สมรรถนะทนไฟของรีแอคทีฟพาวเดอร์คอนกรีต

นายเดเนียล นิโคล เรเยส วาเลริโอ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมโยธา ภาควิชาวิศวกรรมโยธา
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2556

FIRE RESISTING PERFORMANCE OF REACTIVE POWDER CONCRETE

Mr. Daniel Nichol Reyes Valerio

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Civil Engineering
Department of Civil Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2013

Thesis Title	FIRE RESISTING PERFORMANCE OF REACTIVE POWDER CONCRETE
By	Mr. Daniel Nichol Reyes Valerio
Field of Study	Civil Engineering
Thesis Advisor	Assistant Professor Withit Pansuk, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Faculty of Engineering

(Professor Bundhit Eua-arporn, Ph.D.)

THESIS COMMITTEE

....Chairman

(Associate Professor Thanyawat Pothisiri, Ph.D.)

....Thesis Advisor

(Assistant Professor Withit Pansuk, Ph.D.)

....Examiner

(Associate Professor Akhrawat Lenwari, Ph.D.)

....External Examiner

(Associate Professor Burachat Chatveera, Ph.D.)

เดเนียล นิโคล เรเยส วาเลริโอ : สมรรถนะทนไฟของรีแอคทีฟพาวเดอร์คอนกรีต. (FIRE RESISTING PERFORMANCE OF REACTIVE POWDER CONCRETE) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. วิทิต ปานสุข ดร., 4 หน้า.

รีแอคทีฟพาวเดอร์คอนกรีตคือคอนกรีตสมรรถนะสูงมากรูปแบบหนึ่งซึ่งมีค่ากำลังรับแรงอัดสูงมาก มีส่วนผสมของซิลิกาในปริมาณสูงซึ่งช่วยเพิ่มการอัดแน่นตัวของเนื้อคอนกรีต และการผสมเส้นใยเหล็กลงไปจะช่วยควบคุมการแตกร้าวของคอนกรีต และเพิ่มความเหนียวและความทนทาน นอกจากนี้จะใช้ทรายละเอียดและไม่ใช้มวลรวมหยาบเป็นส่วนผสม การใช้หม้อบ่มความดันจะช่วยเร่งระยะเวลาบ่มคอนกรีตและปรับปรุงคุณสมบัติของคอนกรีตได้ในระยะเวลาสั้น อีกทั้งรีแอคทีฟพาวเดอร์คอนกรีตที่ได้รับการบ่มด้วยหม้อบ่มความดันได้รับการพิสูจน์จากรายงานงานวิจัยในอดีตแล้วว่าจะช่วยพัฒนาคุณสมบัติเชิงกลได้ โดยเป็นที่ทราบกันดีว่าคอนกรีตมีความต้านทานต่อเพลิงไหม้ที่ดีเมื่อเทียบกับวัสดุโครงสร้างอื่นๆ อย่างไรก็ตามกำลังรับแรงอัดของคอนกรีตจะแปรผกผันกับความสามารถในการทนไฟและอัตราส่วนน้ำต่อปูนซีเมนต์ จึงทำให้รีแอคทีฟพาวเดอร์คอนกรีตมีความสามารถในการทนไฟลดลงเมื่อเทียบกับคอนกรีตโดยทั่วไป งานวิจัยนี้นำเสนอสมรรถนะของเสารีแอคทีฟพาวเดอร์คอนกรีตหลังถูกเพลิงไหม้โดยมีตัวแปรต่างๆ ได้แก่ ปริมาณเส้นใยเหล็กและการผสมเส้นใยพอลิโพรไพลีน โดยการหลุดล่อนของคอนกรีตและรูปแบบการพังของเสาได้รับการตรวจสอบ และพบว่าการเพิ่มปริมาณเส้นใยเหล็กและการผสมเส้นใยพอลิโพรไพลีนจะทำให้สมรรถนะของรีแอคทีฟพาวเดอร์คอนกรีตในด้านของการทนต่อการหลุดล่อนและความสามารถในการทนไฟนั้นดีขึ้น อย่างไรก็ตามสามารถกล่าวได้ว่าเมื่อไม่มีการติดตั้งวัสดุกันไฟ รีแอคทีฟพาวเดอร์คอนกรีตจะมีความเสี่ยงภัยต่อการใช้งานในสภาวะเพลิงไหม้

ภาควิชา	วิศวกรรมโยธา	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมโยธา	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก	....
ปีการศึกษา	2556		

5570529021 : MAJOR CIVIL ENGINEERING
KEYWORDS: RPC / COLUMNS / FIRE RESISTANCE / STEEL FIBER

DANIEL NICHOL REYES VALERIO: FIRE RESISTING PERFORMANCE OF REACTIVE POWDER CONCRETE. ADVISOR: ASST. PROF. WITHIT PANSUK, Ph.D., 4 pp.

Reactive Powder Concrete (RPC) is a form of Ultra High Performance Concrete that exhibits exceptional compressive strength. The composition integrates high silica content for enhanced packing. Furthermore, the addition of steel fibers limits crack propagation and improves ductility and durability. It also possesses very small grain sizes of sand and eliminates coarse aggregates in its mixture. Autoclaving hastens the curing of concrete and improves its properties in a short period of time. RPC that undergo autoclave curing has proven to have enhanced mechanical properties as reported in recent literature. Concrete is regarded to have excellent fire resistance compared to other structural materials. Recent studies show that compressive strength is inversely proportional to fire endurance and water-cement ratio, thus, making RPC more prone to fire induced damages as compared to Normal Strength Concrete (NSC). This study presents the performance of RPC columns after fire. Parameters such as steel fiber volume fraction and integration of polypropylene fibers are regarded in this study. Spalling of concrete and failure mode of columns have been investigated. It was found out that the increase of volume fraction of steel fibers and incorporation of polypropylene fibers enhances the performance of RPC in terms of spalling and fire resistance. However, without additional fire proofing, RPC was found to be vulnerable against fire.

Department:	Civil Engineering	Student's Signature	....
Field of Study:	Civil Engineering	Advisor's Signature	....
Academic Year:	2013		

ACKNOWLEDGEMENTS

I would like to glorify my God Almighty for the wisdom, endurance, persistence and strength that He provided me in the course of this research.

To my family and friends, who never failed to inspire and give their own pieces of wisdom and prayers for me.

To AUN/Seed-Net, for giving me the opportunity to explore beyond my means to enhance my knowledge and capacity in the field of Structural Engineering.

To Dr. Withit Pansuk, for the never ending support in exhibiting his expertise in my chosen field of research and for the experience that this study instilled in me.

Lastly, to my research committees, Assoc. Prof. Thanyawat Pothisiri, Ph.D., Assoc. Prof. Akhrawat Lenwari, Ph. D., and Assoc. Prof. Burachat Chatveera, Ph.D., for the knowledge that they have shared with me for the betterment of my research.

CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I
INTRODUCTION

1.1 General

Fire is one of the major causes of incidental tragedies that take lives and properties of people. Based on statistics in the United States, a total estimate of 329 billion US dollars or amounting to 2.1% of the country's gross domestic product is the total cost of fire in the year 2011. This includes the losses and the money spent for protection, prevention and mitigation (Hall Jr 2014). Total lives lost also summed up to an approximate number of 3005 people and 17500 injured civilians. Fire can be triggered in many different ways as simple as a forgotten cooking pot or as much as a terrorist attack just like in the World Trade Center twin towers in New York back in 2001. Because of these inevitable fire causes, dwellings must be first and foremost structurally stable and durable to ensure safety of people especially during the time of evacuation. It is also required that structural codes involve effective and efficient guidelines for design, construction and maintenance of structures against fire.

Concrete is the most common structural material used in building construction. In comparison to other structural materials, concrete fairly exhibit better performance. Due to the increase of popularity in use, a lot of different types of concrete had been in consideration for research and construction to optimize shape and space in structures. This fact also leads to better structural performance in terms of durability and high strength. Other than the normal strength concrete (NSC), infusion of different materials into the mixture has been the subject for material researches. Due to modification of the materials used, concrete have become High Strength Concrete (HSC), Fiber Reinforced Concrete (FRC), High Performance Concrete (HPC), Ultra High Performance Concrete (UHPC), Ultra High Performance Fiber-Reinforced Concrete (UHPFRC), Reactive Powder Concrete (RPC) and Hybrid fiber-reinforced Reactive Powder Concrete (HRPC). Generally, concrete performs well in compression and variation in form and mixture of concrete could even be more utilized in innovative structures such as high rise buildings. Considering speed and performance capability in construction, prestressed and precast RPC is regarded as a highly capable material.

The comparison of the performance of NSC and HSC has been the subject of research in the past decade (Kodur and Phan 2007, Liu and Huang 2009, Raut 2011). These shows that HSC performs better based on its possessed higher strength compared to NSC. However when exposed to fire, both types exhibit deteriorating mechanical properties. It is also observed that explosive spalling of concrete during the increase in temperature is more prone to HSC (Kodur and McGrath 2003). This is most likely due to the lowered water-to-cementicious ratio. To overcome spalling, polypropylene fibers (PP) of a desired type and amount could be added to concrete (Bilodeau, Kodur et al. 2004). RPC on the other hand has a denser structure compared to HSC. This could result to a poorer performance of RPC compared to HSC in terms of fire resistance (Zheng, Li et al. 2012). This would also turn into the need of fiber reinforcement such as PP and steel fibers to enhance the capacity of RPC in elevated temperature (Tai, Pan et al. 2011).

The addition of PP and Steel fibers in the mixture of RPC is mainly for prevention of spalling. These fibers which are mixed in HSC also effectively improve the residual mechanical properties of HSC after high temperature (Poon, Shui et al. 2004, Pliya, Beaucour et al. 2011). PP fibers will melt at 170°C and create a network of micro channels within the matrix of the concrete which will serve as a passageway to release trapped water vapor out of the mixture to initially avoid failure (Rodrigues, Laím et al. 2010). On the other hand, the steel fibers incorporated in the mix doesn’t have a direct relation to fire resistance but will act on post-cracking behavior of the matrix to provide high ductility.

Different curing regimes also affect concrete strength. Some of these curing techniques involve air curing, water curing, steam curing and autoclaving. Based on recent research, pressure and temperature involved curing would hasten up the development of strength of concrete (Yazıcı, Yardımcı et al. 2009). This could lead to more controlled production of specimens and structural members in terms of strength considerations. This would also hasten up construction in the concept of prestressed and/or precast systems.

1.2 Problem Statement

High performance concrete is now commonly used in high rise structures and becoming more and more popular as research goes, wherein high strength is associated in compression which is more pronounced in columns. In recent construction, high strength concrete utilization is increasing due to its low permeability and improved durability (Bangi and Horiguchi 2011). However, the demand for high strength structures always has a drawback in the concept of fire resistance. There have been series of researches that explain performance of high performance concrete under fire scenarios on both material and structural level (Kalifa, Chene et al. 2001, Chen and Liu 2004, Lau and Anson 2006, Kodur and Raut 2012). Collectively it was found out that the higher the strength obtained in the mixture, the lower the fire resistance the composition exhibits. High performance composition of concrete tends to be denser and more prone to failure in high temperature due to its high brittleness. It exhibits more serious deterioration than normal strength concrete such as spalling and cracking (Poon, Shui et al. 2004).

Reactive powders concrete, a form of ultra- high performance concrete that can reach 200 to 800 MPa of compressive strength, is one of the newer innovation in the concrete industry (Peng, Kang et al. 2012). It is composed of highly controlled composition of materials that involve Portland cement, silica fume, sand, quartz, superplasticizers and possible addition of steel fibers and steel aggregates (Richard and Cheyrezy 1995). RPC has been achieved based on micro-structural engineering concept by introducing silica components and elimination of coarse aggregates. Incorporation of steel fibers can improve strength and ductility of high performance concrete columns. Steel fibers addition to the high performance concrete matrix was found to be beneficial in enhancing fire endurance of columns providing its post-cracking state wherein the steel fibers form interlocking surface (Kodur, Wang et al. 2004). RPC is regarded as highly capable in prestressed and precast construction. Prestressed and precast specimens are controlled specimens in terms of concrete strength and production could be assured of the strength specification which is critical in design. The introduction of specialized curing method would also improve the strength of the RPC which in turn is a part of the prestressed/precast system specifications. Autoclaving has beneficial effects on the RPC properties. It develops a denser microstructures that results to higher mechanical properties. However, there have been very limited studies conducted regarding RPC in elevated temperatures (Liu and Huang 2009). In its limited research state, it is important to further study the material in its structural level for better understanding for its utilization and confidence in use.

1.3 Objectives

Based on limited previous research, it is clear that the understanding of RPC under elevated temperature remains on its starting phase. The concrete's primary advantage is stressed on its compressive strength capacities, thus columns are the subject of this research. The primary objective of the study is aimed to evaluate the performance of reactive powders concrete columns after fire. To be able to address this need, the following specific research objectives were formulated:

- Conduct a comprehensive literature review on the reactive powders concrete on the material and structural level. This review involves topics about concrete in general, composition of RPC, different curing regimes, fire effects and fire tests on concrete
- Cast material specimens as initial tests to obtain material properties of RPC and curing regimen
- Undertake fire resistance experiments on RPC columns with varying steel and polypropylene fiber content
- Evaluate the fire resisting performance of RPC columns in elevated temperature focusing on spalling depths and residual strength
- Validate failure criteria of columns

1.4 Hypothesis

Fire performance of RPC would be lower than NSC due to its dense microstructure that prevents pressure release from the core of the concrete. However, incorporation of steel and polypropylene fibers yields to better fire resistance based on previous researches (Lau and Anson 2006, Bangi and Horiguchi 2011, Zheng, Luo et al. 2013). The effect of autoclave curing enhances the mechanical properties of RPC columns (Yazıcı, Deniz et al. 2013), which would result to improvement in mechanical properties, however expecting lower fire resistance. With the integration of steel and PP fibers in the mixture, fire performance would be better.

1.5 Significance

The study aims to provide understanding in the performance after fire of RPC columns. RPC is one of the concrete compositions with relatively the highest compressive strength developed. The use of autoclaving would even enhance the compressive strength of RPC at the same time speed up production and development. However as discussed, the higher the strength of material relatively decreases its fire resistance which is a very important factor to consider in building construction.

Fire development in structures is inevitable and safety of the people is still the utmost important. With the knowledge that this research would provide, a better understanding in terms of decision making could be developed. Since this field of study is still in its infancy, further research development could arise and could be opened up in the near future.

1.6 Assumptions

- The materials are properly selected and carefully handled prior, during and after casting the specimens
- The machines used in material casting, curing and testing are properly calibrated prior to use for optimum data gathering

- The specimens are casted carefully and accordingly to represent the desired specifications of RPC

1.7 Scope and Limitations

The study's main focus is to evaluate the fire resisting performance of RPC columns but is limited to the following:

- RPC is made of materials found in Thailand such as ASTM type I cement, Elkem microsilica, CPAC fine sand and Superplasticizer
- Steel fiber used is Dramix 5D
- Autoclave curing was done with a maximum temperature of 140°C and pressure of 4 bar for 4 hours
- Column size is limited to the specifications of the furnace
- Column specimens were not loaded due to the limitation of the loading equipment
- Purely axial residual strength of columns were considered and tested only until its elastic limit

CHAPTER II
COMPREHENSIVE LITERATURE REVIEW

2.1 Introduction

The use of High Strength Concrete (HSC) is of numerous benefits. With continuous use in the past three decades, HSC has proven to be beneficial in line with architecture giving its design a reduced area to give more adequate space. With its enhanced properties such as low permeability and high durability that comes along with higher strength than normal strength concrete (NSC), the term High Performance Concrete (HPC) has emerged. The Petronas Twin Towers in Kuala Lumpur, Malaysia and the Trump World Tower in New York, USA are some of the structures that utilized HPC (Malik 2007).

On further emergence of technology, Reactive Powders Concrete (RPC) which is a form of Ultra High Performance Concrete (UPHC) was developed by Richard and Cheyrezy in 1995. RPC yields to a maximum high strength ranging from 200 to 800 MPa depending on the mix proportions and preparations that include silica, sand, quartz, superplasticizer, steel fiber, water, compacting pressure and heat treatment temperature (Richard and Cheyrezy 1995). The composition of RPC enhances a lot of material properties compared to NSC in terms of rheological, mechanical and durability criteria. Some of the examples of structures that utilized RPC are the Papatoetoe foot bridge in Auckland, New Zealand and the Majata footbridge in Japan (Malik 2007).

Environmental and external effects to structures generally determine the usage of materials used in buildings. One of the most common inevitable causes of structural degradation is incidents involving fire wherein it represents one of the most severe conditions in structural members. NSC generally exhibits better fire resistance than HSC (Raut 2011). The low permeability of HSC is more susceptible in building up pressure in its concrete matrix compared to NSC that results to spalling (Kodur, Wang et al. 2004). This results to a further conclusion regarding the relationship of strength and fire resistance of concrete composition. The higher the strength the concrete exhibits, the more vulnerable the concrete when induced in elevated temperature. In HPC and UHPC, the inclusion of polypropylene (PP) fibers and steel fibers improve fire performance of concrete in preventing spalling (Kalifa, Chene et al. 2001). PP fibers melt at about 170°C and would create micro tunnels that allows the release of water vapor and lessens the pressure inside the concrete. Steel fibers generally provide post-cracking resistance that result to a better ductility performance of the concrete matrix (Rodrigues, Laím et al. 2010).

The composition of RPC results to a relatively high strength, ductility and durability matrix. However, limited studies have been conducted on RPC under elevated temperatures (Chen and Liu 2004, Liu and Huang 2009, Peng, Kang et al. 2012, Zheng, Luo et al. 2013). Furthermore, RPC on a structural member subjected to fire has yet to be considered in research and is the main objective of this study. This section will provide a comprehensive literature review from early research up to the latest available analysis concerning further understanding regarding the utilization of RPC as a material and as a structural element. Materials significant in fire resistance would also be discussed such as fiber additives as well as more innovative ways in attaining a higher strength at an early age such as autoclave curing would be in context.

2.2 Fire on Concrete

Concrete is one of the most common building materials used in construction. Generally, concrete structures exhibit good behavior when subjected to fire. Good fire resistance of concrete is associated with its low thermal conductivity in addition to its great capacity of thermal insulation of steel bars (Kodur and McGrath 2003, Rodrigues, Laím et al. 2010). This section will discuss the behavior of different types of concrete on fire.

2.2.1 Normal Strength Concrete

Concrete is a composite material obtained by the combination of cement, aggregates, water and chemical or mineral additives, placed into molds to achieve a hardened state under convenient conditions (Husem 2006). Normal Strength Concrete has been defined having a concrete strength below 42 MPa (Jau and Huang 2008). Based on previous studies, it is proven that NSC exhibits a good fire performance and may not need additional fire proofing (Kalifa, Menneteau et al. 2000, Kodur and McGrath 2003, Kodur, Wang et al. 2004, Husem 2006, Kodur and Phan 2007, Rodrigues, Laím et al. 2010, Raut 2011).

On the dissertation of (Liu 2009), thermal and mechanical properties of concrete were reviewed. The stated properties influence the fire performance of concrete. Thermal properties vary on the type of aggregate used in the mixture of concrete. Different aggregate types react differently to concrete. Carbonate aggregate concrete provides better spalling resistance than siliceous aggregate (Bilodeau, Kodur et al. 2004). Variation in density, thermal conductivity and specific heat of concrete affect the fire endurance of concrete.

Concrete density was analyzed in the study of Bilodeau et. al. (2004), wherein lightweight aggregate concrete composition exhibited more pronounced concrete spalling compared to the normal-density aggregate concrete mix. This results to a better fire performance for a normal-density or less dense material. Free moisture is more pronounced in lightweight aggregate that results to a higher vapor pressure (Kodur and Phan 2007). Likewise, carbonate aggregates provide better fire performance until 800°C than siliceous aggregates but decreases significantly due to thermal degradation of carbonate contents of the mixture (Schneider 1988).

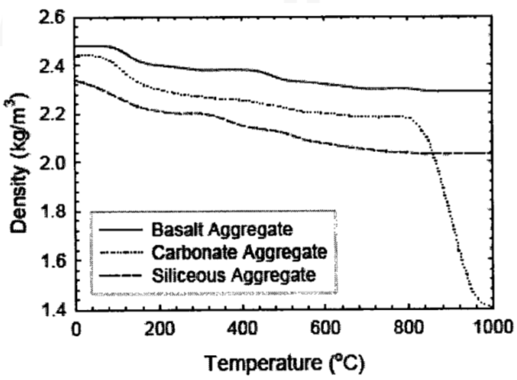

Figure 0-1 Density Variation with respect to Temperature (Schneider 1988) Reported by (Liu 2009)

Carbonate aggregates exhibits high specific heat and low thermal expansion that contributes to its better spalling resistance compared to siliceous aggregates (Kodur and McGrath 2003). The dissociation of the dolomite in carbonate aggregate increases the specific heat which is beneficial in preventing spalling in concrete.

Compressive strength is the most important property of concrete. With the increase of temperature, compressive strength of concrete decreases due to several factors: crack development, loss of bond strength, break down of calcium-silicate-hydrate (C-S-H) gel, aggregate damage and chemical transformation (Liu 2009).

Tensile strength of concrete is not one of the utilized properties of concrete and research on this field is very limited. However, it is still one property that is needed to take into account. Several previous studies model the tensile strength of concrete under elevated temperature (Youssef and Moftah 2007).

In the study of Youssef and Moftah (2007), a summary of relationship of mechanical properties were summarized to predict the behavior of concrete at elevated temperature. Compressive strength, peak strains and modulus of elasticity of concrete relationship with respect to temperature have been formulated by various researchers.

2.2.2 High Strength Concrete

High Strength Concrete is a mixture of composition of concrete that has a compressive strength above 42 MPa based on ACI definition (Prasad and Jha). Mechanical properties of both NSC and HSC decline gradually under increased temperature (Kalifa, Menneteau et al. 2000). HSC was mainly used for applications in construction of bridges, offshore infrastructures and columns of high rise buildings. Compared to NSC, HSC may not exhibit similar performance under elevated temperature. Fire endurance of HSC columns with equivalent levels of confinement may be lower than that of NSC due to its lower permeability that enables the buildup of pressure in the concrete matrix that results to spalling (Kodur and McGrath 2003, Kodur, Wang et al. 2004). Fire induced spalling is more evident in HSC compared to NSC wherein HSC is normally subjected to higher stress levels that create conditions conducive for this type of failure (Raut 2011). High rate of temperature rise can also induce spalling in concrete members (Kodur and Phan 2007).

Concrete spalling is the major concern of fire exposed concrete structures. HSC characterized with its low porosity and low water-binder ratio even increases the possibility of spalling compared to NSC (Kodur, Wang et al. 2004, Lee, Harada et al. 2013). It is a result of a thermo-mechanical process which is associated with dilatation or shrinkage of concrete wherein the stress originates in the gradients of thermal deformation within the material and a thermo-hydral process wherein the concrete spalling is due to the build-up of gas pressure fields in the porous network (Kalifa, Menneteau et al. 2000, Kalifa, Chene et al. 2001). This thermal instability leads to breaking off of layers or pieces of concrete from the thermally exposed surface. Fire reaches deeper layers of the concrete, thereby increasing the rate of heat transmission to the inner core of the member including the reinforcements. Spalling of concrete significantly compromises the structural integrity of the concrete structures (Kodur and McGrath 2003, Bangi and Horiguchi 2011). The effect of fire generation among concrete members is more pronounced especially in materials of higher strength wherein explosive spalling occurs in the heating process. The water within the concrete vaporizes as the temperature increases that result to increase in pressure in the voids which leads to brittle failure (Bilodeau, Kodur et al. 2004, Kodur and Phan 2007, Rodrigues, Laím et al. 2010).

A lot of factors are considered in looking into the fire performance of HSC. the critical factors that govern the fire performance of HSC systems are discussed in previous research (Kodur and Phan 2007). The factors discussed are as follows: Fire output, Material properties such as concrete strength, silica fume content, moisture content, concrete density, fiber use (PP and steel fibers), type of aggregate and specific structural features such as the size of the structure, amount of lateral reinforcement and load type and intensity.

Fire performance of concrete structural systems basically starts with the amount of fire induced in the system. The type of fire, the size of the fire and the heat output significantly influence fire performance. The material properties vary in the influence of fire in the concrete element wherein this disparity is apparent in HSC. The higher the strength associated with lower permeability, the more evident is the degree of spalling in concrete. Strength loss is more noticeable in HSC compared to NSC. Figure 0-2 shows the variation of strength comparing HSC and NSC in the study of Phan (Phan 1996).

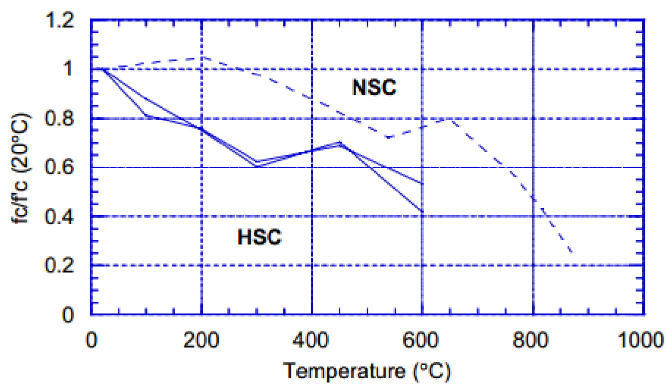

Figure 0-2 Variation of strength as a function of temperature (Phan 1996)

The amount of silica fume in the concrete mixture associated with concrete strength has a noteworthy effect. The addition of silica fume increases the extent of spalling. It appears to reduce the permeability of the concrete and restricts the loss of moisture during the stages of curing, drying and fire testing. HSC of concrete compressive strength of 114 MPa obtained only 4 hours of fire resistance with the same intensity of fire and confinement reinforcement (Kodur and McGrath 2003, Kodur, Bisby et al. 2006) wherein compared with NSC in the study, 6 hours of fire endurance was recorded. The HSC columns with significant amount of silica fume considerably shows the extent of spalling due to increased compactness, thus decreasing fire performance.

Relative humidity (RH) also influences the spalling of concrete. The higher moisture content in the concrete, the greater the effect of spalling in fire. In previous studies, spalling is manifested in RH above 80%, wherein RH below 75% is the acceptable level (Kodur and McGrath 2003, Bilodeau, Kodur et al. 2004). The low permeability of HSC structures prolongs the time required to attain the RH level below 75% compared to NSC structures.

Concrete density also has a relative effect in fire performance of HSC. A dense microstructure in HSC reduces the flow rate of liquid and vapor in water (Pliya, Beaucour et al. 2011). A study was concluded with the utilization of lightweight aggregates, fire performance of structures suffer (Bilodeau, Kodur et al. 2004). Lighweight aggregates contain more free moisture which results to a higher vapor pressure during fire scenarios. However, it is also noted that the extent of spalling is also dependent on the initial saturation degree of the mixture.

The use of polypropylene (PP) and steel fibers has been a widely used technology to accommodate fire resistance requirements in structure especially for HSC. Fibers improve the residual properties of concrete after exposure to elevated temperatures (Kalifa, Menneteau et al. 2000). Studies show that the use of PP fibers minimizes spalling on concrete under fire wherein it melts at a temperature of 170°C and provides a network of voids to release pressure from the internal concrete (Rodrigues, Laím et al. 2010). Steel fiber approximately doubles the toughness of the concrete and effectively reduces the deterioration of the concrete after exposure by providing post-cracking resistance (Poon, Shui et al. 2004).

The type of aggregate influences fire performance of HSC as well. Carbonate aggregates which are predominantly limestone provides better fire performance compared to siliceous aggregates which are predominantly quartz. In previous studies, it was recorded that the fire endurance of HSC columns that utilizes carbonate aggregates provided better fire performance (10% higher) than HSC columns that used siliceous aggregates (Kodur and McGrath 2003, Kodur, Wang et al. 2004).

Based on the literature presented above, it can be concluded that NSC performs better under elevated temperature compared to HSC. Figure 0-3 shows axial deformation difference between columns made out of HSC and NSC in fire exposure. It can be observed that axial deformation for NSC columns is more pronounced in the earlier stage that could lead to gradual ductile failure. However, fire resistance of HSC is noted to be lower than NSC in as time progresses with enhanced temperature induction. HSC becomes brittle at elevated temperature (Kodur, Wang et al. 2004).

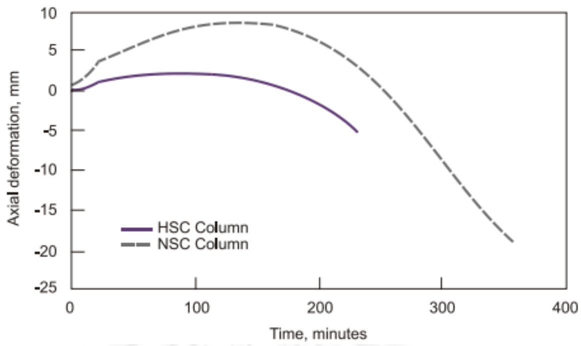

Figure 0-3 Axial deformation versus fire exposure in time
as reported in (Kodur and Phan 2007)

2.2.3 High Performance Concrete

High Performance Concrete also possesses the same characteristics as of HSC but with improved properties. HPC has been defined as concrete with high strength, high durability, good workability and high elastic modulus (Kodur, Wang et al. 2004). The addition of silica fume, fly ash and ground slag in concrete are some of the effective materials in preparing HPC. HPC can also be made up of blast furnace slag, rice husk ash and limestone powder filler (Aïtcin 2003). However, HPC suffers from one major weakness which is high brittleness. It is examined that HPC exposed to high temperatures exhibits more serious deterioration and degradation compared to NSC in the form of spalling and cracking and its integrity may be jeopardized (Kalifa, Chene et al. 2001, Poon, Shui et al. 2004). In research, there have been a limited number of conducted studies about HPC subjected to fire. Its increase in use due to its advantages is as important as its urgency for research. There has also no design standard yet given in most design codes for concrete structure made out of HPC.

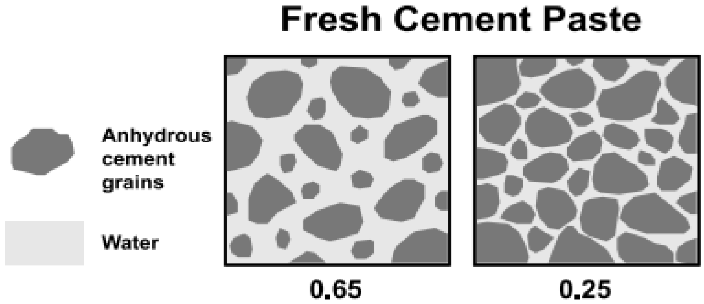

Figure 0-4 Cement Paste Comparison for NSC and HPC (Aïtcin 2003)

The effects of high temperatures were investigated on high performance steel fiber reinforced concrete (HPSFRC) (Lau and Anson 2006). The study focused on the strength, elastic modulus and porosity of the HPSFRC with 1% steel fiber volume content which are subjected to elevated temperatures that range from 105°C to 1200°C. Based on this research, the addition of steel fiber volume of 1% improves mechanical properties as well as fire resistance of the HPSFRC and showed no deleterious effect on the concrete. HPC shows consistently high overall residual compressive strength, flexural strength and modulus of elasticity compared to NSC however it started to degrade when temperature reached 600°C. Due to the initially higher saturation percentage of HPC, a greater decline in strength is more displayed compared to NSC.

The build-up of pore pressure on concrete was studied in previous research (Bangi and Horiguchi 2011). Pore pressure development is influenced by the severity and speed of heating. The duration of heating greatly affects the degree of spalling in the concrete surface. In this research, it was observed that the addition of PP fibers is effective in mitigating pore pressure build-up in the concrete. Steel fiber also reduces pore pressure in the deeper regions of the concrete especially during fast heating.

HPC is basically enhanced with the presence of fiber additives as well as enhanced mixture design concerning concrete strength, durability, workability, ductility and low permeability. However, enhanced properties always have an indirect relationship with fire endurance. The popularity of the use of high performing concrete in structures leads to the immediate need to fully understand fire performance of concrete to give more confidence in its utilization.

Tai, Pan and Kung conducted studies regarding fire on mechanical properties and characteristic appearance of RPC on different temperature levels (Tai, Pan et al. 2011). Compressive strength, tensile strength, modulus of elasticity and color variations at ranges of temperature until 800°C of RPC was analyzed.

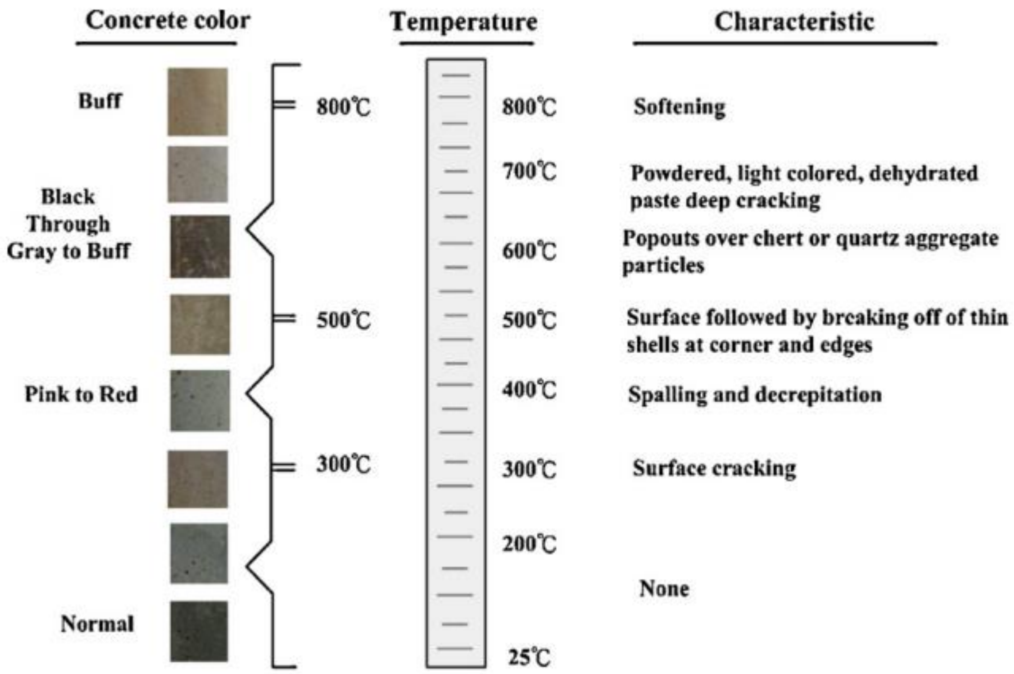

Figure 0-5 Characterization of RPC after high temperature tests (Tai, Pan et al. 2011)

This study also presents equations that represent compressive strength, peak strain and modulus of elasticity of RPC at different temperatures. These equations can be used to estimate the properties of RPC in the field. Each line of equation is for varying steel fiber volume fraction of 1%, 2% and 3% respectively for each property.

$$\frac{f'_{cT}}{f'_c} = \begin{cases} 0.946 + 2.855\times10^{-3}T - 8.375\times10^{-6}T^2 + 4.648\times10^{-9}T^3 \\ 1.059 + 1.053\times10^{-3}T - 4.223\times10^{-6}T^2 + 2.066\times10^{-9}T^3 \\ 0.984 + 9.782\times10^{-3}T - 3.923\times10^{-6}T^2 + 1.919\times10^{-9}T^3 \end{cases}, \quad 25°C < T \le 800°C \qquad 0.1$$

$$\frac{\varepsilon_{cT}}{\varepsilon_o} = \begin{cases} 1.043 - 1.483\times10^{-3}T + 1.142\times10^{-5}T^2 - 9.544\times10^{-9}T^3 \\ 1.129 - 4.177\times10^{-3}T + 2.154\times10^{-5}T^2 - 1.826\times10^{-8}T^3 \\ 1.066 - 3.012\times10^{-3}T + 1.788\times10^{-5}T^2 - 1.478\times10^{-8}T^3 \end{cases}, \quad 25°C<T\leq800°C \qquad 0.2$$

$$\frac{E_{cT}}{E_c} = \begin{cases} 1.011 + 7.21\times10^{-4}T - 6.797\times10^{-6}T^2 + 5.626\times10^{-9}T^3 \\ 1.026 + 4.181\times10^{-4}T - 6.564\times10^{-6}T^2 + 5.832\times10^{-9}T^3 \\ 1.043 - 2.258\times10^{-5}T - 5.487\times10^{-6}T^2 + 5.2\times10^{-9}T^3 \end{cases}, \quad 25°C<T\leq800°C \qquad 0.3$$

Another study by Zheng et. al. (2012) derived equations to predict the behavior of RPC at elevated temperatures.

$$\frac{\sigma_{pT}}{\sigma_p} = \begin{cases} 0.99+0.6\left(\frac{T}{1000}\right), 20°C\leq T\leq120°C, \; R^2=0.999, \\ 1.09-0.28\left(\frac{T}{1000}\right), 120°C\leq T\leq300°C, \; R^2=0.999, \\ 2.29-4.28\left(\frac{T}{1000}\right), 300°C\leq T\leq400°C, R^2=0.998, \\ 0.89-0.79\left(\frac{T}{1000}\right), 400°C\leq T\leq600°C, R^2=0.996, \\ 2.14-2.86\left(\frac{T}{1000}\right), 600°C\leq T\leq700°C, R^2=0.995, \\ 0.07+0.3\left(\frac{T}{1000}\right), 700°C\leq T\leq900°C, R^2=0.989. \end{cases} \qquad 0.4$$

$$\frac{E_{oT}}{E_o} = \frac{E_{pT}}{E_p} = \begin{cases} 0.96+2.12\left(\frac{T}{1000}\right) - 8.70\left(\frac{T}{1000}\right)^2, \; 20°C\leq T\leq400°C, \; R^2=0.996, \\ 1.80-4.83\left(\frac{T}{1000}\right) + 3.41\left(\frac{T}{1000}\right)^2, \; 400°C\leq T\leq900°C, \; R^2=0.974. \end{cases} \qquad 0.5$$

$$\frac{\varepsilon_{pT}}{\varepsilon_p} = \begin{cases} 1.00+5.42\times10^{-3}\exp\left(\frac{T}{1000}\right), 20°C\leq T\leq600°C, \; R^2=0.989, \\ 9.20-10.11\left(\frac{T}{1000}\right), \; 600°C\leq T\leq800°C, \; R^2=0.996, \\ 2.53-1.68\left(\frac{T}{1000}\right), 800°C\leq T\leq900°C, \; R^2=0.988. \end{cases} \qquad 0.6$$

2.2.4 Steel Fiber

Fibers in general are classified according to origin, physical/chemical properties, mechanical properties and shape and size (Naaman 2003). Steel fibers are man-made fabricated fibers with varying shapes and sizes depending on its desired use, generally made of carbon or stainless steel (Abid and Franzen 2011). Tensile strength of steel fibers range from 200 to 2600 MPa. Given this capacity, the failure of concretes incorporated with steel fiber focus on spalling of concrete rather than fiber pullout (Jansson 2008). Likewise, the yielding strength is sufficient enough to prevent fiber rupture. Steel fibers are added to concretes just like any other concrete admixtures. However due to the significant decrease in workability and difficulty in handling, fiber content is limited to 2% volume fraction of concrete (Igarashi, Bentur et al. 1996).

HPC is usually associated with the addition of fiber materials to enhance its ductility and durability. Further studies also found that there is an indirect relationship between fiber content and fire endurance wherein steel fiber generally affects the post-cracking behavior of the concrete composition (Rodrigues, Laím et al. 2010). This subchapter will further discuss the behavior of steel fibers in concrete.

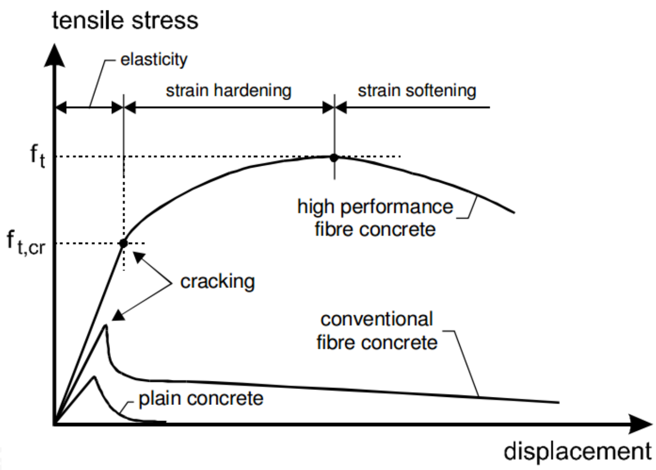

Figure 0-6 Comparison of uniaxial tensile behavior of different types of concrete (Markovic 2006)

Fibers in concrete address brittleness of the material to improve ductility. It bridges cracks that develop in concrete. Fibers increase strain at peak load and absorbs energy of concrete in failure with its random orientation and distribution. Fibers are not only used in structural building application but also in hydraulic structures, transportation works and rehabilitation of earthquake damaged elements (Shah and Ribakov 2011).

The development and utilization of fiber reinforced concrete with short straight and long hooked-end steel fibers with different lengths and aspect ratios were fully discussed (Markovic 2006). In the mix design, the main objective is to obtain the minimum amount of fibers that would accumulate to the best performance possible from this complex concrete composition. The synergy of the different types of fibers was analyzed. Short straight steel fibers address the initial small cracks or microcracks while the hooked-end steel fibers alleviate the propagation of macrocracks into the concrete system. The application of the two types of fibers in one system was studied as an optimum solution to increase tensile strength and ductility of concrete.

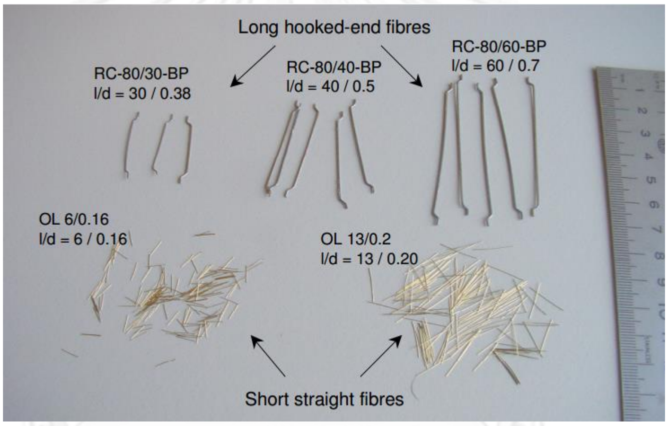

Figure 0-7 Applied types of steel fibers with respective aspect ratios (Markovic 2006)

In the study of fibers especially steel fibers, the pullout behavior of the fibers determines the capacity of the fibers in crack bridging which is its main purpose. The action of steel fibers is similar to the reinforcing bars in reinforced concrete wherein tensile stresses and mitigating with cracks would be attended. In bridging cracks, debonding and frictional pullout of the fibers occur. The fibers take the total tensile force over the crack then transfers into its surrounding concrete. The higher the tensile capacity of the fiber, the better the tensile response of the matrix will be. Pullout tests of steel fibers determine the efficiency of fibers in crack bridging, wherein 80% to 90% of the total tensile strength of the fiber should be utilized. This range is said to be its optimum limit capacity (Markovic 2006). Efficiency depends on the coherence between the applied fiber type and the concrete that serves as its pullout medium.

The mutual bond between each fiber and concrete which is directly related to the quality of material in the interfacial zone between fiber and matrix is called the adhesion bond. The debonding between fiber and matrix occur during the action of tensile stresses. It is the cracking process inside and along the fiber-matrix interface zone wherein pullout force increases during this process. The propagation of very fine cracks in fibers starts from an infinitesimal distance from the fiber through the interfacial zone which is similar to aggregate-cement paste interface (Igarashi, Bentur et al. 1996). The high hardness of the interface zone is a result of the low water-binder ratio.

Different types of fibers react with different pullout force. Pullout force in short straight fibers decreases while it continues to increase for hooked-end fibers. Hooked-end fibers provide mechanical interlock in the pullout mechanism. As the fibers are being pulled out from hooked-end form, the bends on the hooks provides additional pullout resistance and friction due to its distorted configuration, thus hooked-end fibers give more tensile capacity than straight fibers. During the pullout of fibers, frictional stresses accumulate along the interface zones which are generated due to the abrasion and compaction. Fibers are also subjected to "Poisson's contraction" in its transverse direction during pullout as the tensile stresses react along the longitudinal direction.

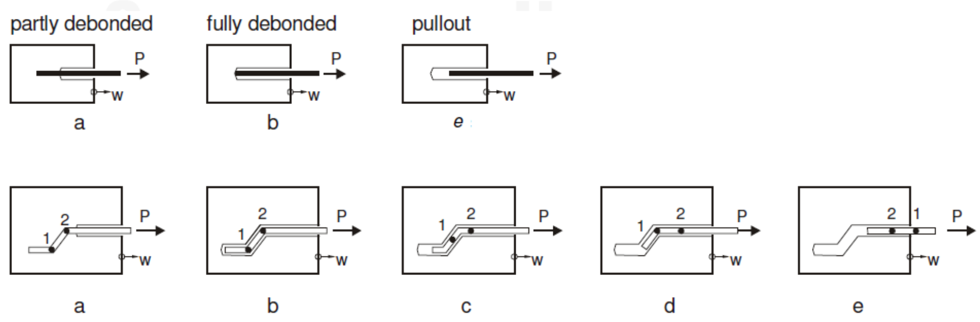

Figure 0-8 Debonding action of straight and hooked-end fibers (Markovic 2006)

The pullout behavior of steel fibers is affected by several factors. Hooked end fibers may develop a 4 to 6 times higher pullout force compared to straight steel. Higher material strength also results to a higher pullout force. High strength steel fiber with yield strength of 2200 to 2600 MPa would perform 50 to 100% better than medium strength steel fiber of 1200 MPa. The diameter of steel fibers also affects its performance. Larger diameter fibers would result to higher tensile stress. The diameter determines the tensile and bending stiffness capacity of the fiber hooks. The length of embedment on the concrete significantly increases the friction and pullout resistance which is a result of a larger surface contact area between fiber and concrete. Fiber inclination also has an advantage depending on the extent of the inclination is. With reference to the direction of the tensile force which is along the axis of the fiber, pullout forces result to a better performance up to an inclination of 15°, however decreasing as the inclination increases. Lower water-binder ratio results to higher microhardness wherein better result for fiber pullout performance is expected. The presence of fine filler materials efficiently fills empty spaces that increase the packing density which improves the overall strength and quality of the interfacial zone. This also results to improved shrinkage and debonding and frictional resistance during the pullout process.

2.3 Reactive Powders Concrete

The Reactive Powders Concrete (RPC) is a form of Ultra High Performance Concrete (UHPC) with a high compressive strength up to 800 MPa. The composition is made up of fine materials that result to a less permeable, more ductile and durable mixture. It was first initiated in France (Richard and Cheyrezy 1995). This section would further discuss the mechanical properties, mixture composition and use of RPC as a material and as a structural element.

RPC is composed of low porosity cementitious material with high cement and silica fume contents, low water-binder ratios and a new generation of superplasticizer (Malik 2007). It is also composed of a large amount of steel fibers or synthetic fibers for better durability and ductility. Coarse aggregates were removed in the mix and were replaced by fine sand and quartz. Table 0.1 presents the typical compositions of RPC (Richard and Cheyrezy 1995).

Normal strength concrete is made out of coarse and fine aggregates, cement and water. The materials are heterogeneous in nature wherein size varies indefinitely between the aggregates that are bound by the cement paste. RPC addresses this issue of heterogeneity as follows:

- Replacement of coarse aggregates by fine sand which are limited to a maximum of 600 μm;
- Improved mechanical properties of the paste; and
- Reduction in the aggregate/matrix ratio

Table 0.1 Typical RPC mixture (Richard and Cheyrezy, 1995)

	RPC 200				RPC 800	
	Non fibered		Fibered		Silica aggregates	Steel aggregates
Portland Cement	1	1	1	1	1	1
Silica Fume	0.25	0.23	0.25	0.23	0.23	0.23
Sand 150 - 600μm	1.1	1.1	1.1	1.1	0.5	-
Crushed quartz d_{50} = 10μ	-	0.39	-	0.39	0.39	0.39
Superplasticizer (polyacrylate)	0.016	0.019	0.016	0.019	0.019	0.019
Steel fiber L = 12 mm	-	-	0.175	0.175	-	-
Steel fiber L = 3 mm	-	-	-	-	0.63	0.63
Steel aggregates < 800 μm	-	-	-	-	-	1.49
Water	0.15	0.17	0.17	0.19	0.19	0.19
Compacting pressure	-	-	-	-	50 MPa	50 MPa
Heat treatment temperature	20°C	90°C	20°C	90°C	250-400°C	250-400°C

The aggregate size enhanced mechanical properties and limitation in the sand content has various advantages in the RPC mixture. In conventional concrete, cracks are generated in the interfacial zone of aggregate and paste based on the application of the forces applied. Crack sizes are relevant to extent of zone which are under tension or shear. Due to the deduction of size of the RPC mixture, macrocrack size would also be reduced. Improved mechanical properties of the paste used in RPC also reflect better performance. It is noted that the enhanced modulus of elasticity of the RPC paste satisfies the associated disturbance of the mechanical stress field. The use of finer materials in RPC was optimized due to its ability to better minimize the voids and does not form a skeleton of adjacent granular elements in the elimination of the coarse aggregates (Richard and Cheyrezy 1995).

Granular material selection in the RPC mixture is a very important factor for material performance. Fine quartz sand aggregate, cement, crushed quartz and silica fume are the major granular materials with steel fiber as special additive.

Sand is selected based on its mineral composition, mean particle size, granular range, and particle shape and mixture ratio by weight. Quartz in particular is a very hard material and possesses excellent aggregate/paste adhesion. Mean particle size of sand is important to satisfy homogeneity in the mix. The range of the granular size was limited to 600 μm at maximum and 150 μm at minimum. The specific range prevents interference of the smaller particles (<150 μm) to the largest value. Natural sand is also preferred since water demand would be less compared to screened crushed sand.

Cement consideration in the mixture is important for better adhesion between the aggregates. High-silica-modulus cement is best for better mechanical performance in terms of rheological properties which is similar to the use if siliceous aggregates.

Silica fume is an effective pozzolanic material. Compressive strength, bond strength and abrasion resistance of concrete is improved with silica fume. Other than the aforementioned advantages, silica fume in RPC has three main functions as follows:

- Filling the voids between the next larger class particles (cement);

- Enhancement of rheological characteristics by the lubrication effect resulting from the perfect sphericity of the basic principles; and
- Production of secondary hydrates by pozzolanic reaction with the lime resulting from primary hydration

Steel fiber enhances durability and ductility of the RPC especially tensile strength which is normally poor criteria in NSC. Steel fiber also produces a denser and more readily compacted mortar with less entrapped air which improves material properties. Steel fiber increases the performance of RPC. Figure 0-9 shows the effect of steel fiber to the compressive strength of RPC (Lee and Chisholm 2005).

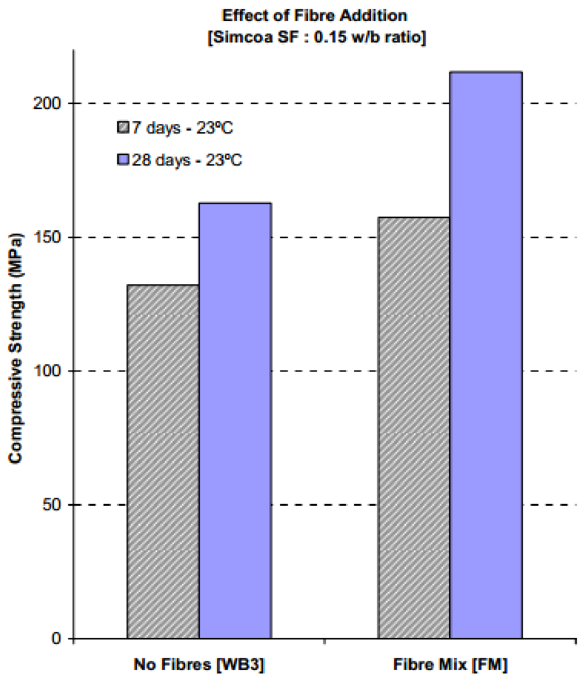

Figure 0-9 Effect of fiber addition to the compressive strength of RPC (Lee and Chisholm 2005)

Based on the experiment of Richard and Cheyrezy (1995), Malik (2007) summarized the results in Table 0.2. It can be observed that heat-curing and confinement improves the compressive strength of the RPC mixture relatively. The study of Lee and Chisholm (2005) also shows relevant results on the effect of curing to RPC compressive strength. Table 0.3 also summarizes the mechanical properties of the RPC mix designs presented in the earlier development of RPC.

Table 0.2 Compressive strength of RPC with varying confinement and heat-curing mechanism (Richard and Cheyrezy 1995)
Reported by (Malik 2007)

Casting Method	Curing Temperature (°C)	Compressive Strength (MPa)
No confinement	250	488
	400	524
50 MPa confinement	250	631
	400	673

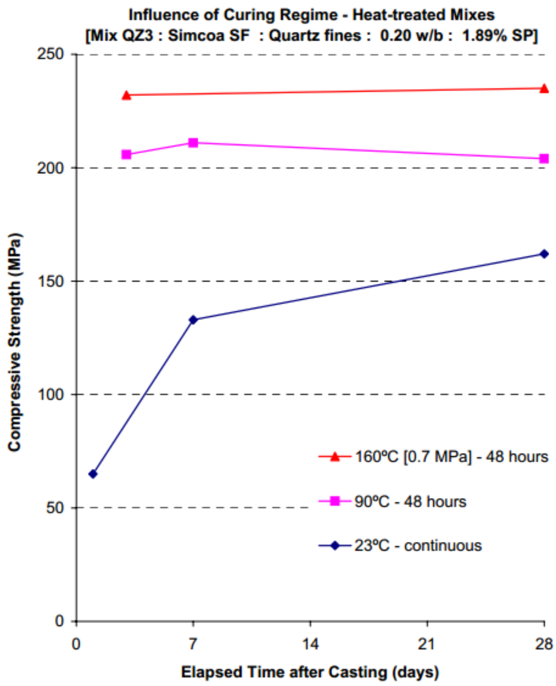

Figure 0-10 Strength gain by high temperature curing (Lee and Chisholm 2005)

With enhanced material properties, RPC has a lot of possible applications. The elimination of the supplementary reinforcing bars is one concept that most researchers have been dwelling about. However this concept is still under debate due to confinement issues. RPC is also a highly dense material which is evidently impermeable. This characteristic made it possible to be considered to be used for nuclear waste storages wherein harmful toxins may be present that necessarily require the prevention of leakage for safety.

Table 0.3 Mechanical properties of RPC200 and RPC800 (Richard and Cheyrezy 1995) Reported by (Malik 2007)

Property	RPC200	RPC800
Compressive strength of cylinders	170-230 MPa	490-680 MPa[#] 650-810 MPa[@]
Modulus of rupture	30-60 MPa	45-141 Mpa
Fracture energy	20-40 N/mm	1.2-20 N/mm
Young's modulus	50-60 Gpa	65-75 Gpa
Pre-setting pressurization	None	50 Mpa
Heat-treating (3days)	20-90 degrees centigrade	250-400 degrees centigrade

using quartz sand @using steel aggregate

2.4 Size Effect

Sizes of specimens have a significant effect in the performance of the material. RPC utilization exemplifies the ability to use smaller dimensions and sections of concrete due to its increased mechanical properties. In the previous study, size effect of RPC was discussed and evaluated (An, Zhang et al. 2008). As the size of the specimens increases, the resulting compressive strength decreases. Conversion coefficients were also formulated with reference to 100mm cube specimens with steel fiber content ranging from 0% to 2% using the concept of size-effect theory (Bazant 2000). Despite the increase in toughness and compressive strength brought by the addition of steel fibers in the matrix, the size effect of High fiber dosage difference is more pronounced.

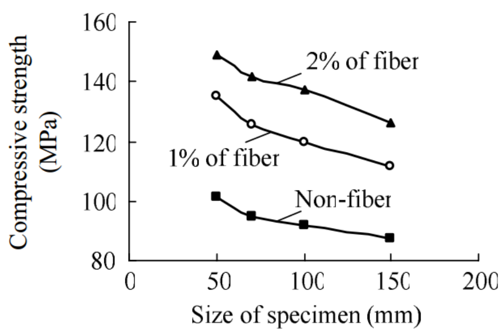

Figure 0-11 Size effect of RPC (An, Zhang et al. 2008)

2.5 Autoclave Curing

Different curing regimes are available for concrete to be able to achieve its maximum strength. Autoclave curing is one of the methods wherein with induced pressure and temperature would hasten the strength development of the concrete matrix. This subchapter will discuss the processes involved in autoclave curing as well as optimum curing results from previous studies.

Reactive powders concrete is recent generation cement based composite which is developed by microstructure enhancement technique as discussed in the previous section. It remarkably increased durability based on its ultra-dense microstructure which is a result of high cement content, very low water cement ratio, the inclusion of highly reactive silica fume, proper granulometric adjustment of fillers, low CaO/SiO2 ratios by addition of silica components, and incorporation of steel microfibers. It is a highly impermeable, dense microstructure with superior mechanical properties such as very high compressive strength, flexural strength, fracture energy and toughness that classifies RPC as Ultra high performance concrete (Richard and Cheyrezy 1995, Yazıcı, Yardımcı et al. 2009, Yazıcı, Deniz et al. 2013).

Thermal curing has a strong effect on mechanical properties of concrete as observed in previous studies (Richard and Cheyrezy 1995, Lee and Chisholm 2005). Autoclaving generates change in the microstructure of RPC. In 28 days, the majority of the cement grains remain unhydrated due to the very high cement content and low water-binder ratio. If curing would be hastened, hydration of cement would be faster and higher strength would be achieved at an early stage. This means that the 28-day strength of the RPC could be attained in a very short period of time by autoclave curing.

The mechanical properties (compressive and flexural strength) of reactive powder concrete (RPC) have been investigated under autoclave curing and compared with standard water curing condition (Yazıcı, Deniz et al. 2013). Autoclave temperature, pressure and time were investigated. The effects of silica fume and steel microfibers incorporation on mechanical performance were also studied. There is critical duration time for each pressure and temperature conditions wherein mechanical properties can be influenced negatively. SEM micrographs are also presented. Steel fiber volume was set at a volume which is the optimum volume fraction based on previous researches (Zheng, Li et al. 2012, Zheng, Luo et al. 2013). Figure 0-12 to Figure 0-15 show the flexural and compressive strength charts with respect to the duration of autoclaving.

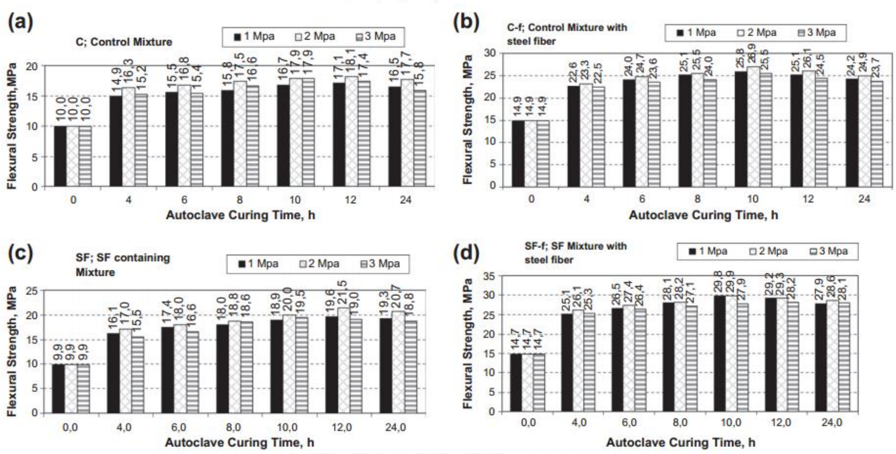

Figure 0-12 Influence of autoclave pressure, temperature and time on flexural strength of RPC mixtures (Yazıcı, Deniz et al. 2013)

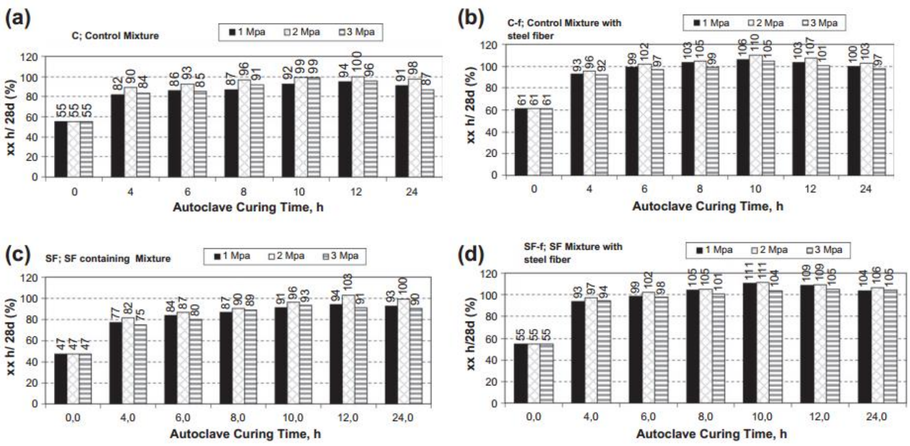

Figure 0-13 Relative flexural strength of RPC mixtures (Yazıcı, Deniz et al. 2013)

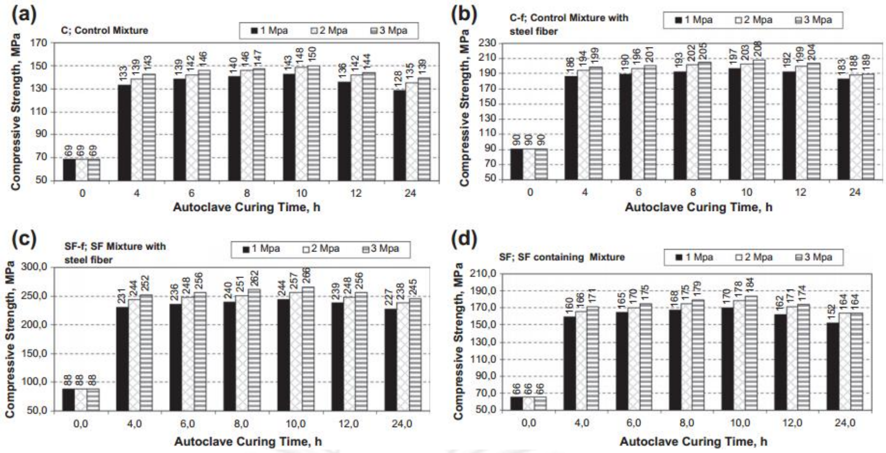

Figure 0-14 Influence of autoclave pressure, temperature and time on compressive strength of RPC mixtures (Yazıcı, Deniz et al. 2013)

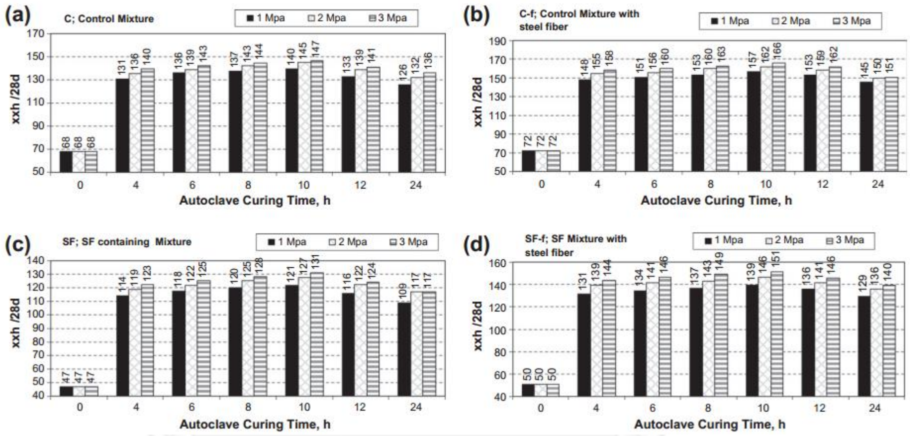

Figure 0-15 Relative compressive strength of RPC mixtures (Yazıcı, Deniz et al. 2013)

Based on the graphs presented, it can be observed that at a pressure of 2MPa and 10 hours of duration in the autoclave, flexural strength of RPC was obtained at an optimum state. Flexural strength reduces as time goes. Compressive strength at 10 hours of duration could still be observed to be optimum but pressure of 3 Mpa resulted to a higher performance. It was also observed that some parts of RPC did not react after 28 days which could lead to a less performing mixture. (Neville 1995) stated that the 28-day strength in standard curing can be achieved in 24 hours with the use of autoclave curing. However the downside comes from the lessened bond strength of about (50%) that results to a more brittle material property than ordinary concrete (Yazıcı 2007).

2.6 RPC Columns

A study about the application of fiber reinforced RPC as columns was conducted (Malik 2007). Six fiber reinforced RPC columns were tested under concentric and eccentric axial loading with the use of a combined compression and bending stiff testing frame in a closed loop servo controlled loading system. 2% steel fiber content was remained to be constant as reported by previous researchers to be of optimum value for improved durability and ductility. Tie reinforcement was removed from the system to see its effects on the overall performance of the fiber reinforced RPC column system. It was found out in the experimental tests that high volumes of steel fibers is an effective way to prevent spalling of concrete cover as well as mitigate the effects of buckling of the longitudinal reinforcements despite the removal of conventional ties. This in turn would result to the possibility of reduction or total elimination of lateral tie reinforcement for RPC columns. The findings would also be associated to the reduction of cost in construction.

The specimen used in the column was shaped as seen in Figure 0-16. The columns had a cross-section of 150 mm x 150 mm, 1450 mm high and haunched at both ends to prevent premature failure at column ends. Linear variable displacement transducers (LVDT's) were used to measure strains and curvatures at the column mid height. Each of the specimens was tested using a stiff testing frame.

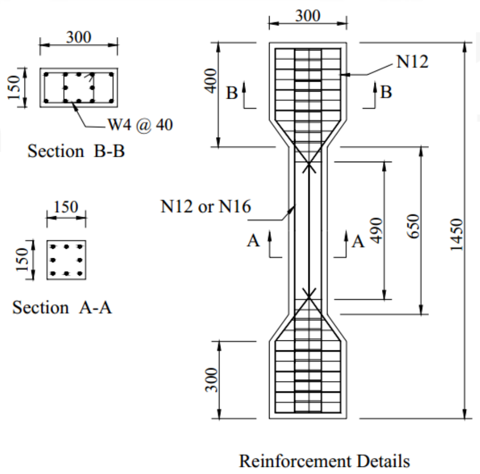

Figure 0-16 Specimen dimension and reinforcement details (Malik, 2007)

Columns tested in concentric loading failed in compression by crushing of concrete below the gaged zone which continues to deflect the resulted to a combined compression and bending failure. However results of the concentrically loaded columns could not be finalized due to flaws during the experiment.

2.7 Fire Resistance Test on Concrete

Fire resistance is the duration during which a structural member exhibits adequate resistance with respect to structural integrity, stability and temperature transmission under fire conditions (Raut 2011). Different fire resistance test standards are available however same principle applies. The heat flow in concrete will cause buildup of pore pressure, thermal expansion, and moisture evaporation that in turn will affect its material properties (Khoury, Andelberg et al. 2007). Fire tests are done to assess structural member performance and material properties with respect to time exposure to elevated temperature. Based on building codes, it is required in high rise buildings to have a fire resistance rating of 1 to 4 hours based on the use and occupancy of the building (ACI 1997).

ASTM E119 discusses the standard test methods for fire tests of building construction and materials. This standard provides guidelines on the limitations of the materials and equipment to be tested and used respectively. Figure 0-17 shows the time-temperature cure of the standard. This curve is the approximate furnace heating pattern to be simulated in fire tests.

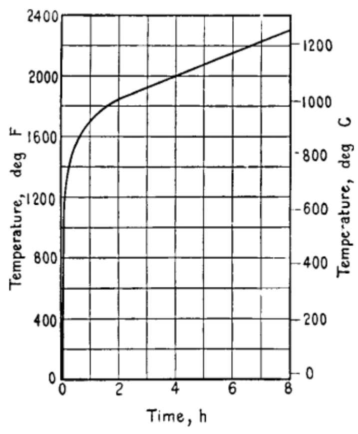

Figure 0-17 Time-Temperature curve (ASTM 2008)

2.8 Summary

Reactive powders concrete (RPC) is a form of ultra-high performance concrete (UHPC) with a superiorly high compressive strength, ductility and durability. However, fire performance of this type of concrete is still in its infancy. It is important to establish better understanding in the utilization of RPC not only with its enhanced mechanical properties but also on its thermal properties especially when exposed to high temperature. Fire on structures should be considered in choosing the right materials necessary for building construction since its detrimental effects are definitely addressed to the safety of human lives.

CHAPTER III
RESEARCH METHODOLOGY

3.1 Introduction

Fire resistance test of high strength concrete has been studied in the literature presented in the previous chapter. As observed in the earlier studies, there is an inverse relationship between concrete strength and fire resistance. The higher the concrete strength obtained, the lower its fire resistance. Various researches tried to find ways to mitigate the problem of spalling of concrete with high strength. Some studies looked into the tie reinforcement spacing and configuration, wherein closer tie spacing and modified tie pattern prevents concrete spalling of the concrete core of columns (Kodur and McGrath 2003, Kodur, Wang et al. 2004, Kodur and Phan 2007). Amount of fibers have also been a consideration wherein 1% to 2% volume fraction of steel fibers were recorded to have better fire resistance (Lau and Anson 2006). Likewise, the incorporation of polypropylene fibers to mitigate spalling has been a favorable solution for most cases. Autoclave curing enhances the mechanical properties of RPC (Yazıcı, Deniz et al. 2013). However, only a number of researches have been made that discusses the effects of elevated temperature on RPC as a material (Liu and Huang 2009, Tai, Pan et al. 2011, Peng, Kang et al. 2012, Zheng, Luo et al. 2013). The experiment of RPC as a column has been discussed by a previous research (Malik 2007), though fire resistance test was not incorporated in the scope of the study. With the prior knowledge available, this study aims to determine the fire resisting performance of RPC columns under autoclave curing.

The experimental procedure in this research was intended to determine the performance of autoclave cured RPC columns after fire. The program was divided into two phases; the preliminary phase and the final phase. The preliminary phase of this experiment concluded trial mix designs of RPC stated in the previous studies which also made use of the original mix design by Richard and Cheyrezy in 1994 (Chatveera, Kongsaktrakoon et al. 2007). The Final phase incorporated the mix design from the preliminary results. RPC columns were casted with along with the cylindrical specimens. Columns and respective cylindrical specimens underwent autoclave curing prior to fire resistance and mechanical tests respectively. Materials have been carefully chosen based on the best possible availability for the concrete mix.

3.2 Phase I: Preliminary Phase

Preliminary tests of RPC were done in order to understand the behavior of the concrete on its fresh state. This phase included the investigation of RPC cubes that involved variation in material composition proportions. Previous reports such as (Lee and Chisholm 2005) and (An, Zhang et al. 2008) discussed RPC cube specimen analysis incorporating size effect (Bazant 2000). Mixture proportions in steel fiber, superplaticizer and water-to-cementicious ratio were looked at. Properties such as strength and workability were analyzed.

3.2.1 Mix Design and Materials

The original mix design of RPC in Table 0.1 by Richard and Cheyrezy (1995) was used in the preliminary stage of this study.

3.2.1.1 Cement

Table 0.1 Cement Specifications

Chemical Component	ASTM Type I Cement
SiO_2	20.7
Al_2O_3	5.2
Fe_2O_3	3.4
MgO	1.7 (max 6.0)
CaO	65.2
Total Alkalies (Na_2O + K_2O)	0.1 + 0.4 (max 0.6)
SO_3	2.5 (max 3.5)
Free CaO	0.7
LOI	1.4 (max 3.0)
Specific Gravity	3.15

The cement used is a TPI brand ASTM Type I Cement which is locally available in Thailand. The cement is packed in 50 kg bags. The properties of the cement are stated in Table 0.1.

3.2.1.2 Silica Fume

The Silica Fume used in this study is an Elkem brand Densified Microsilica. It is packed in 20 kg bags and the properties are stated below.

Table 0.2 Silica Fume Specifications

Chemical and Physical Properties	Specification
SiO_2	>90
H_2O moisture content when packed	<1.0
LOI	<3.0
Retained on 45 micron sieve	<1.5
Bulk Density	500-700

3.2.1.3 Sand

The Sand used for the mixture of the RPC is from CPAC packed in 25 kg bags with maximum grain size of 1mm. Sand is air dried prior to mixing to eradicate excess moisture in the package.

3.2.1.4 Superplasticizer

The superplasticizer used in this study is a MasterGlenium ACE 8320 from BASF Chemical Company. It is a high activity superplasticizer designed for demands for initial resistance in reduction of curing cycles specially made for High Performance Concretes. It has great water reduction power, increases the initial and final setting time of concrete, does not produce delayed settings and has excellent cohesion in decreasing porosity.

3.2.1.5 Steel fiber

The steel fiber used in the preliminary stage was the 13 mm straight high strength steel fibers by Dramix. It has an aspect ratio of 13/0.2 providing high performance and crack resistance producing optimal ductility for high strength but brittle concrete from 100 MPa of concrete.

3.2.2 Mixing, Curing and Testing

Mixing of RPC in the preliminary stage followed the mixing procedure done by (Lee and Chisholm 2005) as stated in Table 0.3.

Table 0.3 Mixing Procedure

Mixing Protocol	Elapsed time in minutes
Lightly grind cement and silica fume to break-up agglomerates	-
Add all dry powders and aggregate	0
Start mixing	0.5
Add 87% of water and 50% of super-plasticizer	3
Add steel fibres	5
Add remaining water and super-plasticizer	8
Stop mixing and cast test specimens	30

A total of twenty-one (21) different mix designs were casted and tested to obtain the most appropriate mixture of RPC for the criteria of strength and workability given the available materials. RPC samples were mixed in a mortar mixer casted in 50 mm cube molds. Specimens were cured in water until the day of testing. Parameters such as steel fiber content, water content, superplasticizer content and curing duration were varied.

Figure 0-1 Equipment for RPC cube specimens

3.2.3 Fire Test

A total of forty-two (42) 150 x 300 mm cylindrical specimens were casted for the investigation of the effect of fire to RPC cured in water. Nineteen (19) of the specimens underwent ASTM Fire for 120 minutes to evaluate the effect of fire as preliminary investigation. The other twenty-three (23) specimens were used to determine compressive and splitting tensile characteristics of RPC cylinders. The specimens have varying steel fiber content and water-to-cementitious ratio. The residual parameters due to fire of 2 hours are intended to be achieved. Due to intense fire, all specimens spalled off. This result made the range of fire for the final phase to become 30 to 60 minutes only. On the other hand, compressive and tensile properties of RPC cylinders were obtained.

Figure 0-2 RPC cylinders (a) before fire (b) after fire

3.3 Phase 2: Final Phase

The Final phase integrates the varied mix design and mixing procedure after the preliminary investigation of the RPC. This also follows the reduced duration of fire for the fire test of columns. This phase includes the casting, autoclaving, firing and mechanical testing of RPC columns and respective cylindrical specimens.

3.3.1 Test Specimens

Table 0.4 RPC column

RPC column Specimen	RPC cylindrical Specimen	Steel fiber content (% volume)	PP fiber content (% volume)	Fire Duration (minutes)	Column loading
COL-A	CA	0%	0%	0	Axial
COL-B	CB	0.5%	0%	30	Axial
COL-C	CC	1.5%	0%	60	Axial
COL-D	CD	1.5%	0%	30	Axial
COL-E	CE	1.5%	0.1%	30	Axial

Five RPC columns of dimension 200 mm square and 1250 mm in height were casted with each respective 150x300 cylindrical concrete specimen for material properties test. Each column exhibited different specifications based on the variable parameters considered in this study to analyze mechanical and fire resisting performance of RPC. Table 0.4 summarizes the specifications that were integrated in each respective RPC column. COL-A is the control specimen which is unfired and no steel fiber content in the matrix.

3.3.2 RPC mix design

The RPC mix design used in this study was based on the preliminary phase results. The basis for the deviation of mix proportions were made due to the difference in materials used and workability issues. The mix design used in the study is shown in Table 0.5.

Table 0.5 RPC mix design ratio by weight of cement

Compositions	RPC 200
Portland Cement	1
Silica fume	0.25
Sand	1.1
Superplasticizer	0.02
Steel fiber	Varying fiber content by volume of concrete
PP fiber (COL-E)	0.01
Water	0.25

3.3.3 Steel reinforcement

Steel reinforcement for the column specifications of RPC was based on structural design code (ACI 2008). Based on initial analytical computation, the main reinforcing bars were made of 4-12mm diameter with yield strength of 400 Mpa. The steel ties were composed of 9mm diameter with yield strength of 275 MPa. The configuration of steel reinforcement was discussed in the succeeding subtopic. Main steel reinforcement was a constant parameter in this study.

The steel fiber integrated for the final phase specimens is Dramix 5D from Bekaert due to the limitation of material during the preliminary phase. It has a tensile strength of 2300 MPa and a modulus of elasticity of 210 GPa. It has a unique 5-bend hook for increased anchorage strength compared to normal hooked end steel fibers. Other specifications are presented below.

Table 0.6 Steel Fiber

Fiber family	5D
Length (l)	60 mm
Diameter (d)	0.90 mm
Aspect Ratio (l/d)	65

3.3.4 Column fabrication

The RPC column specimens that was casted for this study would have a gross cross sectional area of 200 x 200 mm^2 comprised of 4-12mm diameter main longitudinal bars and 9mm diameter steel ties. The dimensions and configurations are based on the limitation of the testing equipment. Column dimension and steel reinforcing configurations are based on ACI design code chapters 7.10, 10.8 to 10.10 and 21.6 (ACI 2008). The column specification is shown in Figure 0-3.

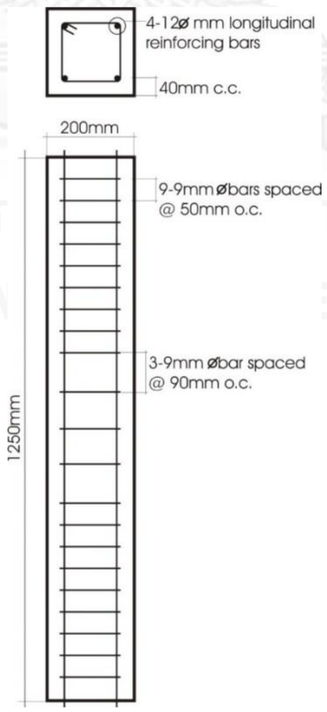

Figure 0-3 Column dimension

3.3.5 Equipment and Instrumentation

3.3.5.1 Furnace Specifications

The furnace used in this study was located in the Fire Safety Research Center (FSRC) of Chulalongkorn University. The furnace has an internal dimension of 1.8x0.9x2.6 m^3. Six gas burners are integrated within the furnace associated with a loading frame installed on top for load simulation on fire. The image below shows the schematic figure.

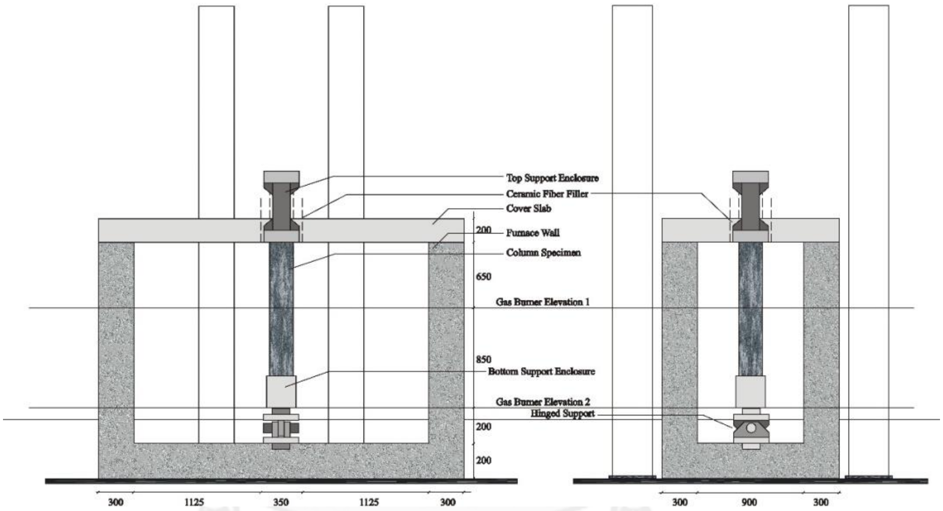

Figure 0-4 Furnace specifications

3.3.5.2 Autoclave specifications

The autoclave is a pressure-temperature chamber that can be used in curing concrete. The autoclave machine specifications are presented in Table 0.7.

Table 0.7 Autoclave Specifications

Specification	
Diameter	2.1 meters
Length	2.2 meters
Maximum Temperature	160°C
Pressure Range	0 to 10 bar

Figure 0-5 Autoclave

3.3.6 Casting and Mixing of RPC column

The RPC column followed a revised mixing procedure based on the preliminary results to accommodate workability issues primarily due to the use of steel fibers incorporated in the mixture. This procedure was observed in casting all specimens in the final phase. Table 0.8 summarizes the procedure.

Table 0.8 Mixing procedure

Mixing Protocol	Elapsed time in minutes
Lightly grind sand to break-up agglomerates	-
Add all dry cement and silica fume	0
Start mixing	3
Add water and super-plasticizer	15
Add fiber components	20
Stop mixing and cast test specimens	25

Sand was placed prior any component of the concrete to avoid excessive dispersion of microparticles of the fine binders into the air. Grinding of sand ensures that particles are evenly broken down to keep a good distribution of the material to the matrix. Cement and silica fume were added and mixed until even distribution was observed. Superplasticizer was added to the water component before pouring into the mixer to achieve a good consistency of the liquid components of concrete. Finally, fibers are added once good workability is achieved. This ensures even distribution of fibers to the mixture as well as to avoid premature stacking. It shall be noted that the PP fibers integrated in the mixture of COL-E was not part of the preliminary investigation and was added to evaluate its effects to the RPC after fire. The PP fibers used has a density of 0.9 g/cm^3 and length of 19 mm. It was saturated to water for 24 hours prior to casting of the RPC.

A total of five (5) columns and fifteen (15) cylindrical specimens of RPC were casted in the concrete laboratory of Chulalongkorn University. An 80 liter revolving mixer was used to mix the RPC. Molds were formed and securely locked prior to casting. Once concrete was poured in the mold, the specimens were covered by cloth to secure the moisture in the concrete to mitigate early drying shrinkage. The molds were detached from the specimens after 1 day.

3.3.7 Autoclaving

In order to achieve better mechanical properties of RPC, autoclave curing of RPC has been investigated. In literature, RPC curing have been significant in improving properties of high performance concretes (Lee and Chisholm 2005, Aydın, Yazıcı et al. 2008, Yazıcı, Deniz et al. 2013). Temperature and pressure rise hastens the chemical reaction of the C-S-H gel in the mixture, thus improving the material properties of RPC. Autoclaving changes the microstructure of the concrete. Hydration of cement will be faster and will result to higher compressive strength in a short time. Prior to use of the equipment, a series of demonstrations were conducted by the company for information and safety.

Figure 0-6 Autoclaver Components

After all specimens were casted, the specimens were brought to Saraburi Laboratory of Chulalongkorn University to cure into an autoclaver 1 to 3 days after casting. The specimens were cured in the autoclaver all at once. The autoclave was operated for 4 hours with a maximum pressure of 4 bar and temperature of 140°C.

Figure 0-7 RPC in autoclave

3.3.8 Fire Test

RPC is expected to have a low fire resistance which is inversely proportional to the high compressive strength that it possesses. It is required for a building to withstand fire for about 1 to 4 hours (ACI 1997). A pilot test of specimen with steel fiber content of 1.5% in volume was done for 60 minutes in order to assess the damage. The rest of the columns to be fired were assessed up to 30 minutes under the ASTM fire curve due to severe results on the pilot test. All fire tests were conducted in the Fire Safety Research Center of Chulalongkorn University located in Uthen Thawai Campus in more than 28 days after autoclave curing. Load was not present during the fire test due to the limitation of the equipment, thus, residual strength of RPC columns were analyzed instead. Tests were set and conducted with professional fire tester personnel.

The column is positioned in a vertical manner positioned with a bottom hinge support of the furnace and a cover top support enclosed with a cover slab as shown in Figure 0-4. The end supports, surface of the furnace and the cover slab were properly insulated by ceramic fiber to protect against fire.

Figure 0-8 Fire Laboratory

3.3.9 Cylindrical Specimens Tests

To validate the material properties of RPC with the previous literatures and preliminary test results, each respective mix design of columns had representative cylindrical specimens for testing its material properties. The specimens were tested more than 28 days after autoclave curing. Strain gages were properly installed in the transverse and longitudinal direction halfway through the length of the specimen. The maximum compressive strength, elastic modulus, poisson's ratio and stress-strain curves were obtained from the tests executed in the Material Testing Laboratory of Chulalongkorn University with the use of a data logger, load cell and the compression machine.

Figure 0-9 Cylindrical RPC specimens and testing equipment

3.3.10 Column Test

To obtain the relationship of residual strength of RPC columns after fire, column specimens underwent axial tests in the Material Testing Laboratory of Chulalongkorn University. Each specimen was assessed and analyzed by the induced load, axial deformation and failure mode.

Figure 0-10 Column Test Equipment

Figure 0-11 Test setup of Specimen COL-A

As can be seen in Figure 0-11, the load cell was positioned directly below the specimen with the LVDT measuring the deformation in the lower left corner of the bottom plate. The bottom plate of the testing equipment moves up as the applied force resisted by the top support.

3.3.11 Investigation

Different parameters have been considered to be able to evaluate the performance of RPC columns. One of which is the spalling depth observed in the surface of the columns. Spalling depths were measured on each face of the column in five different sections to visualize the damage brought by the fire. Crack propagation and color deviations were also observed for the physical characteristic investigation of each fired RPC columns. Cracks were measured by a thin acrylic sheet with respective width measurements. Color deviation was analyzed based on Figure 0-5 for visual evaluation.

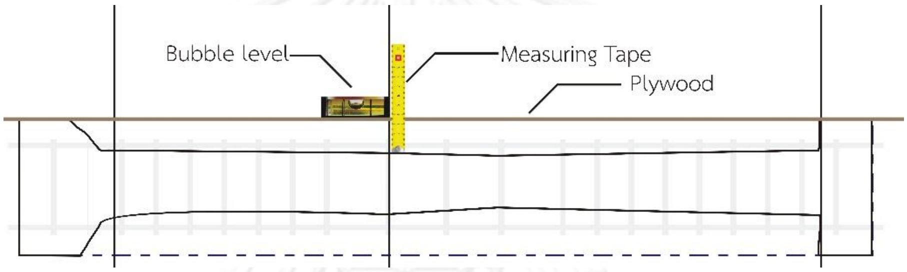

Figure 0-12 Measurement of spalling depth

Strength test evaluated the performance of the RPC column based on stiffness and failure mode characteristics. Load-deflection curves of each column were determined from the actual tests. Estimate of the modulus of elasticity based on previous literature were also looked at. Steel fiber volume fraction differences and polypropylene fiber inclusion were also evaluated in terms of reduced concrete area due to spalling. Furthermore, computational failure mode criteria were derived to confirm the actual failure observed during tests.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Introduction

RPC is one of the recent forms of concrete that has been around for nearly two decades. Its utilization has been increasing however fire related studies have not been issued on actual structural members. Pilot tests have been concluded prior to the actual RPC specimens casting and autoclaving.

Notations have been assigned to name each respective specimen. Table 0.4 in the previous chapter summarizes the designation of each RPC column with their respective representative cylindrical specimens. The notations stated will be used to the entirety of the discussion in this chapter.

4.2 Preliminary Results

50 mm cube specimens have been investigated for initial tests of RPC. Steel fiber content, water-to-cementicious ratio variation, superplasticizer volume and curing days prior to tests were examined.

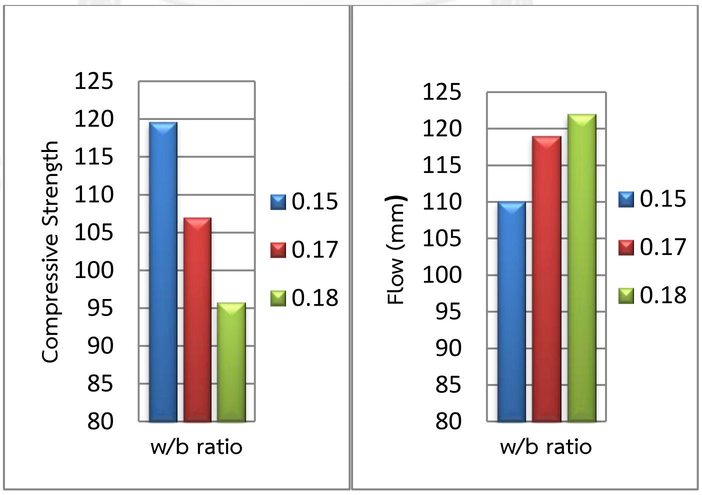

Figure 0-1 Compressive strength and flow against water binder ratio at 1 week curing with 2% steel fibers

Figure 0-1 illustrates the relationship of compressive strength and flow to the water-to-cementitious ratio of RPC. It can be concluded that as the w/b ratio increases, the compressive strength decreases. Evidently, flow increases with increased amount of water. This trend is expected wherein less water is associated with increased strength.

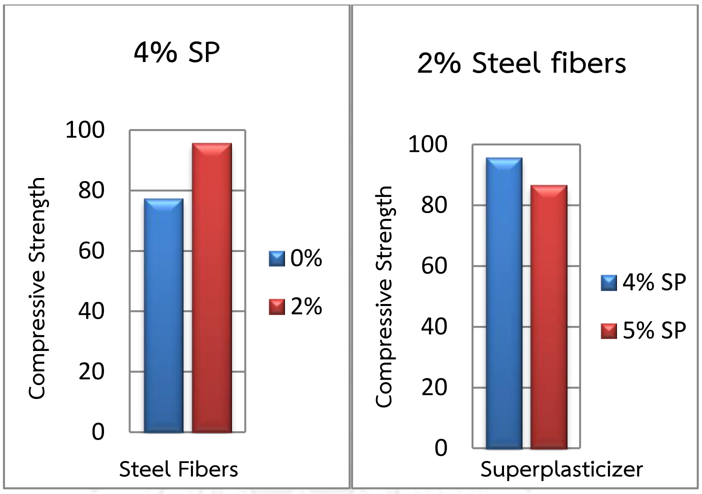

Figure 0-2 Compressive strength at 1 week of 0.18 w/b ratio

Figure 0-2 shows the variation of compressive strength with steel fiber presence in the mixture as well as superplasticizer content. Based on literature, the range of 1 to 2% of steel fiber in the mixture results to the optimum compressive strength for fiber reinforced concrete. It was found out that the integration of steel fibers also results to higher compressive strength value for the cube specimens. Comparing fibered and non-fibered, steel fiber also improved the compressive strength of RPC due to its additional post cracking behavior. On the other hand, increasing superplasticizer content reduces the compressive strength of RPC. This can be attributed to the segregation of steel fibers in the mixture which can be associated to higher w/b ratios up to 0.25. It shall be noted that the following strength measurements were made from a small 50 mm cube and size effect would result to a lower compressive strength value if bigger specimens would be considered for analysis (An, Zhang et al. 2008).

Preliminary fire test conducted on cylindrical RPC specimens for 120 minutes experienced extreme spalling and degradation of the material. Cylinders without the presence of steel fiber spalled off completely while specimens with steel fibers tend to have significant amount of volume of RPC left. However, all specimens were geometrically incapable for any mechanical test. Thus, it can be concluded that a 2-hour fire rating for RPC is high enough for the material to spall off completely.

Interestingly, cylindrical specimens of RPC were casted as the representative specimens for the non-fired category for comparison of the initial and residual fire scenario. The compressive strength and tensile strength characteristics of the RPC cylinders were compared with respect to steel fiber content and water-to-cementitious ratio.

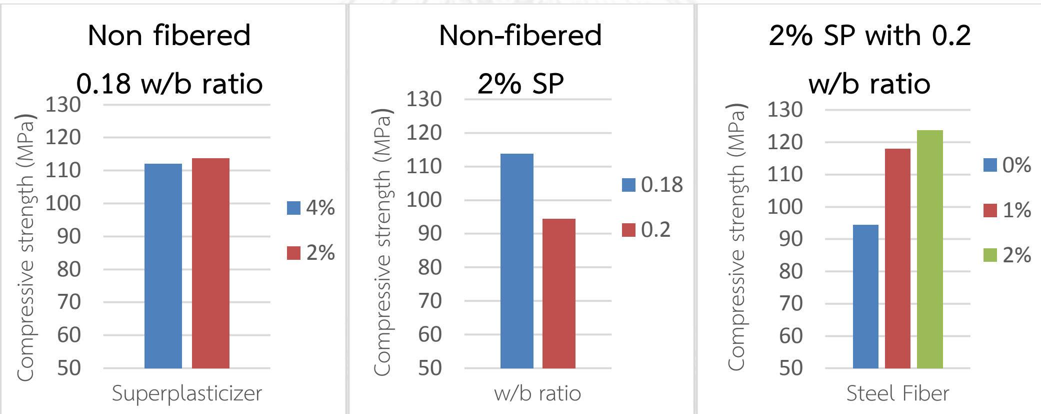

Figure 0-3 Compressive strength relationship (a) superplasticizer (b) w/b ratio (c) steel fiber volume fraction

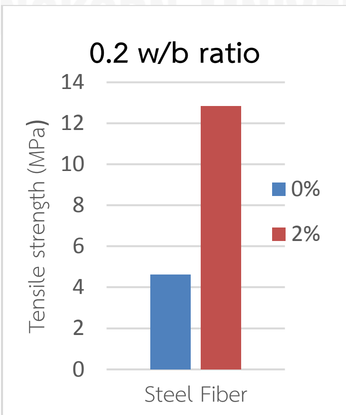

Figure 0-4 Tensile strength vs steel fiber volume fraction

Higher superplasticizer volume in the mixture has a great effect in the fresh concrete state. On the contrary, it has a minimal effect on the compressive strength of RPC. Evidently, lower water-to-cementicious ratio yielded to greater compressive strength giving the same trend as the cube specimens. Steel fiber inclusion in the matrix has improved the compressive strength of concrete. A minimal increase was observed in the range of 1% to 2% in steel fiber volume fraction. Steel fiber effect is exhibited in the tensile strength characteristics of RPC as seen in Figure 0-4. It shall be noted that the RPC cylinders are cured for 30 days prior to testing and resulted to greater values as compared to the cube specimens. However, it can also be observed that results from the cube specimens are yielding similar trends as compared to cylindrical specimens.

4.3 Material Properties

Each representative cylindrical specimen was casted and cured together with each respective RPC column. The material properties such as compressive strength, modulus of elasticity and poison’s ratio were obtained and analyzed in this subchapter.

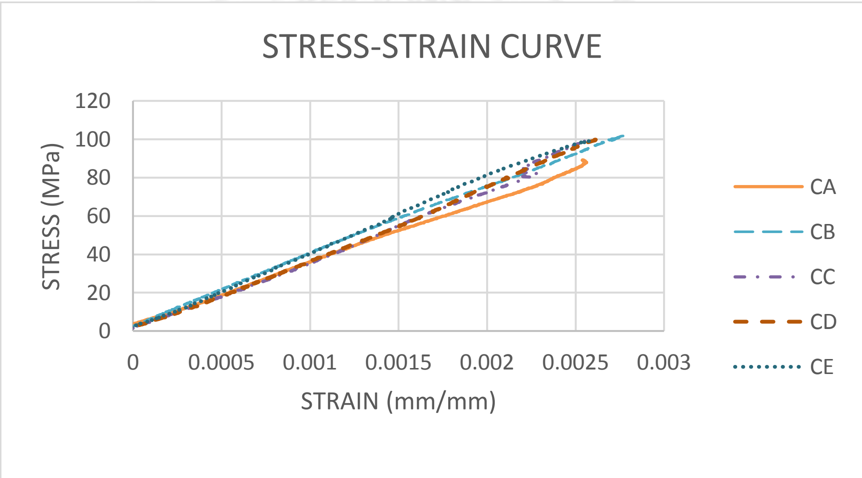

Figure 0-5 Stress-Strain Relationship of RPC

Figure 0-5 shows the stress-strain curves of RPC. It can be noted that the results were only obtained until 180 tons or about 100 MPa of force due to the limitation of the load cell used during testing. Specimens were divided into two groups. The first group is to obtain the maximum compressive strength and the other group is to be tested under a limited strength for determination of the RPC's elastic properties. It can be observed from the graph that there is a clear linear relationship in the elastic region. The compressive strength was obtained from the test following ASTM C39 while the modulus of elasticity (E) and poisson's ratio (μ) were obtained from ASTM C469 standard. Sample computation is as follows for specimen series CD:

Formula:

$E = (S_2-S_1) / \varepsilon_{l2}-0.00005$ 0.1

$\mu = (\varepsilon_{t2} - \varepsilon_{t1}) / \varepsilon_{l2} - 0.00005$ 0.2

where:

S_1 = stress at longitudinal strain value of 0.00005 = 3.47 MPa

S_2 = stress at 40% of the ultimate load = 44.7 MPa

ε_{t1} = transverse strain at S_1 = 0.000031101

ε_{t2} = transverse strain at S_2 = 0.00026658

ε_{l2} = longitudinal strain at S_2 = 0.00122775

Substituting to the formula:

E = (44.7-3.47) / 0.00122775-0.00005 = **35069 MPa**

μ = (0.00026658 – 0.000031101) / 0.00122775 – 0.00005 = **0.20**

Table 0.1 RPC properties

Specimen	Compressive Strength (MPa)	Modulus of Elasticity	Poisson's Ratio
CA	116	32896	0.19
CB	118	34186	0.19
CC	121	34946	0.22
CD	112	35069	0.20
CE	104	38461	0.20

The trend of the results were similar to previous literatures regarding the properties of RPC (Richard and Cheyrezy 1995, Tai, Pan et al. 2011) wherein the modulus of elasticity ranges from 20 to 40 GPa and poisson's ratio ranges from 0.2 to 0.25. It can be observed from the succeeding figures that as the steel fiber content increases, there is an increase in compressive strength, modulus of elasticity and poisson's. It should be noted that specimens CC and CD have the same mix design.

4.4 Fire Test Results

The ASTM E119 standard fire curve was used to evaluate the fire resisting performance of the RPC columns. It can be noted that Specimen COL-C was the pilot test for 60 minutes of fire and the rest of the columns were heated for 30 minutes. Figure 0-6 shows the average oven fire curves of the tests.

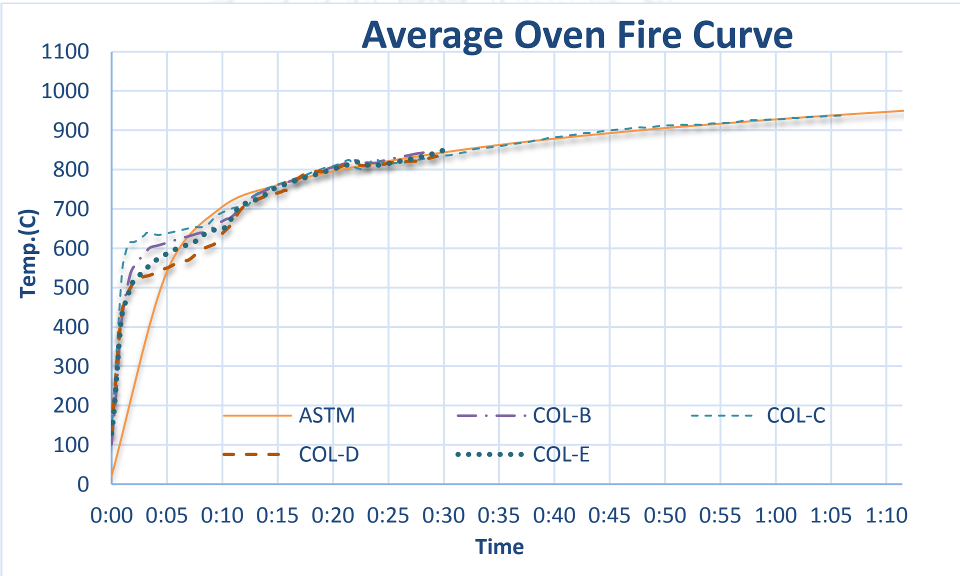

Figure 0-6 Fire Curve

From this figure it is clear that fire generation of the actual test deviates to an early rise of temperature until the range of 500°C to 600°C. Differences can also be observed at the span of time from the 4th to 11th minute and a more consistent trend thereafter.

4.4.1 Spalling Depth Analysis

In the conclusion of the fire test of RPC columns, severe spalling have been observed from all columns and this phenomenon have been a concern in all fire related studies. Spalling depths in 5 different sections along the length of each fired columns were analyzed to understand the spalling behavior of fire damaged RPC columns. . Sections were chosen in accordance to the position of the column in the furnace considering unfired depths on each ends of the column due to support conditions. The specimens are 200x200x1250 RPC columns fired on all sides.

Figure 0-7 shows the furnace set up of the fire test. Labeled in the figure are the designated face number and section depths that are necessary for the presentation of spalling depths. Table 0.2 summarizes the spalling depths measured on the RPC column specimens after fire.

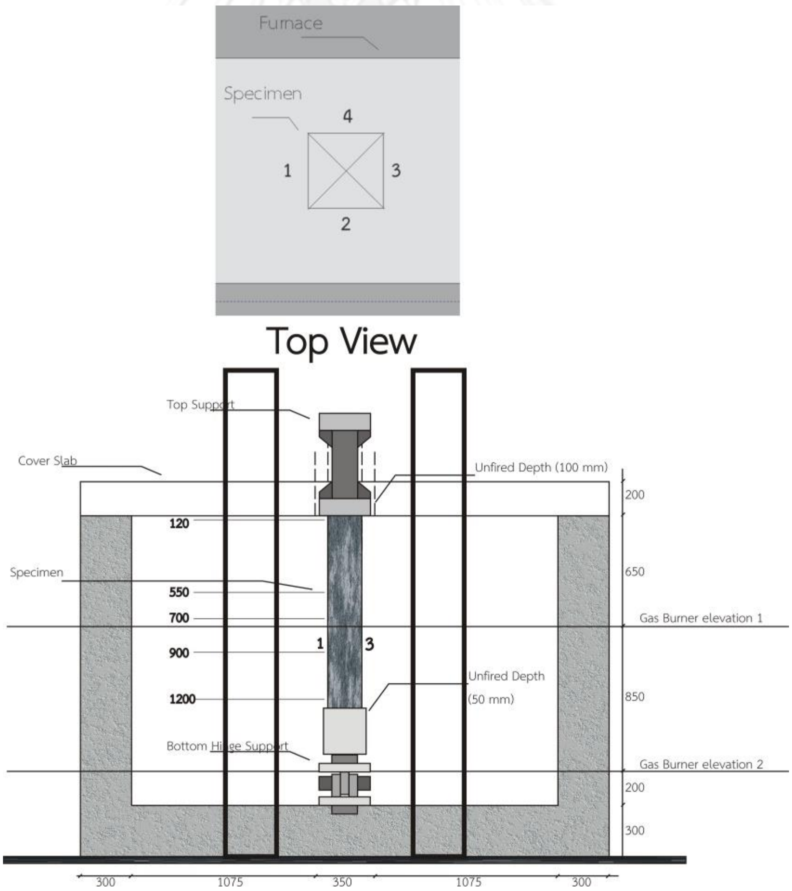

Figure 0-7 Furnace Set up

Table 0.2 Column Spalling Depth per Section

SECTION	FACE	Specimen Name			
		COL-B	COL-C	COL-D	COL-E
		Spalling Depths (mm)			
1 = 120 mm	1	45	42	50	45
	2	52	38	40	45
	3	52	56	45	45
	4	42	70	40	30
2 = 550 mm	1	63	43	50	60
	2	57	82	65	35
	3	66	92	55	50
	4	57	75	50	40
3 = 700 mm	1	52	65	50	70
	2	64	95	50	55
	3	72	90	70	55
	4	63	85	60	60
4 = 900 mm	1	64	57	70	100
	2	58	50	70	100
	3	70	65	45	100
	4	76	60	60	100
5 = 1200 mm	1	65	45	40	100
	2	64	45	75	100
	3	68	65	75	100
	4	78	70	40	100

The spalling depth measured is the perpendicular distance from the surface of the original unfired column to the furthest depth of spalling. The larger the value, the deeper the spalling of concrete was observed. It was observed that most values are greater than 40 mm, which is the depth of the concrete cover. This indicates that the spalling phenomenon happened to expose the main reinforcing bars of the column which indicates the poor performance of RPC in fire. It can also be noted the severe spalling depth in sections 4 and 5 wherein a burner was in close contact to the aforementioned sections. In this case, two parts of columns will be presented. The first part is the upper portion of the column under the sections 1 to 3 and the second part is the lower portion which involves sections 4 and 5. It shall be noted that specimen COL-C was exposed to fire for 60 minutes as compared to the rest of the column specimens which are exposed to fire for 30 minutes.

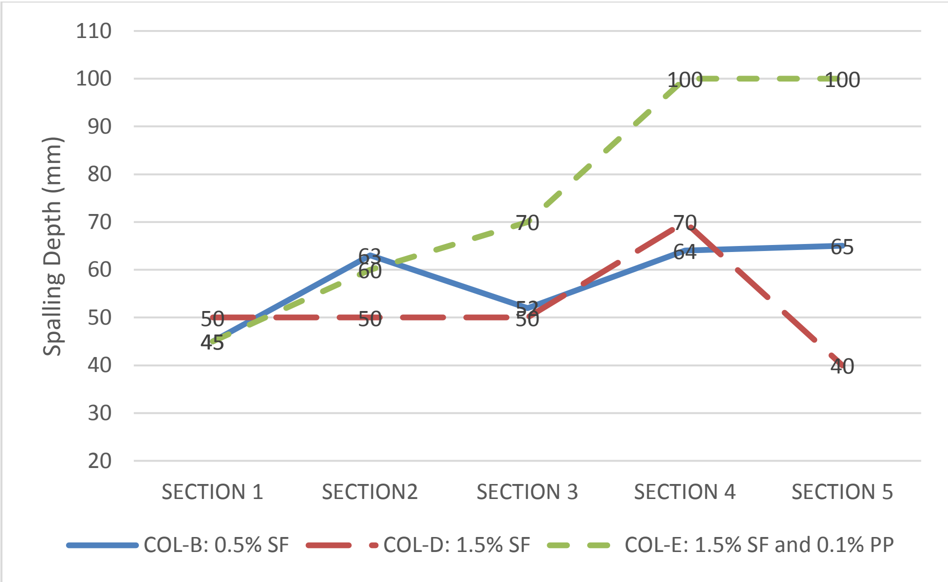

Figure 0-8 Spalling depth in face 1 of columns

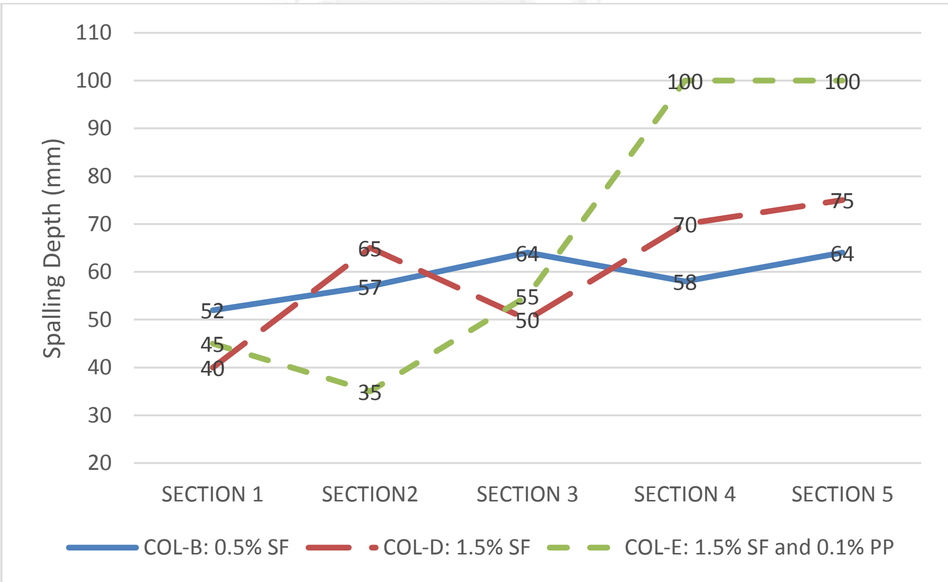

Figure 0-9 Spalling depth in face 2 of columns

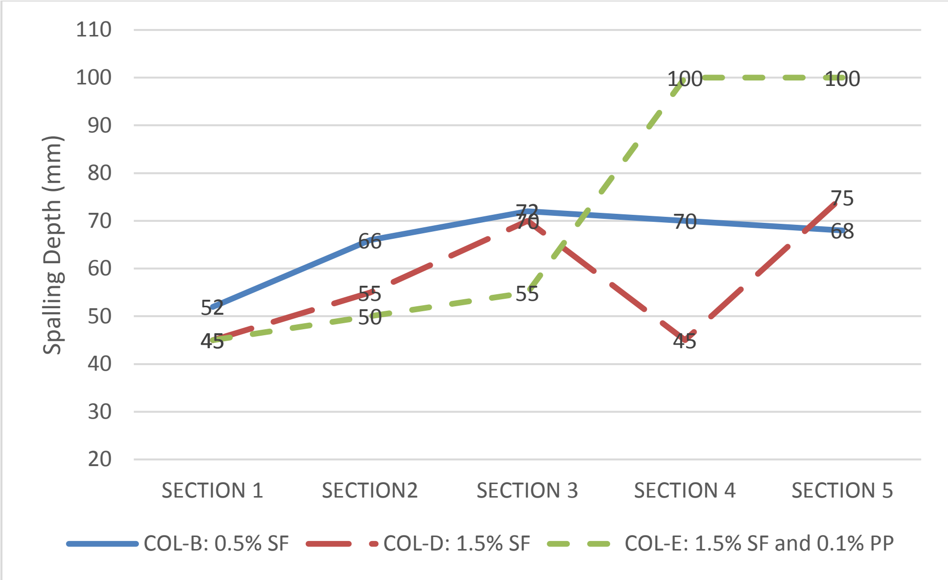

Figure 0-10 Spalling depth in face 3 of columns

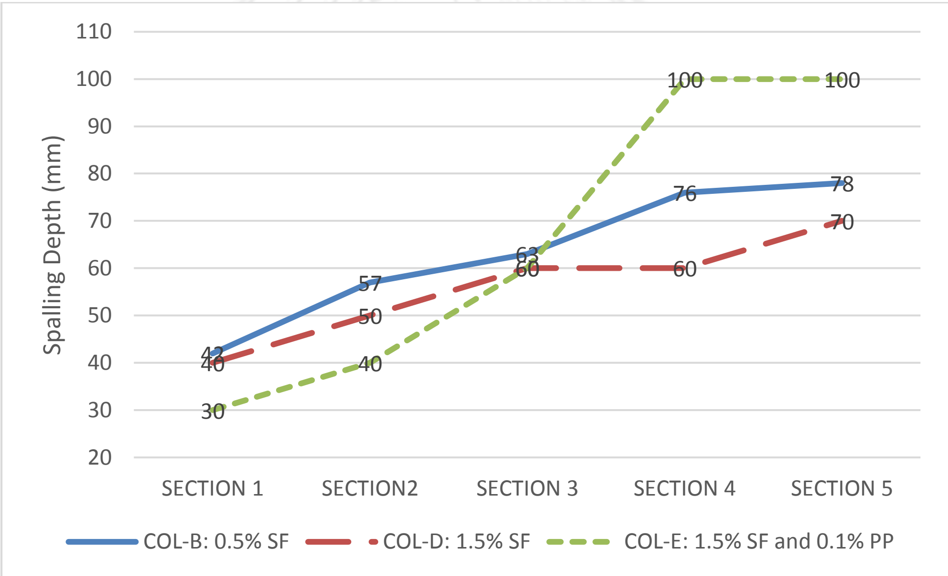

Figure 0-11 Spalling depth in face 4 of columns

Specimen COL-B was observed to have the worst scenario of spalling as compared to specimens COL-D and COL-E with the same fire exposure. 0 to 20 mm spalling depth difference was observed in each face as compared to the other specimens. That can be attributed to a section loss of about 50%. Spalling depth is more pronounced throughout the height of the specimen. This can be attributed to fewer fibers in the matrix. The mixture with less fibers tend to experience earlier spalling due to less components holding the dense microstructure of the RPC. Early pressure development caused by a high rate of increase of temperature by the furnace in the concrete have caused worse spalling scenario. The early preheating stage caused the trapped free water in the concrete which was not eliminated, thus increased the pressure. Comparing its fire generation in the fire curve, it also had an early acceleration of heat compared to specimens D and E. Faster acceleration of heat can be attributed to this phenomenon. Figure 0-11 to Figure 0-11 show the differences in spalling depths along the height of the columns exposed to 30 minutes. The uneven distribution of fire that happened along the height of the column was exhibited. As can be observed in the figures, the spalling of COL-E is least pronounced compared to COL-B and COL-D which is true for all faces.

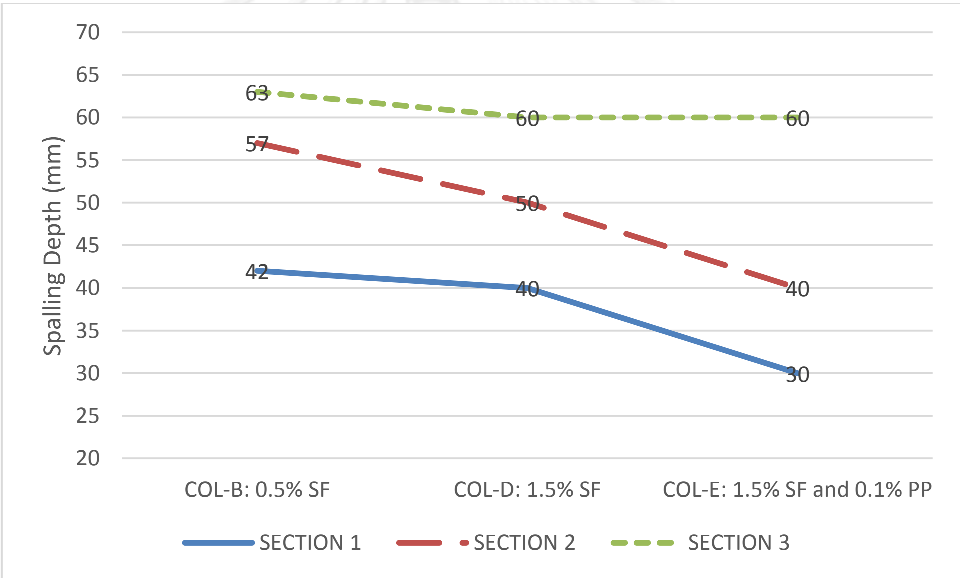

Figure 0-12 Spalling depth of different sections in face 4

Specimen COL-D and COL-E have the same steel fiber content of 1.5%. COL-E was introduced with 0.1% polypropylene fibers to evaluate the benefits of PP fibers to the RPC. Based on discussions by previous research, PP fibers improve the fire resisting performance of concrete and limit the effect in spalling. This is due to the melting characteristics of PP fibres at 170ºC then builds interconnected capillary networks that helps in releasing the internal pressure in concrete caused by high temperature in the presence of fire (Noumowe 2005, Pliya, Beaucour et al. 2011). In the upper portion of the two columns, sections 1-3, the advantage of PP-fiber infused specimen was observed. Difference of 0 to 15 mm spalling depth was obtained from measurements. Fire generation during test is similar. This difference can be attributed to the inclusion of pp fibres in the matrix. In the upper sections, concrete cover in specimen COL-D is relatively more exposed compared to COL-E. Figure 0-12 shows the spalling depth of each section per column.

COL-C experienced the worst case after fire in terms of spalling depths, texture and color difference which is evidently caused by the longer duration of fire exposure. It shall be noted that COL-C and COL-D have the same mix design. Comparing the two specimens with their difference in fire exposure, spalling depth differences of 10 to 30 mm was observed, giving the advantage to the latter. That is about amounting to 75% section loss which is a very dangerous scenario for fire scenarios in buildings.

Table 0.3 Least and Average Remaining Area

SECTION	COLUMN			
	B	C	D	E
1	10918	9384	12600	13750
2	6106	2795	8075	11250
3	5548	900	7200	6375
4	4356	7020	5950	N/A
5	3886	7650	7225	N/A
Least Remaining Area (mm^2)	3886	900	5950	6375
Average Remaining Area (mm^2)	6163	5550	8210	10458

The smallest remaining area was evaluated to understand the worst case performance of the RPC columns exposed to fire. The least area is a measure of how much area of concrete can still resist the load after fire exposure. This result to the more favorable outcome for columns incorporated with PP fibers and 1.5% SF case.

It can be observed in Table 0.3 that there is a little discrepancy between the results for columns D and E wherein steel fiber volume fraction is high. The section of the least area is located on the lower sections from 4 to 5 which is caused by the burner exposing the columns in direct fire. The values of the average remaining area would be used in the evaluation of the failure mode in the succeeding chapters. Furthermore, Figure 0-13 shows the difference in the remaining area in the upper sections of the column.

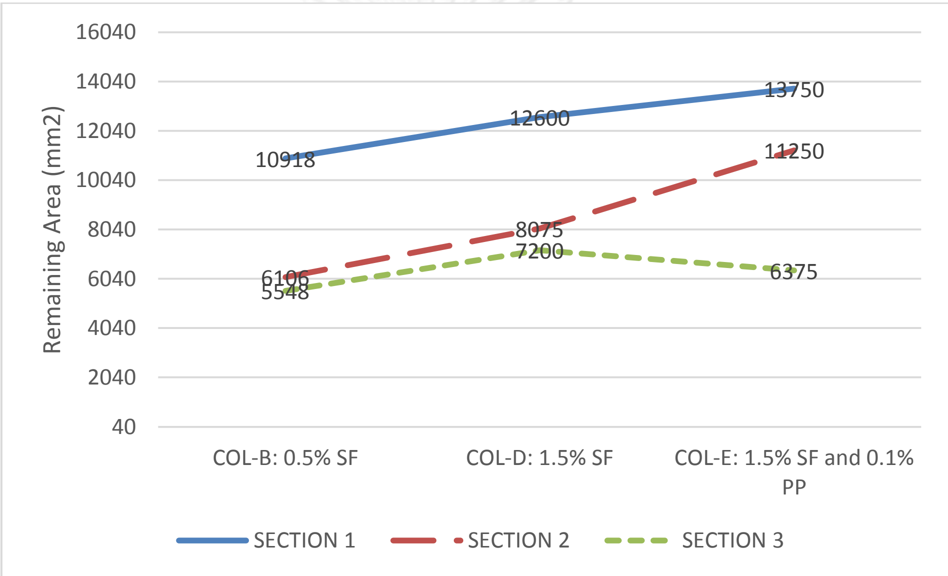

Figure 0-13 Remaining Area in three sections

4.4.2 Color and Texture Characteristics

In recent literature, color and texture difference of RPC exposed to different temperature have been analyzed (Tai, Pan et al. 2011). The aforementioned study ranks the appearance and characteristics of RPC in different ranges of temperature. Figure 0-5 summarizes the appearance characterization of RPC after high temperature tests.

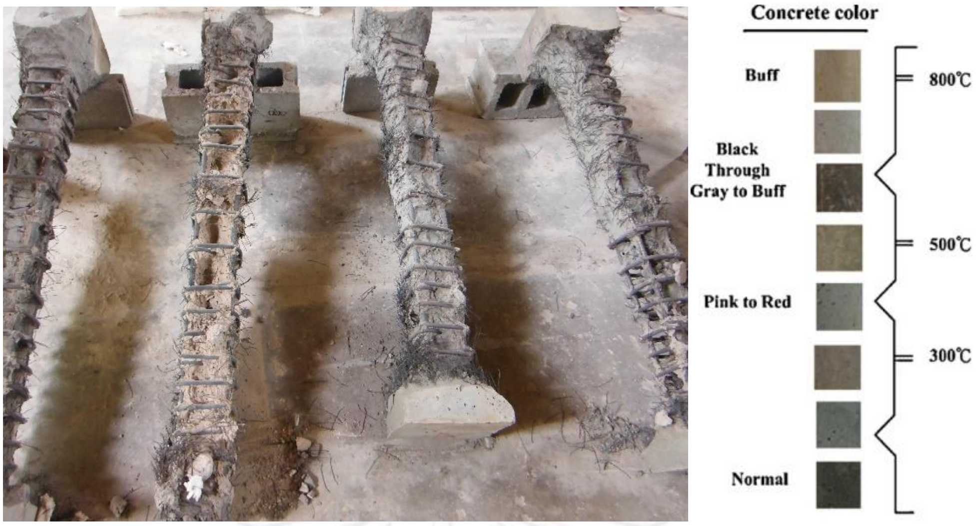

Figure 0-14 Color difference in different fire exposure of RPC columns

Figure 0-14 shows the variation of color of the RPC column specimens of COL-B to COL-E positioned from left to right respectively. It was observed that the specimens change in appearance is caused by chemical reactions brought by the increase in temperature. It can be noted that following the ASTM E119 fire curve assures that each specimen reached 800°C. Specimen COL-C underwent 60 minutes of fire exposure and was observed to exhibit the characteristics of brittle, powdered and light brown colored appearance. Time exposure of specimens provides significant difference in color and texture.

Specimens fired for 30 minutes were observed to have a light gray color on the remaining core of the concrete. This means that the fire have not penetrated significantly to cause chemical reaction to the remaining core concrete. However, change in color can be seen as the depth of spalling increases. Concrete fragments that remain intact to the steel bars were observed to have light brown color and a more brittle texture compared to the concrete on the core. This can be attributed to longer fire exposure of the surface concrete as the depth reaches the core. Together with color variation, texture also differs as the spalling depth deepens. The light brown color was observed to have a more brittle, powdery configuration which is pronounced on the concrete nearer the surface, while gray to normal color of concrete with spalling and cracking phenomena was observed in the remaining core surface. This criterion can be used in order to estimate the fire severity of fire that the concrete experienced. This could also be a measure in predicting the material properties of the fired concrete based on the equations presented in section 2.2.3.

4.4.3 Mechanism of Fibers

Steel fiber functions in the post cracking behavior of fiber reinforced RPC. The interlocking mechanism of fibers is expected to bridge gaps and provide additional resistance compared to non-fibered mixtures. Hooks at the end of the fibers also add additional locking resistance in the phenomenon of possible fiber pullout. In the fire cases of RPC columns, micro cracks have been observed, however, steel fiber functions more on holding the spalling of concrete with its interlocking mechanism.

COL-C specimen that underwent fire of 60 minutes experienced the worst spalling and loss of mass. Steel fibers on the spalled off surface have been observed to have a change of color from gray to dark gray as shown in Figure 0-15Figure 0-15. The color transformation was due to the heat induced by the steel, thus making the fibers more brittle than ductile. Fiber melting was not observed. Fibers were also spotted to be bent in the case of preventing the spalling of concrete during fire. As observed in Figure 0-17, hook ends were observed to be embedded onto the concrete even after spalling occurs. Crack widths of 0.1 to 0.5 were detected to run along the fiber embedment to small honeycombs.

Figure 0-15 COL-C: Color change and bending of fibers

Figure 0-16 COL-C: Cracks running along fiber

Figure 0-17 COL-C: Hook ends embedment in spalled-off concrete

Color change for the steel fibers of specimens COL-B, COL-D and COL-E exposed to 30 minutes were not significant as compared to the drastic change of color for COL-C. Microcracks were observed smaller than the ones noted from COL-C. Steel fibers interlocking mechanism prevents the spalling of concrete and bridging cracks were not prevalent.

Figure 0-18 COL-B: Hook end embedment in spalled-off concrete

Figure 0-19 COL-D: Hook end embedment in spalled-off concrete

Figure 0-20 COL-E: (a) Hook end embedment (b) Prevention of spalling

The five-bend hooks of the steel fibers exemplify the good bond between fibers and concrete in prevention of spalling. Hooks are tightly locked in the concrete mixture while the concrete expands and spalls off in the region between the hooks. Figure 0-18, Figure 0-19, and Figure 0-20 shows the effectiveness of hook bonding in the concrete to prevent from spalling. Bends in the steel fibers were also observed as a reaction to expansion of concrete.

4.5 Column Stiffness and Failure Mode Investigation

Four out of the five RPC column specimens underwent the ASTM E119 curve. However, due to the limitation of the testing equipment, simultaneous application of load and fire did not materialize. This limitation paved way to the analysis of the residual strength of the RPC column specimens.

Specimen COL-A was assigned as the control specimen. This column would be the reference of the analysis for the rest of the fired columns. In the course of this analysis, it is assumed that the elastic region of each column is similar. Steel fibers will be in effect on the post cracking behavior of the column. Furthermore, specimen COL-C was not analyzed due to the severe effect of fire. It can be noted that the load on this specimen will only be supported by the main reinforcing bars. Columns COL-B and COL-D were analyzed to determine the effect of steel fiber volume to the residual strength of RPC columns after fire. Due to the spalling induced by COL-E on its lower portion, only the reaction of steel bars was obtained from the column test which can be related to the failure criteria of COL-C.

4.5.1 Load-Deformation Relationship

The material properties as presented in section 4.3 have shown the differences of each RPC material casted. The modulus of elasticity in different volume fraction of steel fiber has close values wherein it is assumed that behavior of RPC will be the same in the elastic region of the stress strain curve.

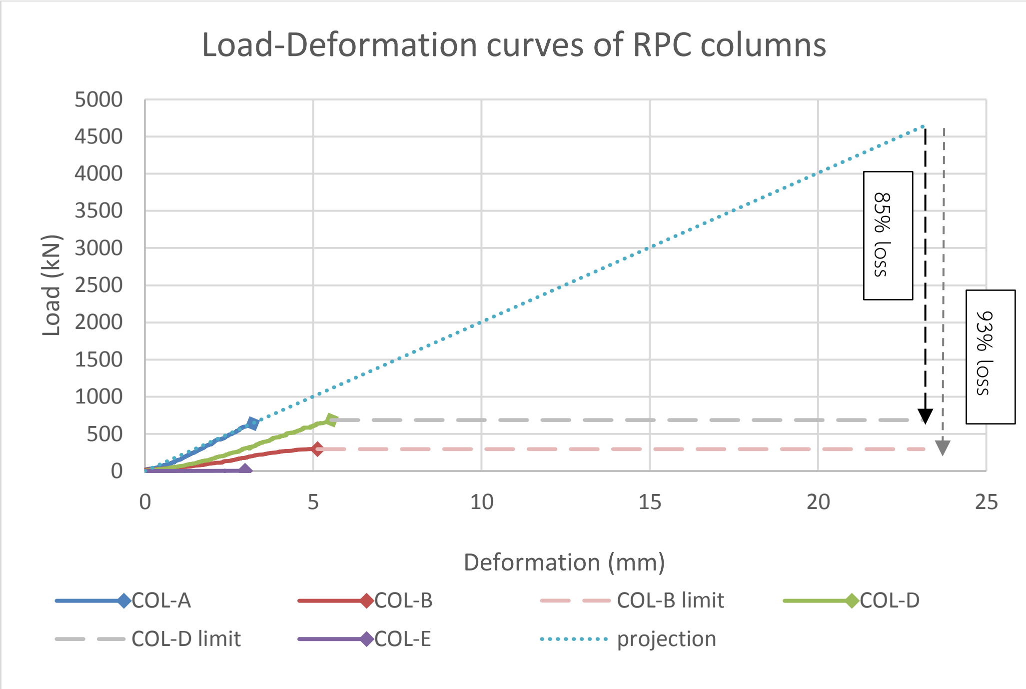

Figure 0-21 Load-Deformation curves of RPC Columns

It can be observed from the figure that the ideal slope projection of the unfired column is straight. The projection was made due to the limitation of testing for safety concerns and the testing of COL-A was terminated at 637 kN of force because of premature corner failure. Due to fire induced phenomenon, the behavior of columns relatively changed with lesser slope that indicates the loss in the modulus of elasticity of the material. The residual strength of columns decreased significantly with the loss of cross-sectional area and shift of failure mode from crushing of concrete to buckling.

4.5.2 Determination of the Analytical Modulus of Elasticity (E_a)

Modulus of elasticity (E) is a measure of the deformability of a material. It is simply the slope on the elastic region of the stress-strain curve of concrete. Concrete values for E ranges from 20000 to 30000 MPa for normal strength concrete. Based on literature, RPC's modulus of elasticity ranges from 50000 to 60000 MPa (Richard and Cheyrezy 1995). This means that as the concrete compressive strength increases, the modulus of elasticity increases. Since E is a relevant measurement for the stiffness of columns in relation to its capacity, it is important to determine this property for each specimen. However, the initial modulus of elasticity of the fired specimens could not be obtained directly from the tests. It is important to obtain the analytical modulus of elasticity of the columns in order to fully understand the residual strength of the fired specimens. As discussed earlier, the elastic behavior of each RPC column would be assumed to be similar.

To obtain the analytical modulus of elasticity (E_a) of each of the fired columns, the load-deformation relationship would be used. Fire scenario have affected the total area and length due to the configuration of the fire test, Thus, the average reduced area and reduced length was used to compute the E_a of the fired RPC columns. Sample computation for COL-B is as follows:

From the Load-deformation relationship:

Δ = PL/AE

Force at 0.4P of column (0.4P) = 118 kN

Adjusted unbraced length (L_u) = 1100 mm

Adjusted average remaining area from Table 0.3 (A_r) = 6163 mm^2

Deformation at force 0.4P (Δ) = 2.29 mm

Solving for analytical modulus of elasticity of the column (E_a) = 9197 MPa

Doing similar computation, the analytical modulus of elasticity of fired columns is summarized in Table 0.4.

Table 0.4 Analytical Modulus of Elasticity of fired RPC Columns

Specimen	Analytical Modulus of Elasticity (E_a) MPa
COL-B	9197
COL-D	12995

Based on the results, the column with a higher volume fraction of steel fibers yields to have a higher result of the residual modulus of elasticity of RPC. This indicates that the increase in steel fiber dosage could lead to better fire resisting performance of RPC. Specimen COL-E was not analyzed due to severe spalling of concrete.

Recent literature has predicted the behavior of concrete at different fire levels in terms of compressive strength, peak strains and modulus of elasticity. Equations 2.3 and 2.5 were used to evaluate the relationship of the modulus of elasticity of the RPC to the predicted modulus of elasticity based on the aforementioned literature. Also an equation for normal strength concrete was used to show the difference of results by various authors.

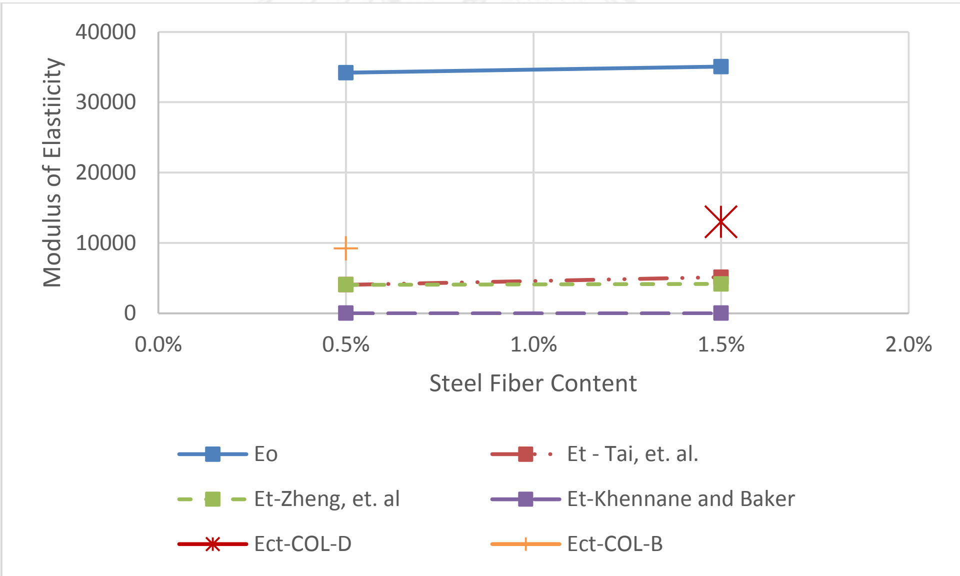

Figure 0.22 Modulus of Elasticity vs %SF of fire damaged concrete

Figure 0.22 shows the relationship of the modulus of elasticity from derived equations to the actual RPC casted. Variable E_o represents the modulus of elasticity of the cylindrical specimens. The computed modulus of elasticity of concrete for specimens COL-B and COL-D yielded higher values as compared to the estimates from literature. It should be noted that the values of the modulus of elasticity incorporates the combined modulus of elasticity of steel and concrete of a composite section after fire.

4.5.3 Failure Mode Criteria

To confirm the failure mode of the axial compression test of RPC columns, failure mode criteria was formulated. Failure of axially loaded RPC columns was observed and three modes were noticeable. These modes are the crushing of concrete, buckling of combined concrete and steel and buckling of steel alone. Each RPC column has a unique failure mode limiting values and was analyzed individually.

4.5.3.1 Crushing of Concrete

The crushing of concrete is simply the ultimate capacity of the concrete column. It is the most unexpected mode of failure for fired RPC columns since spalling have been prevalent and the loss of concrete area makes the column slender in which bucking failure governs. However, the unfired column may expect concrete crushing failure, making this failure mode as the upper limit criteria. The solution is stated below:

$$P_u = f_c'(A_g - A_{st}) + A_{st}f_y \qquad 0.3$$

Where,

P_u = capacity of the concrete column

f_c' = concrete's compressive strength

A_g = gross area of concrete

A_{st} = area of steel reinforcing bars

f_y = yield strength of steel

4.5.3.2 Buckling of Concrete and Steel

The buckling of columns happens due to the reduced section area induced by fire in the form of spalling. In this phenomenon, slenderness of the column governs. The force that the column resisted is expectedly lower than the crushing of concrete since moments will be present to cause the buckling failure. Analysis is as follows:

Determination of the slenderness ratio kL/r

Where,

k = slenderness factor depending on the support conditions

$L = L_u$ = unbraced length of the column

R = radius of gyration = sqrt(I/A)

Slenderness is neglected if the slenderness ratio < 22

The buckling load is computed as:

$$P_{cr} = \pi^2 E_a I/(kL_u)^2 \quad 0.4$$

Where,

E_a = modulus of elasticity of column from analytical computation

I = transformed moment of Inertia of the section

4.5.3.3 Buckling of Steel

The buckling of steel is the worst case wherein the steel is the only component interacting with the force due to the loss of concrete area in the section of the column. In cases of total concrete spalling due to long duration of fire, this failure mode governs. Taking the same buckling load criteria:

$$P_{cr} = \pi^2 E_s I_s/(kL_u)^2 \quad 0.5$$

Where,

E_s = modulus of elasticity of steel

I_s = moment of inertia of the steel

4.5.3.4 Sample Computation

To fully understand the failure mode criteria to confirm the failure mode observed during the axial compression test of the columns, a sample computation is stated below. Solving for the failure mode criteria of COL-D, the solution yields:

4.5.3.4.1 Crushing of Concrete

$P_u = f_c'(A_g\text{-}A_{st}) + A_{st}f_y$

f_c'= compressive strength of concrete from cylinder specimens = 112 MPa

A_g = average remaining area of concrete = 8210

A_{st} = total section of steel reinforcing bars = $4*0.25\ \pi*12^2$ = 452.39 mm^2

f_y = yield strength of steel = 400 MPa

Solving for $\mathbf{P_u}$ **= 1050 kN**

4.5.3.4.2 Buckling of Damaged Columns

E_a = 12995 MPa

Slenderness ratio kL/r

Pin-fixed connection: k = 0.8

L = L_u = reduced effective length = 1100 mm

r = radius of gyration of concrete = sqrt(I/A)

I = moment of inertia of the remaining section

$I_c = s^4/12$ where s is the length of one side of the square concrete section

The remaining concrete area is assumed to be square for simplicity

s = sqrt(8210) = 90.61 mm

I_c = 5617008 mm^4

$I_s = \pi D^4/64 = \pi (12)^4/64 = 4071.5$ mm^4

A_c = average remaining concrete area = 8210 mm^2

r = sqrt(I/A) = 26.15 mm

slenderness ratio results to: **33.64 > 22, therefore column is slender**

It shall be noted that the value of E_a is the residual modulus of elasticity of the column.

Solving for the critical buckling load: $P_{cr} = \pi^2 E_a I_g/(kL_u)^2$

E_a = 12995 MPa

I = 5617008 mm^4

L_u = 1100 mm

P_{cr} = 930 kN

4.5.3.4.3 Buckling of Steel

Using the critical buckling load formula, $P_{cr} = \pi^2 E_s I_s/(kL_u)^2$

E_s = 200000 MPa

I_s = 4071.5 mm^4

L = 500 mm

P_{cr} = 50.2 kN

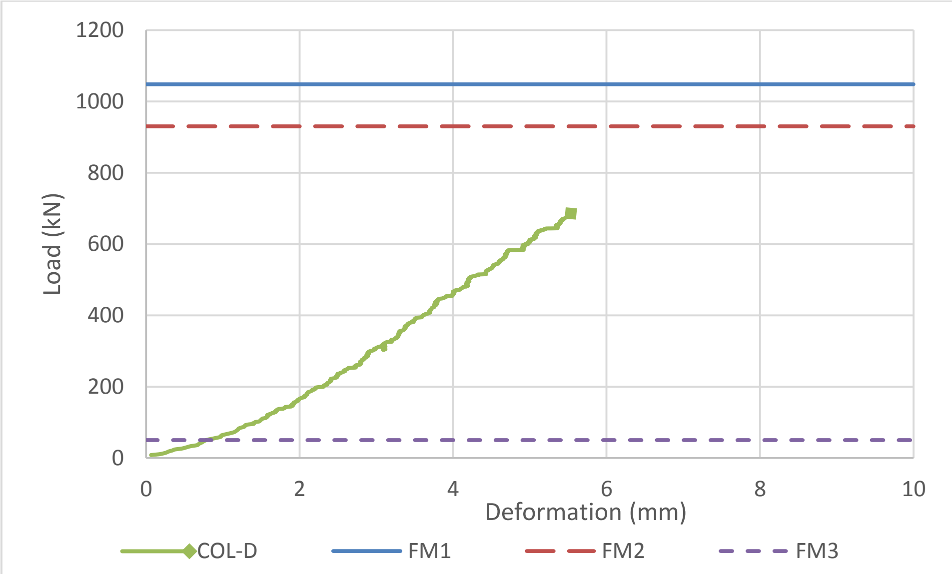

Figure 0-23 Failure mode criteria for COL-D

The failure mode criteria with the actual load-deformation curve of the specimen COL-D exhibits the characteristic failure mode limits for the specific column specimen. Figure 0-23 shows that the failure of COL-D is on the upper limit of the buckling of concrete and steel. This indicates that the column fails in buckling of concrete and steel.

4.5.4 Failure Analysis

In determining the failure mode criteria of each column, the observed failure mode of concrete during tests could be justified. This would confirm that the results of the analysis for residual strength of fired RPC columns are in line with the actual scenario.

4.5.4.1 Specimen COL-A

Specimen COL-A is the control specimen without steel fibers and unexposed to fire. The failure mode expected prior to test would be the crushing of concrete since the column was designed to be non-slender, symmetric and axially loaded only. However, this could not be observed for safety reasons. The column does not incorporate steel fibers and increased load could lead to failure resulting from explosion of sharp fragments of concrete. Figure 0-24 illustrates the load-deformation characteristics of specimen COL-A together and the projected failure mode. The graph of the load-deformation curve of the column is expected to extend until the failure mode set.

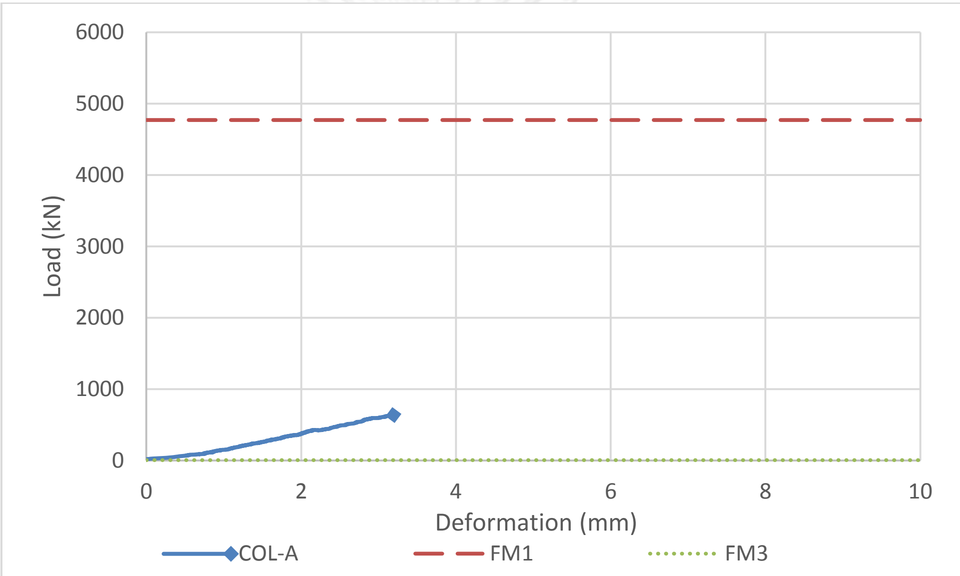

Figure 0-24 Load-Deformation Curve of specimen COL-A

In the actual test, sharp corner cracks at the ends have been observed which indicates the failure of high performance concrete. This is possible due to the uneven loading of the columns that causes premature corner failures.

Figure 0-25 COL-A failure
(a) buckling on the lower 1/3 portion of the column (b) corner cracks on the ends

4.5.4.2 Specimen COL-B

The failure mode of specimen COL-B was expressed to be at the lower limit of the buckling of the damaged column. With the presence of fire, spalling have been prevalent and transformed the column section to a relatively weaker concrete. Steel bars were exposed and this imposes a great indication of severity of the effect of fire in the RPC columns. The removal of the concrete from the surface transformed the specimen into a slender section. However, it shall be noted that steel fibers are present in the concrete matrix. The presence of steel fibers act in the buckling of the column specimen which could increase the column's buckling load capacity. Eventually, the load induced by the specimen will be smaller and buckling failure was expected.

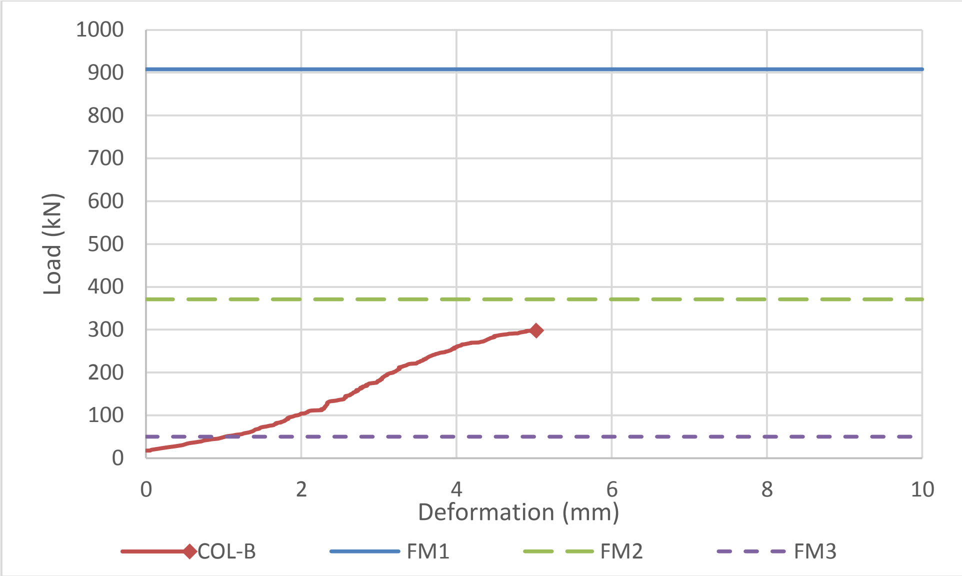

Figure 0-26 Load-Deformation Curve of specimen COL-B

The actual buckling of the steel was observed in the actual tests as the reinforcing bars are exposed. The deformation was at the location of mid height of the specimen which was expected from a typical slender member. Eccentricities may have also affected the failure of the concrete since the cross section of the column was transformed into an asymmetric section.

Figure 0-27 COL-B Failure

4.5.4.3 Specimen COL-D

Specimen COL-D incorporates the steel fiber volume fraction of 1.5%. The spalling criteria was significantly improved compared to columns with less volume fraction of steel fibers. The failure mode of this specimen was observed to be in the lower limit of the buckling of the damaged column. This could be attributed to the slenderness as observed with the spalling of concrete surfaces. Steel fibers in the concrete matrix may also have improved the capacity of the column with its improved interlocking mechanism caused by the five hooked-end steel fibers. Nonetheless, the effect of fire to the performance of the RPC integrated with steel fiber is still very much pronounced. The difference in slope from the analytical curve indicates the severity of the effect of fire in the column.

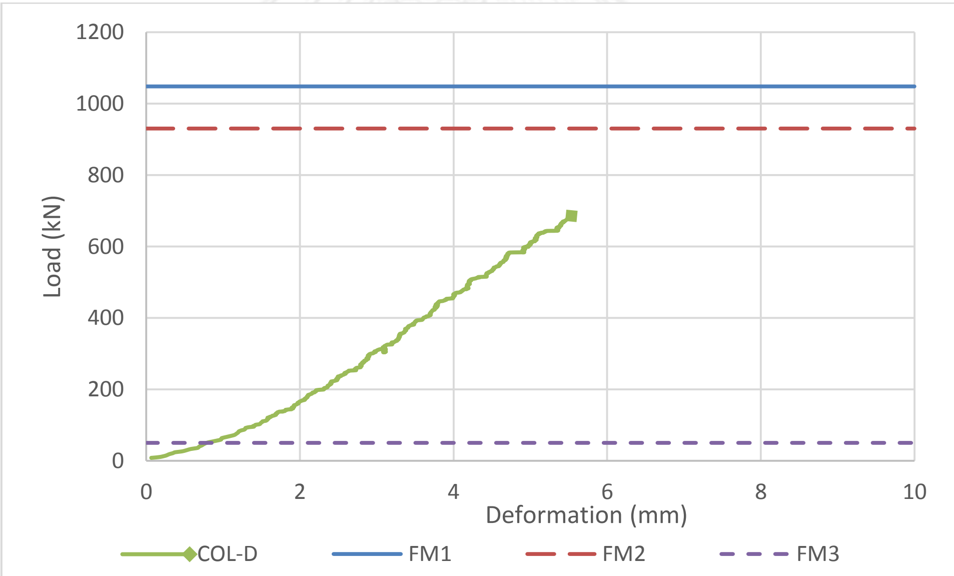

Figure 0-28 Load-Deformation Curve of specimen COL-D

Figure 0-28 indicates the failure mode of the column specimen at the buckling region. In the actual test, the buckling of the column was observed at midheight despite the differences in cross-sectional area in the column along its length. The failure was primarily due to eccentricities brought by the asymmetric conditions. However, with the increased volume fraction of steel fiber, the slope of the load-deformation curve was improved.

Figure 0-29 COL-D Failure

4.5.4.4 Specimen COL-E

Specimen COL-E exhibits the densest structure of RPC with 1.5% volume fraction of steel fibers and 0.1% volume fraction of polypropylene fibers. However due to extensive fire in the lower portion of the column during fire test, a significant loss of concrete section spalled off and actual column test of this specimen could only represent the effect of fully spalled off section of column. The total spalling of the concrete in the lower portion this specimen can be attributed to the presence of PP fibers. Despite the improvement in the fire melting characteristic of PP fibers, wherein it melts at an about 170°C of fire, the RPC mixture is generally weak in fire especially with concentrated exposure. Even the PP fiber melts and paved way to the release of pressure in the column, the RPC also degraded at a higher temperature. In turn, the result of this phenomenon could be related to specimen COL-C that experienced fire duration of 60 minutes and was found to have relatively spalled off sections of concrete. This means that the analysis of this column would be focused on the buckling of steel as the failure mode criterion.

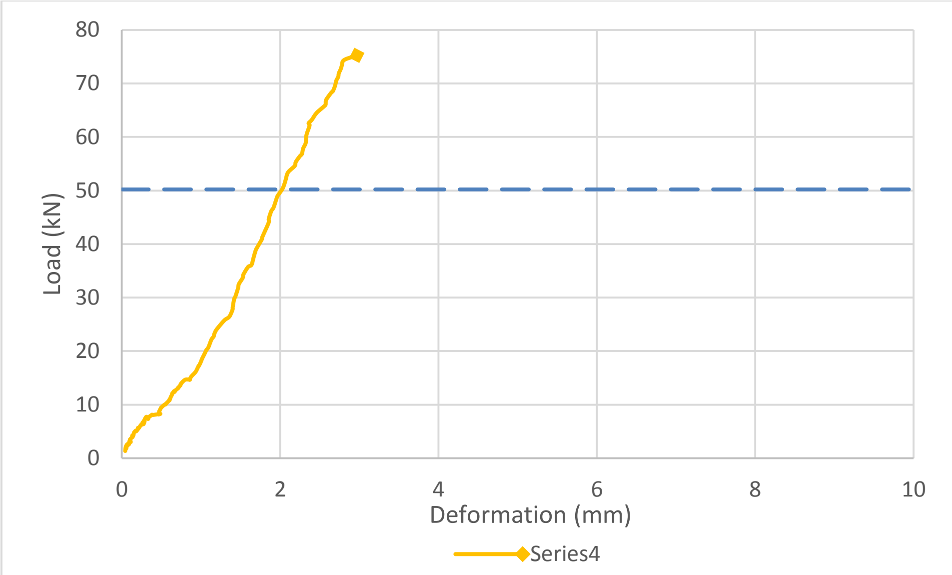

Figure 0-30 Load-Deformation Curve of specimen COL-E

The actual test shows the prevalent buckling of steel. This phenomenon could be expected if the fire duration of RPC columns would be exceeded than 30 minutes.

Figure 0-31 COL-E Failure

CHAPTER V
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Reactive Powder Concrete, one of the latest forms of ultra-high performance concrete has been studied for its performance in column specimens after fire. Mix proportions of RPC were derived from the original mix design and were adjusted depending on workability and material availability. Autoclave curing of specimens was introduced and the curing regimen was based on previous literature (Richard and Cheyrezy 1995, Lee and Chisholm 2005). Literature states that properties of RPC would be improved under a pressure-temperature state of 1 to 3 MPa of pressure and 160°C of temperature for 4 hours of autoclaving. However due to the limitations of the autoclaver, the pressure-temperature setting was just at 4 bar of pressure in 140°C of temperature for 4 hours. The improvement of material properties was minimal. The size effect in specimens affect the results wherein previous literature derived the relationship in strength reduction depending on the size of the specimen (An, Zhang et al. 2008). This can be attributed to the minimal improvement of material properties in RPC specimens. Nonetheless, it shall be noted that materials used by each researcher is different as well. Regardless of this limitation, all RPC specimens were cured in the autoclaver and its effects to fire resisting performance of RPC was beyond the scope of this research.

As a new material, RPC has been around for nearly two decades and its utilization have been increasingly popular. Despite the excellent properties that the RPC possesses, fire resisting performance of RPC in structural members has yet been studied. Concrete is known for its compressive strength, thus column was chosen as the structural component to be analyzed. RPC columns subjected to fire were investigated based on its material properties, spalling effect, physical characteristics and residual strength parameters.

The results of the material properties of RPC show the improvement in mechanical properties of concrete with increased steel fiber content. Compressive strength, modulus of elasticity and poisson's ratio were obtained and a clear relationship was observed. However, in terms of fire, previous studies have various results whether steel fibers improve the fire performance of concrete or not. The use of equations presented by recent literature about RPC at elevated temperature was used to predict the mechanical properties of the casted RPC.

In the series of fire tests, RPC columns were subjected to fire ranging from 30 to 60 minutes without loading. Specimen COL-C, exhibited severe spalling after fire of 60 minutes. Color was relatively different as compared to the rest of the fired specimens. Its residual strength characteristics were also not obtained due to the loss of core concrete due to spalling. This indicates that RPC specimens fired for 1 hour would not resist any chance of survival. Only the steel bars would be able to resist the loading and buckling failure may occur.

For the rest of the fired column specimens, only 30 minutes of fire was conducted. The steel fiber amount was observed and it was concluded that better fire performance is expected in increasing steel fiber volume. Spalling depths are evidently less as compared to specimens with fewer fibers. The inclusion of polypropylene fibers in the matrix enhances the spalling criteria of the column. Load-deformation relationships of each column were also observed. It was found that the loss of material property in the column is more pronounced with fewer fibers in the matrix. The effect of steel fiber volume fraction ranging from 1 to 2 % was proven to be the optimum range considering physical and mechanical implications of the concrete. However, by looking deeply in the macrostructure of spalled surfaces, increasing fiber volume does not necessarily lead to improve the RPC resistance against fire. It was observed that hook ends are bonded deeply in the concrete however spalling still happens in the area between the hooks. Improvement of the concrete mixture is important for fire resistance consideration.

The failure mode of each column was also discussed and failure mode criteria were formulated to confirm the actual failure observed during tests. The fired specimens resulted to a change of failure from non-slender to slender due to spalling. Buckling of column was observed in most cases and the failure was observed on mid height of the specimen. In the actual tests, the buckling of steel is exhibited as the steel is exposed. Eccentricities may have also affected the axial compression capacity of the column due to uneven sections caused by the asymmetric characteristics brought by spalling.

5.2 Recommendations

RPC was proven to have enhanced mechanical properties as compared to normal strength concrete, but in terms of safety especially in fire, poor performance was observed. Without additional fire proofing measures, RPC should not be utilized in normal structures for it causes serious damage especially with the early generation of fire.

To further evaluate the performance of RPC after fire, SEM analysis of RPC could be done. The difference in the microstructure could be observed. Fresh state properties, shrinkage effects and fire proofing on RPC under elevated temperature could be studied. Future research regarding RPC could also consider looking into the impact resistance, permeability and focus more on the mechanical advantages of RPC wherein fire is less likely to be generated.

REFERENCES

Abid, A. and K. B. Franzen (2011). Design of Fibre Reinforced Concrete Beams and Slabs. Master's Degree Master's Thesis, Chalmers University of Technology.

ACI (1997). Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies. ACI 216.1-97. Farmington Hills, MI.

ACI (2008). Building Code Requirements for Structural Concrete (ACI 318M-08) and Commentary. 38800 Country Club Drive Farmington Hills, MI 48331, American Concrete Institute.

Aïtcin, P. C. (2003). "The durability characteristics of high performance concrete: a review." Cement and Concrete Composites **25**(4-5): 409-420.

An, M.-z., L.-j. Zhang and Q.-x. Yi (2008). "Size effect on compressive strength of reactive powder concrete." Journal of China University of Mining and Technology **18**(2): 279-282.

ASTM (2008). Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM E119. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, United States, American Society for Testing and Materials.

Aydın, S., H. Yazıcı and B. Baradan (2008). "High temperature resistance of normal strength and autoclaved high strength mortars incorporated polypropylene and steel fibers." Construction and Building Materials **22**(4): 504-512.

Bangi, M. R. and T. Horiguchi (2011). "Pore pressure development in hybrid fibre-reinforced high strength concrete at elevated temperatures." Cement and Concrete Research **41**(11): 1150-1156.

Bazant, Z. P. (2000). "Size Effect." International Journal of Solids and Structures **37**: 69-80.

Bilodeau, A., V. K. R. Kodur and G. C. Hoff (2004). "Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire." Cement and Concrete Composites **26**(2): 163-174.

Chatveera, B., T. Kongsaktrakoon and N. Makul (2007). "Basic Properties of Reactive Powder Concrete." 177-189.

Chen, B. and J. Liu (2004). "Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures." Cement and Concrete Research **34**(6): 1065-1069.

Hall Jr, J. R. (2014). The Total Cost of Fire in the United States, National Fire Protection Association.

Husem, M. (2006). "The effects of high temperature on compressive and flexural strengths of ordinary and high-performance concrete." Fire Safety Journal **41**(2): 155-163.

Igarashi, S., A. Bentur and S. Mindess (1996). "The Effect of Processing on the Bond and Interfaces in Steel Fiber Reinforced Cement Composites." Cement and Concrete Composites **18**(5): 313-322.

Jansson, A. (2008). Design methods for fibre-reinforced concrete: a state-of-the-art review. Göteborg, Sweden, CHALMERS University of Technology**:** 21-36.

Jau, W.-C. and K.-L. Huang (2008). "A study of reinforced concrete corner columns after fire." Cement and Concrete Composites **30**(7): 622-638.

Kalifa, P., G. Chene and C. Galle (2001). "High-temperature behavior of HPC with polypropylene fibres from spalling to microstructure." Cement and Concrete Research **31**: 1487-1499.

Kalifa, P., F. Menneteau and D. Quenard (2000). "Spalling and pore pressure in HPC at high temperatures." Cement and Concrete Research **30**: 1915-1927.

Khoury, G. A., Y. Andelberg, K. Both, J. Fellinger, N. P. Hoj and M. C. (2007). Fire design of concrete structures - materials, structures and modelling. Lausanne, Switzerland, International Federation for Structural Concrete (fib). **38**.

Kodur, V. and N. Raut (2012). "A simplified approach for predicting fire resistance of reinforced concrete columns under biaxial bending." Engineering Structures **41**: 428-443.

Kodur, V. K. R., L. A. Bisby and M. F. Green (2006). "Experimental evaluation of the fire behaviour of insulated fibre-reinforced-polymer-strengthened reinforced concrete columns." Fire Safety Journal **41**(7): 547-557.

Kodur, V. K. R. and R. McGrath (2003). "Fire Endurance of High Strength Concrete Columns." Fire Technology **39**: 73-87.

Kodur, V. K. R. and L. Phan (2007). "Critical factors governing the fire performance of high strength concrete systems." Fire Safety Journal **42**(6-7): 482-488.

Kodur, V. K. R., T. C. Wang and F. P. Cheng (2004). "Predicting the fire resistance behaviour of high strength concrete columns." Cement and Concrete Composites **26**(2): 141-153.

Lau, A. and M. Anson (2006). "Effect of high temperatures on high performance steel fibre reinforced concrete." Cement and Concrete Research **36**(9): 1698-1707.

Lee, J., K. Harada, S. Kang, Y. Kwon and M. Yamazaki (2013). "Entire and Partial Heating Tests of High Strength Concrete Small Columns." Procedia Engineering **62**: 804-812.

Lee, N. P. and D. H. Chisholm (2005). Reactive Powder Concrete. Judgeford, New Zealand, BRANZ Ltd.

Liu, C.-T. and J.-S. Huang (2009). "Fire performance of highly flowable reactive powder concrete." Construction and Building Materials **23**(5): 2072-2079.

Liu, L. (2009). Fire Performance of High Strength Concrete Materials and Structural Concrete. Doctor of Philosophy Dissertation, Florida Atlantic University.

Malik, A. R. (2007). AN INVESTIGATION INTO THE BEHAVIOUR OF REACTIVE POWDER CONCRETE COLUMNS. Doctor of Philosophy, THE UNIVERSITY OF NEW SOUTH WALES.

Markovic, I. (2006). High-Performance Hybrid-Fibre Concrete Development and Utilisation. Doctor of Philosophy Dissertation, Delft University of Technology.

Naaman, A. E. (2003). "Engineered Steel Fibers with Optimal Properties for Reinforcement of Cement Composites." Journal of Advanced Concrete Technology **1**(3): 241-252.

Neville, A. M. (1995). Properties of Concrete. New York, Longman.

Noumowe, A. (2005). "Mechanical properties and microstructure of high strength concrete containing polypropylene fibres exposed to temperatures up to 200 °C." Cement and Concrete Research **35**(11): 2192-2198.

Peng, G.-F., Y.-R. Kang, Y.-Z. Huang, X.-P. Liu and Q. Chen (2012). "Experimental Research on Fire Resistance of Reactive Powder Concrete." Advances in Materials Science and Engineering **2012**: 1-6.

Phan, L. T. (1996). Fire Performance of High Strength Concrete: A report of the State-of-the Art. Gaithesburg, Maryland.

Pliya, P., A. L. Beaucour and A. Noumowé (2011). "Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature." Construction and Building Materials **25**(4): 1926-1934.

Poon, C. S., Z. H. Shui and L. Lam (2004). "Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures." Cement and Concrete Research **34**(12): 2215-2222.

Prasad, P. V. S. and K. Jha High Performance Concrete. Project work done for Course No.624 - Sr.Professional Course (Bridges & General), IRICEN/PUNE.

Raut, N. (2011). Response of High Strength Concrete Columns Under Fire Induced Biaxial Bending. Doctor of Philosophy, Michigan State University.

Richard, P. and M. Cheyrezy (1995). "COMPOSITION OF REACTIVE POWDER CONCRETES." Cement and Concrete Research **25**(7): 1501-1511.

Rodrigues, J. P. C., L. Laím and A. M. Correia (2010). "Behaviour of fiber reinforced concrete columns in fire." Composite Structures **92**(5): 1263-1268.

Schneider, U. (1988). "Concrete at high temperatures — A general review." Fire Safety Journal **13**(1): 55-68.

Shah, A. A. and Y. Ribakov (2011). "Recent trends in steel fibered high-strength concrete." Materials & Design **32**(8-9): 4122-4151.

Tai, Y.-S., H.-H. Pan and Y.-N. Kung (2011). "Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800°C." Nuclear Engineering and Design **241**(7): 2416-2424.

Yazıcı, H. (2007). "The effect of curing conditions on compressive strength of ultra high strength concrete with high volume mineral admixtures." Building and Environment **42**(5): 2083-2089.

Yazıcı, H., E. Deniz and B. Baradan (2013). "The effect of autoclave pressure, temperature and duration time on mechanical properties of reactive powder concrete." Construction and Building Materials **42**: 53-63.

Yazıcı, H., M. Y. Yardımcı, S. Aydın and A. Ş. Karabulut (2009). "Mechanical properties of reactive powder concrete containing mineral admixtures under different curing regimes." Construction and Building Materials **23**(3): 1223-1231.

Youssef, M. A. and M. Moftah (2007). "General stress–strain relationship for concrete at elevated temperatures." Engineering Structures **29**(10): 2618-2634.

Zheng, W., H. Li and Y. Wang (2012). "Compressive stress–strain relationship of steel fiber-reinforced reactive powder concrete after exposure to elevated temperatures." Construction and Building Materials **35**: 931-940.

Zheng, W., B. Luo and Y. Wang (2013). "Compressive and tensile properties of reactive powder concrete with steel fibres at elevated temperatures." Construction and Building Materials **41**: 844-851.

VITA

Daniel Nichol R. Valerio was born on May 10, 1991. After studying in Santa Rosa Science and Technology High School, he entered De La Salle University and obtained a Bachelor of Science degree in Civil Engineering and graduated Honorable Mention. He passed the Philippine Civil Engineering Licensure Examination on May 2012 and started the Master of Engineering program in Chulalongkorn University under the AUN/SEED-Net Master's Degree scholarship program.

Publications

Valerio, D.N.R. and Pansuk, W. (2013). Steel Fibre Reinforced High Strength Concrete Exposed to Fire. The Twenty-Sixth KKHTCNN Symposium on Civil Engineering. National University of Singapore, Singapore.

Galicia, K., Lejano, B., Sia, J. and Valerio, D.N.R. (2011). Retrofitting of Reinforced Concrete Columns with Steel Fibre Reinforced Mortar. 15th ASEP International Convention. Dusit Thani Hotel, Makati City, Philippines.