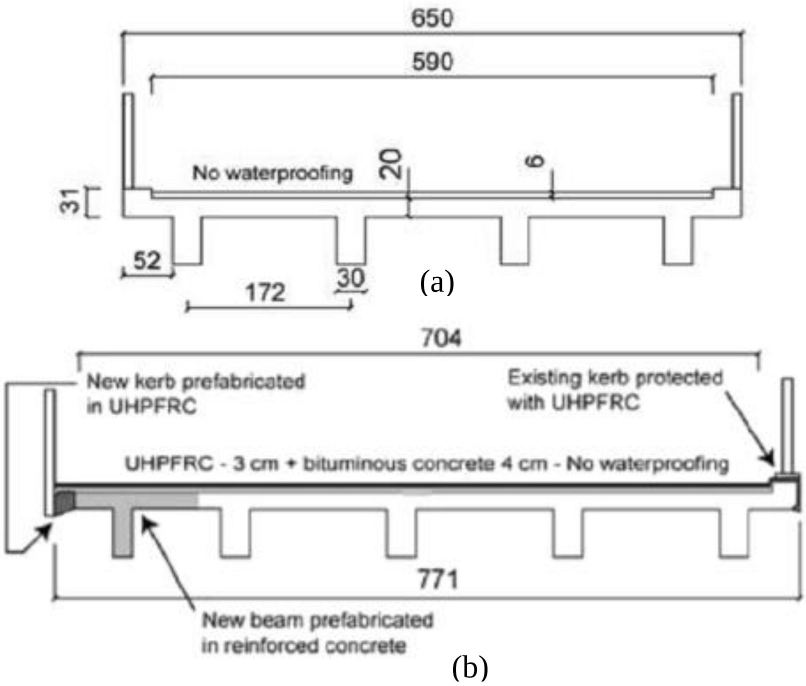



Figure 2.6 Cross section of the bridge (a) before and (b) after rehabilitations (dimension in cm)

In July 2009, UHPFRC was applied in the rehabilitation of a bridge deck over Šoka River in Slovenia. It was 65 m bridge with a 5% longitudinal slope. The UHPFRC was used to cast the upper surface of the bridge, the external side of the edge beam and also the footpath as shown in Figure 2.7.

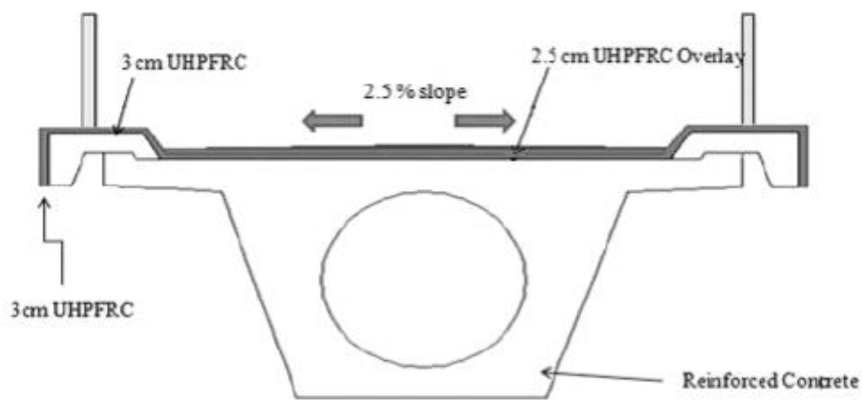



Figure 2.7 Cross section of bridge rehabilitation with UHPFRC (Denarié and Bruhwiler, 2011)

UHPFRC also was used in strengthening of an industrial floor. The 50 year-old dribble reinforced concrete floor of a fire brigade building had damaged due to overloading. In order to increase the load carrying capacity of that RC slab, 4 cm thick UHPFRC was overlaid on top of RC slab as shown in Figure 2.8 below. The UHPFRC layer makes the slab become thicker which provide an excellent dispersion of local wheel loads. It also increases the static height and strength of material to resist both compression and tension stresses (Brühwiler and Denarié, 2013).

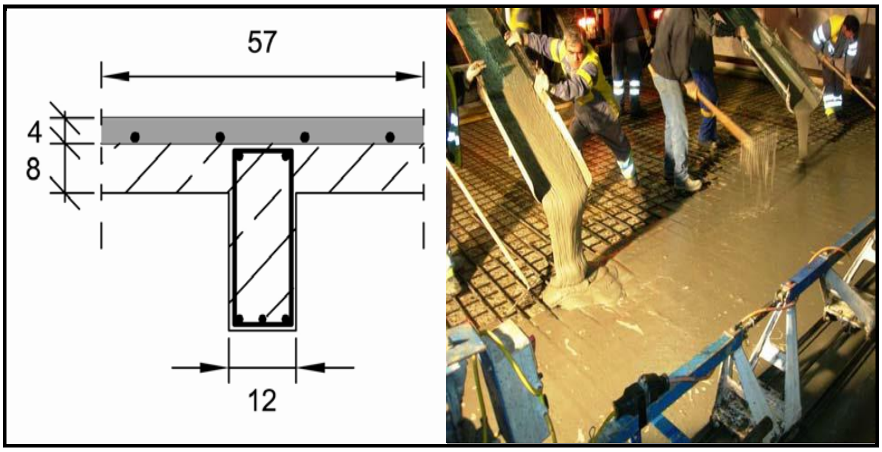



Figure 2.8 Cross section with UHPFRC layer in gray and view of UHPFRC casting (Brühwiler and Denarié, 2013)

The usage of UHPFRC in rehabilitation is being proved by Krstulovic-Opara and Toutanji (1996). They used a thin layer of High Performance Fibre Reinforced Cementitious Composite (HPFRCC) to repair deteriorated structures such as cracked pavement and bridge. They have found that the HPFRCC improve the substrate deformation and energy dissipation capacity. Thus, HPFRCC overlay are able to link existing cracks in the concrete substrate.

CARDIFF is one of the repair designs using HPFRCC. This fibre reinforced concrete has been used as bonded strips to the tensile face to repair and improve reinforced concrete beam (Habel et al., 2007). The beams were tested using four –