Study on the Potential of Repair Fire-Damaged Reinforced Concrete Beams Using Ultra High Performance Concrete with Curing at Ambient Temperature

by

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LIST OF ABBREVIATIONS

UHPC	Ultra High Performance Concrete
UHPFRC	Ultra High Performance Fibre Reinforced Concrete
FRP	Fibre Reinforced Polymer
CFRP	Carbon Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
RPC	Reactive Powder Concrete
JSCE	Japanese Society of Civil Engineering
ASTM	American Standard Testing Method
NWAC	Normal Weight Aggregate Concrete

Kajian Tentang Potensi Pemuliharaan Konkrit Bertetulang Rosak Akibat Kebakaran Menggunakan Konkrit Berprestasi Tinggi yang Diawet Pada Suhu Sekeliling

ABSTRAK

Konkrit bertetulang yang rosak akibat kebakaran memerlukan pembaikan bagi mempertingkatkan kebolehkhidmatan struktur dan mengelakkan kegagalan struktur binaan secara keseluruhan. Pendedahan haba yang tinggi terhadap struktur konkrit bertetulang akan menyebabkan kemerosotan kekuatan dan kebolehtahanlasakan struktur. Konkrit yang rosak akibat kebakaran lazimnya diperbaiki dengan menggunakan *shotcrete* dan konkrit kekuatan normal. Di dalam kajian eksperiman, pemuliharaan konkrit terbakar dilaksanakan dengan membalut atau melekatkan polimer bertetulang serat (FRP). Kaedah ini mampu meningkatkan kekuatan struktur yang dipulihara tetapi hanya terdapat sedikit peningkatan dari sudut kekukuhan. Kajian ini menggunakan konkrit berprestasi tinggi (UHPC) sebagai bahan pemulihara. UHPC terdiri daripada aggregat bersaiz halus, simen, *silica fume* dan *superplasticizer*. Satu lagi komposisi UHPC yang turut mengandungi serat besi dipanggil konkrit tetulang serat prestasi tinggi (UHPFRC). Campuran bahan-bahan ini menghasilkan konkrit yang mempunyai ciri-ciri mekanikal yang hebat berbanding konkrit kekuatan tinggi. Manakala kehadiran serat besi di dalam campuran meningkatkan kemuluran konkrit UHPFRC. Berbeza dengan kaedah pengawetan yang lazim digunakan bagi UHPC, penyelidikan ini menggunakan pengawetan suhu sekeliling dan bukan pada suhu yang tinggi. Ini adalah untuk memudahkan aplikasi UHPFRC di tapak. Objektif penyelidikan ini adalah untuk membaiki konkrit tetulang yang rosak akibat kebakaran dengan dua jenis UHPFRC iaitu konkrit tanpa serat besi berprestasi tinggi (UHPC) dan konkrit tetulang serat besi berprestasi tinggi (UHPFRC). UHPC yang tidak mempunyai serat besi akan dituang pada permukaan mampatan bagi rasuk konkrit bertetulang yang rosak akibat kebakaran. UHPC diklasifikasikan sebagai bahan pemulihara yang lebih ekonomikal berbanding UHPFRC dan bertindak sebagai lapisan mampatan tambahan bagi rasuk yang terbakar. UHPFRC yang mempunyai serat besi akan dituang pada permukaan regangan bagi rasuk konkrit bertetulang yang rosak akibat kebakaran. UHPFRC disasarkan untuk memulihara rasuk bertetulang yang rosak akibat kebakaran sebagai lapisan regangan tambahan bagi struktur komposit rasuk tersebut. Penilaian akan dibuat terhadap struktur rasuk komposit berdasarkan kekuatan lenturan, kapasiti beban puncak, keteguhan dan kekukuhan anjal bagi menilai kesesuaian UHPC sebagai bahan pemulihara rasuk konkrit terbakar. Pembaikan sampel yang dibakar pada suhu $400^{o}C$ menggunakan UHPC mengembalikan kapasiti beban puncak dan keteguhan asalnya. Pembaikan sampel yang dibakar pada suhu $400^{o}C$ menggunakan UHPFRC mengembalikan kekuatan lenturan, kapasiti beban puncak dan keteguhan asalnya. Pembaikan sampel yang dibakar pada suhu $600^{o}C$ menggunakan UHPC dan UHPFRC gagal mengembalikan kekuatan lenturan, beban puncak, keteguhan dan kekukuhan anjal asalnya. Kesimpulannya, UHPC dengan 20mm ketebalan tidak sesuai sebagai bahan pembaikan bagi rasuk konkrit bertetulan yang rosak akibat kebakaran.

Study on the Potential of Repair Fire-Damaged Reinforced Concrete Beams Using Ultra High Performance Concrete with Curing at Ambient Temperature

ABSTRACT

Fire-damaged reinforced concrete structure requires repair work to improve its serviceability and prevent structural failure. The intense fire exposure on the structure deteriorates its strength and durability. Fire-damaged concrete structure was normally repaired using the shotcrete and normal strength concrete as practised previously. In experimental work, usage of fibre reinforced polymer (FRP) as repair material to retrofit or wrap around the fire-damaged concrete indicates improve strength but has lower effect on stiffness. This study used Ultra High Performance Concrete (UHPC) as repair material. UHPC composed of fine size aggregate, cement, silica fume and superplasticizer. Another composition of UHPC that also includes steel fibre is considered as ultra high performance fibre reinforced concrete (UHPFRC). This material has an excellent mechanical properties compared to high strength concrete and steel fibre in the UHPFRC enhances its ductility behaviour. Contrary to normal practise of curing regime for UHPC, this research adopted ambient temperature curing instead of high temperature curing. This is to ease the application of UHPC on site. The aim of this research is to repair fire-damaged reinforced beam concrete with 2 types of material which is UHPC and UHPFRC. UHPC which does not incorporate steel fibre in the mix was laid on compressive face of fire-damaged beam sample. UHPC is considered as economical compared to UHPFRC and aimed to repair fire-damaged beam as additional layer of compression. UHPFRC has steel fibre in the mix and is placed on tensile face of fire-damaged beam. UHPFRC is aimed to repair the fire-damaged sample as additional tensile layer of composite structure. Assessment is made based on flexural strength, peak load capacity, toughness and elastic stiffness to evaluate the suitability of UHPC as repair material. Repair of 400^{o}C fire-damaged samples using UHPC fully regained its original peak load capacity and toughness. Repair of 400^{o}C fire-damaged samples using UHPFRC fully regained its original flexural strength, peak load capacity and toughness. Repair of 600^{o}C fire-damaged samples using UHPC and UHPFRC failed to fully rehabilitate its peak load capacity, flexural strength, elastic stiffness and toughness. In conclusion, UHPC of 20mm thickness is not viable as repair material for fire-damaged concrete.

CHAPTER 1

INTRODUCTION

1.0 Introduction

Exposure of intense fire on concrete will degrade the mechanical properties of concrete. Normal strength concrete exposed to 600^{o}C of heat lost 55% of compressive strength and 75% of tensile strength (Chan et al, 1999). Exposure of intense fire may also lead to spalling of concrete. Spalling of concrete in reinforced concrete structure will exposed its reinforcement bar hence reducing its durability. Hence, the structures exposed to intense fire can be considered as under strength and cannot perform as required by design structural code. Rather than demolish the structure, it is cost-effective to rehabilitate the structure should the structure is viable to be repaired. Previous rehabilitation work for fire-damaged structure mostly involves normal strength concrete. An example of rehabilitation of fire-damaged structure is the repair of Dean's Brook Viaduct at London. The viaduct is a pre-stressed concrete bridge which was fire-damaged due to a fire in a scrap yard at south span of the bridge. The repair work was carried out with sprayed concrete reinforced with wire mesh (Wheatley et al., 2014). However, in all the examples above, the repair material used was normal strength concrete which was sufficient for the fire-damaged structure. Higher strength material is required should the assessed fire-damage is larger.

Experimental work involves high strength material mostly used Fibre Reinforced Polymer (FRP) such as Glass Fibre Reinforced Polymer (GFRP) or Carbon Fibre

Reinforced Polymer (CFRP). The results indicate that retrofitting of FRP to fire-damaged concrete produces high compressive and flexural strength but low toughness and secant-stiffness value. Another downside of FRP is that it requires adhesive material for it to be retrofitted to concrete sample. This is because FRP is prefabricated material and is not similar to normal strength concrete which can be cast directly on to fire-damaged concrete. FRP also need to be cut to sizes that fit the fire-damaged concrete. This may produce repair layer that has many joints or make the FRP unpractical for certain circumstances.

Recent researches in the ultra high performance concrete (UHPC) provide an alternative material for rehabilitation of fire-damaged concrete. UHPC has high compressive and workability. It can be easily placed on-site due to its high workability value (Denarié et al., 2005). Fibre reinforced of UHPC which is considered as utra high performance fibre reinforced concrete (UHPFRC) has high flexural strength due to the inclusion of steel fibre in its composite. Experimental work using prefabricated UHPFRC applied as bonded strips to tensile face of reinforced beam indicates an improvement in flexural performance of the beam (Farhat et al., 2007). However most researches cure the UHPFRC at high temperature and use prefabricated UHPFRC instead of directly cast it on to the test sample. Richard P. and Cheyrezy M. (1995) stated that high temperature curing of UHPC enhanced its microstructure. However, high temperature curing may complicate UHPC application as cast in situ material. Ambient temperature curing material is more practical as cast in situ repair material.

The main purpose of this study is to assess the suitability of ultra high performance concrete (UHPC) cured at ambient temperature to be utilized for repair of heat-damaged concrete. The UHPC is cured at ambient temperature and is directly cast on to fire-damaged sample. Flexural test will be conducted on composite structure of fire-damaged beam and UHPFRC. The aim of the flexural test is to determine the mechanical properties gained by fire-damaged beam after it has been repaired with UHPFRC in comparison with non-damaged beam. Assessment is made based on the flexural strength, peak load capacity, toughness and stiffness value.

1.1 Problem Statement

Many repair materials have been adopted in actual repair work and experimental work. However, these materials were lacking in certain area which can be improved using new material of UHPC. The following problem statement outlined the challenges and improvement regarding repair work of fire-damaged concrete.

- Intense heat exposure toward reinforced concrete structure will reduce its mechanical properties and durability
- Previously repair method for fire-damaged concrete structure only involved normal strength concrete
- Experimental work on repair material for fire damaged concrete utilized FRP caused sudden failure of composite structure
- Repair using FRP requires adhesive medium which complicates its application
- FRP is a prefabricated material which is hard to suit certain dimension and shape of fire-damaged structure
- Repair of fire-damaged concrete using FRP or prefabricated material produce repair layer with many joints and compromised its mechanical properties
- UHPC has high compressive strength and flexural strength compared to normal concrete

- UHPC has high workability compared to FRP which enables UHPC to suit any shape or dimension of fire-damaged concrete
- Most guidelines and experimental work on UHPC indicates that high temperature curing is required
- This study aims to produce UHPC that is cured at ambient temperature to facilitate in situ application rather than precast

1.2 Objectives

The objectives of this study includes the production of UHPC as repair material and its effect on repaired fire-damaged concrete beam as highlighted below.

- To determine UHPC and UHPFRC mix design that provides 80-100MPa of compressive strength under ambient temperature
- To investigate the mechanical properties of fire-damaged normal concrete repaired with UHPC
- To assess the suitability of UHPC as repair material for fire-damaged concrete beam

1.3 Scope of Works

The scope of work for this study begins with determination of concrete mixes. UHPC mix has 2 variations. The first mix did not contained any fibre and denoted as UHPC while the 2nd mix contained steel fibre and denoted as UHPFRC. Normal concrete mix for beam sample was designed to 30MPa of compressive strength. The scope of work also includes heating of beam sample and repairing of fire-damaged beam sample. Overall scope of work is shown below.

- Design of mixture composition for UHPC and UHPFRC
- Design of reinforced concrete beam as test sample in accordance to BS8110:1997
- Heating the test sample at 400oC and 600oC for 2 hours
- Roughening of fire-damaged samples' surface using mattock
- Repair of fire-damaged sample with 20mm thickness of UHPC at compression face
- Repair of fire-damaged sample with 20mm thickness of UHPFRC at tension face
- Conducting flexural test on all sample

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Repairing of fire-damaged structure is important as it prolongs the serviceability of the damaged structure. Researches have been conducted regarding this topic and mostly involves high strength material of FRP. Case studies of repair work for fire-damaged structure indicate wide application of normal strength concrete and epoxy. This shows the importance of fire-damaged concrete structures repair work and the possibility of concrete structure caught on fire.

2.1 Fire-damaged Concrete

Fire accident can occur to building structure and even to public infrastructure. Example of building structure damaged due to fire accident is St. Elizabeth Hospital in Holland (De Lange, 1980). The fire accident occurred in 1950 and used epoxy injection and shotcrete in the repair work. Example of fire accident on infrastructure is the explosion of tanker truck under 60 Freeway in California on 14^{th} December 2011 (Figure 2.1). The fire caused guardrail to melt and charred concrete structures. On 27^{th} April 2007, a gasoline truck overturned and erupted into flames caused California Highway to collapse (Figure 2.2). Another example of infrastructure fire accident is Dean's Brook Viaduct. The viaduct located in London was fire-damaged due to fire in scrap yard at south span of the bridge (Wheatley et al., 2014).

Figure 2.1: Tanker truck exploded beneath the 60 Freeway in California which caused damage to overhead bridge (LA Times, 2011).

Figure 2.2: Collapsed freeway overpass near San Francisco, California (New York Times, 2007)

Fire hazard in bridges typically involves petrol fires (Garlock et al., 2012). In Table 2.1, Garlock et al. (2012) listed major bridge fires in United State of America from 1995 until 2009. Most of the fire damage involved gasoline tanker crashing or over-turned. This is obvious as the road infrastructure serves major traffic and tankers are among the road users. Any accident occurred involving vehicle carrying flammable material will cause fire-damage to its surroundings.

Table 2.1: Case studies related to the structural assessment of fire damaged bridges (Garlock et al., 2012)

Bridge/location	Date	Cause of fire	Damage description
Bridge over I-75 near Hazel Park, MI, USA	July 15, 2009	A gasoline tanker struck an overpass on I-75	Complete collapse of the bridge, which fell on the freeway below
Big Four Bridge, Louisville, KY, USA	May 7, 2008	Electrical problem of the lighting system, took two and a half hours to control the fire	Minor structural damage, resulting in large amount of debris on the bridge
Stop Thirty Road, State Route 386 Nashville, TN, USA	June 20, 2007	A fuel tanker truck rear-ended a loaded dump truck. The tanker erupted into flames beneath the bridge	The bridge sustained very little damage and traffic was reopened after minor repairs
I-80/880 interchange in Oakland, CA, USA	April 29, 2007	A gasoline tanker crashed	A 160 m section of the interchange collapsed
Bill Williams River Bridge, AZ, USA	June 20, 2007	A gasoline tanker over-turned	Concrete girders were damaged by the fire and subsequently repaired, but it was not necessary to replace any of the girders
Belle Isle Bridge in NW Expressway, Oklahoma City, OK, USA	January 28, 2006	A truck crashed into the bridge	Concrete girders were slightly damaged by the fire. The safety of the bridge was assessed and the bridge was reopened to traffic
Wiehltalbridge in motorway A4, Cologne-Olpe, Germany	August 26, 2004	Following an accident, a gasoline tanker fell down and started a fire under the first bridge span	Web buckiling in one of the main girders of the bridge that experienced maximum displacements of ±120 mm and local plastic deformations in the cantilevering part of the steel deck
Bridge over the Norwalk River near Ridgefield, CT, USA	July 12, 2005	A tanker truck carrying 30.3 m^3 of gasoline overturned, caught fire, and burned out on the bridge	The deck was replaced by a new one but its beams were tested by the FHWA
I-95 Howard Avenue Overpass in Bridgeport, CT, USA	March 26, 2003	A car struck a truck carrying 30.3 m^3 of heating oil	Collapse of the southbound lanes and partial collapse of the Northbound lanes
I-20/I-59/I-65 interchange in Birmingham, AL, USA	January 5, 2002	A loaded gasoline tanker crashed	Main span sagged about 3 m (10 feet)
I-80W/I-580E ramp in Emeryville, CA, USA	February 5, 1995	A gasoline tanker crashed	Deck, guardrail and some ancillary facilities were damaged

Hence, it is possible for building structure or infrastructure to be caught on fire as highlighted previously. Intense fire exposure degraded the reinforced concrete structure by reducing its compressive strength, flexural performance and spalling of concrete cover. Repairing the fire-damaged structure is cost-efficient should the structure is still intact and viable to be repair. This should be based on site assessment of the fire-damaged structure as practised previously.

2.1.1 Physical Appearance of Fire-damaged Concrete

Fire-damaged concrete changes colour according to the exposed temperature of heat. The colour transition provides general guide of temperatures, whether the colour represents the original surface or its spall pieces (Erlin et al., 1972). Figure 2.3 shows the changes of colour occurred to concrete after being exposed to certain degree of heat. There are no changes in colour for fire exposure until 300^{o}C. According to the figure, sample in this study will turn “pink to red” for heat between 300^{o}C to 600^{o}C.

Other indications are surface crazing, popouts by quartz or chert aggregate particles, spalling and dehydration. This physical apperances also serve as general indication of degree of temperature exposed to the concrete. Other possible physical effect is the crazing of concrete surface. According to the figure, there will be popouts over chert or quartz aggregate particles and surface crazing for the sample in this study based on the exposed fire temperature.

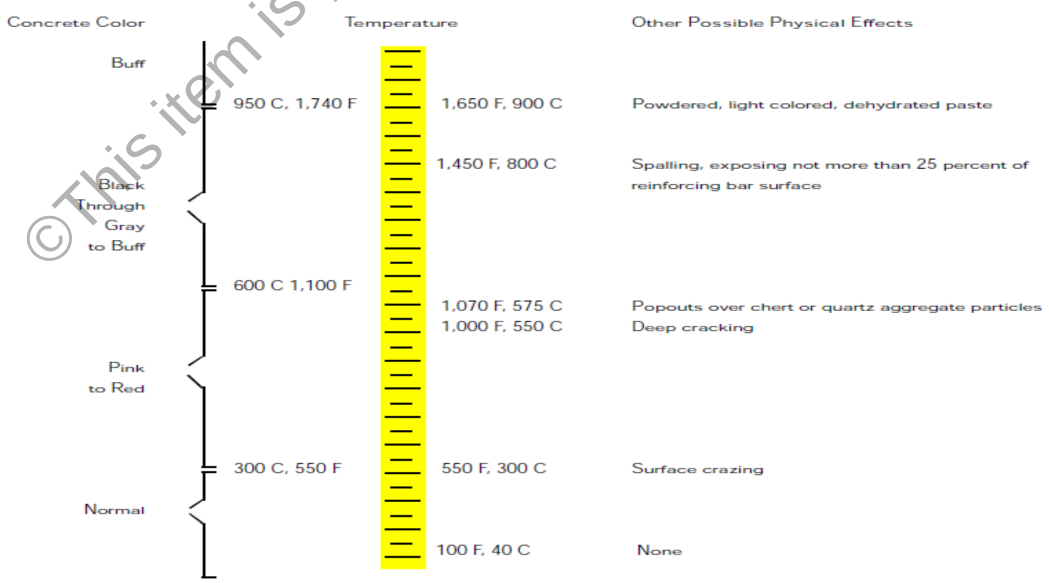

Figure 2.3: Visual evidence of concrete colour transition according to temperature of exposed heat (Erlin et al., 1972).