Investigating the Properties of Reactive Powder Concrete (RPC) – Compressive and Flexural Strength

By

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CERTIFICATE OF APPROVAL

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

This research is aimed at investigating the compressive and flexural strength of Reactive Powder Concrete (RPC), while considering lack of ductility in conventional concrete as one of the major problem limiting design in structures. With developing technology in the construction industry, RPC has been developed as a prime solution to the above mentioned problem. RPC is composed of fine aggregates, additives, cement and steel fibers which is an evident to its ultra-high strength and ductile behavior. The elimination of coarse aggregate from the mix design and incorporation of steel fibers in the mix design, provides ductility to the concrete structure. A target compressive and flexural strength of 150 – 200 MPa and 30 – 50 Mpa were targeted at the start of this project to be achieved respectively. However, the results obtained did not reach the target due to change of materials to available local materials having different material characteristics and low quality control due to poor storage conditions. The mixing, casting, curing and testing work were all carried out in the concrete laboratory with 6 different mix proportions to attain the required results. The conventional concrete mixing procedures were followed. The fresh concrete is then casted in 100mm x 100mm x 100mm cube and 100mm x 100mm x 500mm beam forms, then cured in water tank at room temperature of 25℃ and tested for compressive and flexural strength after the curing periods of 3, 7, 28 and 56 days. The results were recorded and discussed. Conclusion and further recommendations were drawn based on the result achieved.

Key words: Reactive Powder Concrete, Compressive and Flexural strengths, Ductility, Mix Proportions.

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ABBREVIATIONS AND NOMENCLATURES

RPC	Reactive Powder Concrete
RPM	Reactive Powder Mortar
UHPC	Ultra High Performance Concrete
HPC	High Performance Concrete
MPa	Mega Pascal
GPa	Giga Pascal
OPC	Ordinary Portland cement
GP	General Portland
LH	Low Heat
HES	High Early Strength
SR	Sulphate Resisting
T50	Time taken by fresh concrete flow to reach 500mm diameter
VSI	Visual Stability Index

CHAPTER 1: INTRODUCTION

1.1 Background

Dating back from the emergence of civilization unto modern day, the construction industry has evolved from the use of low strength materials such as mud and wood to a more high strength materials such as concrete, plastic and steel coupled with sophisticated technology. The reason behind this evolution is due to research and development effort put in improving the safety and comfortability of mankind.

As one of the most used construction materials, concrete has been subject of major research and development. Beside its structural and durable performance, concrete is now suitable for most of the environmental conditions it is subjected to. With the introduction of concrete admixtures such as refined pozzolanic materials, super plasticizers, silica fumes and other performing enhancing material, concrete has been developed from a normal performance to high performance concrete (HPC).

The ever progressive construction industry is advancing from high performance concrete (HPC) to a more superior concrete due to innovation and flexibility in the composition and mix design of the concrete. As a result, this Thesis is focused on investigating the compressive and flexural Strength of **Reactive Powder Concrete (RPC)** as one of the current superior concrete in the construction industry.

RPC is an ultra-high performance concrete invented by P. Richard and M. Cheyrezy in 1994, and was first produced by researchers at Bouygues' laboratory in France. It is characterized by super high strength, extreme durability and superior toughness. RPC has a compressive strength in the range of 200 MPa – 800 MPa, flexural strength of 6 MPa – 40 MPa and modulus of elasticity of 50 – 60 GPa, depending on the mix proportion and curing conditions used.

Overseas and more recently in Malaysia, RPC has made its way into many niche markets in applications where these high characteristic strength and superior durability can be fully utilized. Examples include prestressed beams forming part of bridge structures, columns and core walls in tall buildings and structural members in severe environment. The use of RPC enables not only superior mechanical performance of the structure but also ensures a significantly extended life service due to its inherent material properties.

According to research by Lee N. P. & Chisholm D. H (2005), RPC have been developed by Richard and Cheyrezy (1994), particularly with 5 design principles which includes;

i. Enhancement of homogeneity by elimination of coarse aggregate.
ii. Enhancement of compacted density by optimizing the granular mixture and optional applying pressure before and during setting.
iii. Enhancement of microstructure by heat treatment after hardening.
iv. Improve ductility through incorporation of steel fibers.
v. Maintaining mixing and casting procedures as close as possible to existing industry practice.

1.2 Problem Statement

Most concrete structures have become susceptible to earth quake by failing suddenly due to low or no ductility at all. This problem is mostly experienced in the conventional concrete, and hence the invention of reinforced concrete as a mitigation measures. On the other hand, one of the attraction of RPC as a construction material is the opportunities it offers for the improvement of seismic design of concrete structures. This is feasible because of the inclusion of steel fibers in the mix design. Furthermore, due to its high compressive and shear strengths, lighten floor systems and reduced columns cross-section can be designed, hence reducing the dead load. This can be difficult to execute using conventional concrete techniques due to congestion of the reinforcement steels.

1.3 Objective of Study

To solve the problem of sudden failure (no ductility), this study aims at investigating the strength properties of Reactive Powder Concrete (RPC) compared to the conventional concrete. The two main objectives of this study are;

i. Develop a mix design and produce RPC based on selection of composition materials, proper mix proportions and curing conditions to achieve the target compressive and flexural strengths.
ii. To deduce on the suitability of RPC in the construction of high strength structures based on the targeted compressive strength (150 – 200 MPa) and flexural strength (30 -50 MPa), ductility and weight of structural element.

1.4 Significance

The high strength and ductility characteristics of RPC are of particular importance as its primary marketing strategies. Cavil and Rebentrost (2005) defined RPC as an ultra-high performance material for resistance to hazardous environment.

The use of RPC in reinforced application is still limited due to the view of high cost of the materials and production, however, its high strength and ductility makes it an ideal concrete material for slender structural elements in the ultimate and serviceability design.

1.5 Scope of Study

The central focus of this Thesis is an investigation into the properties of RPC. The investigation covers reviews on past researches about RPC, mix design and materials preparation, the production of RPC, testing for the Compressive and Flexural strengths, discussing the results, conclusion and recommendations.

i. Production

The production of RPC involves all the process of the conventional concrete production such as forming the mix design, mixing and workability test, casting and curing. However, the difference is that RPC does not use coarse aggregate like conventional concrete. Steel fibers are used instead of coarse aggregates.

ii. **Testing for compressive and flexural strength**

The testing of the strength is done based on the material composition and targeted strength of RPC in the concrete laboratory. Hence, the strength of the concrete determines the load resistance and durability of the structure on which it is used. To achieve the targeted compressive and flexural strength, about 6 different mix proportions of the materials were used. The test were carried out on the 3rd , 7th , 28th and 56th day after casting of the fresh concrete using the 3000KN compressive and 1800KN flexural loading capacity testing machines respectively.

The mixing and testing were all carried out in concrete laboratory based on the mix design, curing and expected time for testing. The mixing is done using inclined drum rotary mixer and the testing is done on compressive and flexural testing machine respectively. The results were recorded and discussed and possible conclusion is drawn with recommendations.

CHAPTER 2: LITERATURE REVIEW AND THEORY

2.1 Composition of RPC

To achieve the target strengths of RPC, careful selection of raw materials with adequate proportioning and quality control is highly recommended. According to research by Gowripalan et al. (2003), RPC is composed of the following materials; silica sand, steel fibers, silica fumes, cement, super plasticizers, water and silica flour. He used about 6.5 kg of steel fibers compared to Richard and Cheyrezy (1994) who used about 7.3 kg. His research further illustrates its mix proportion as in Figure 1 below.

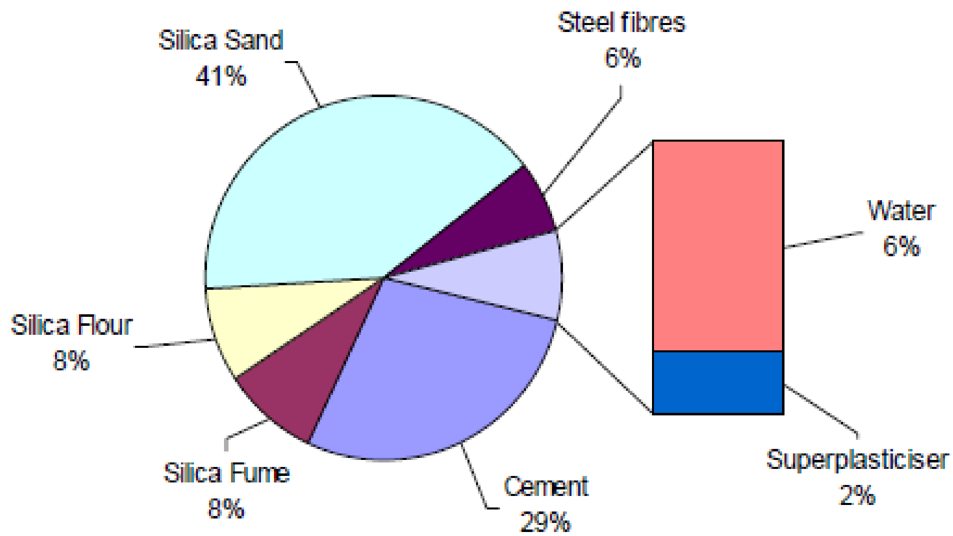


Figure 1 Materials proportion in a typical RPC mixture (%total mix weight), Growripalan et al. 2003

The key aspects of RPC composition are summarized in the Table 1 below;

Table 1 Key aspects of RPC composition (Menefy, 2007)

Aspect	Description
A high binder content	Cement and silica fume
Use of fine powders	Fine sand coupled with refined sand in the form of powder
Optimal and admixture dosage	Low water cement ratio and high range superplasticizer
Inclusion of steel fibers	High tensile straight steel fibers

Another article by Mestrovic. D, Cizmar. D & Stanilovic. V, indicates the possibility of making RPC with compressive strength up to 200 Mpa using different mix proportion varying the size of the steel fibers. The research selected class of Portland cement, PC 55 without mineral ingredients, fine quartz sand of maximum size of 0.5mm, two sizes of steel fibers 13 ± 2 mm long, with diameter 0.2 ± 0.02 mm and 40 ± 3 mm, diameter 0.5 ± 0.02 mm respectively. Lastly is silica fumes of 45 µm.

2.1.1. Binder Composition and Content

The binder composition of RPC mixtures is the combination of cement and silica fume. Collepardi e al. (1996) and Coppola et al. (1997), investigated the effect of cement and silica fume type on the relative performance of RPC. Their findings showed that the water demand of RPC is greatly affected by the choice of binder type. They however recommended the use of low calcium aluminate (C_3A) Portland cement and a white silica fume which are further discussed below;

2.1.1.1 Cement

Menefy (2007), explained that different types of cement has been used in RPC including General Portland (GP), low heat (LH), sulphate resisting (SR) and high early strength (HE). The predominant factors in the choice of cement are the requirements for strength development and durability. The calcium silicates (C_3S and C_2S) and to a lesser extent calcium aluminate (C_3A) are the cement constituents predominantly responsible for strength of the hydrated cement paste. The presence of C_3A is however undesirable especially after hydration due to long term durability implications (Neville and Brooks, 1997).

Therefore, Richard and Cheyrezy (1994), in their mix design recommended the use of sulphate resisting cement consisting of low C_3A content and high silicates content. Growripalan et al. (2003) recommended the use of high early strength (HE) cement because it enables the early transfer of pre-stress for precast pre-stressed application of RPC. However in recent researches, most subsequent mix designs for RPC have incorporated General Portland (GP) cement due to its ready availability and relatively low cost. And for this research in particular, Type I Ordinary Portland cement (OPC) will be used.

2.1.1.2 Silica Fume

Silica fume (SiO4), a by-product from the manufacture of zirchonia (ZrSiO4), silicon and ferrosilicon alloys, is a well-known pozzolanic admixtures and has been used widely in the development of many high strength concretes. It is made of superfine spherical particles that fills the void left by the cement particles leading to more discontinuous pore structure within the concrete (Bonneau, et al., 2000). It also accelerates the pozzolanic reactions in the hydration process increasing the amount of calcium silicates hydrate, hence further reducing the size of pores in the concrete mix. According to study by De Larrard (1989) on optimum proportions of a number of pozzolanic filters in obtaining high strength concrete, he reported that the optimum proportion of silica fume is between 20% and 25 % of the cement content. On the other hand, Chan and Chu (2004) reported similar findings while investigating the effect of silica fume on the bond strength of RPC, a proportion between 20% and 30% was also reported as optimum. The optimum proportion of this study will however be based on the original mix design of Richard and Cheyrezy (1994).

Apart from the use of silica fume in the production of RPC, this research will also use MIRHA as a replacement for the silica fume for the last three mixes. This will allow a comparable study between the strengths of concrete using MIRHA to that of silica fume. The significance of choosing MIRHA is because it is locally produced within Malaysia, hence cost effective and it has been proven to perform better in normal concrete than silica fume.

2.1.2. Fine Powders (Silica powder, Quartz powder, etc.)

Historically, Roy and Gouda (1973) reported that “theoretically higher strengths should be achieved when there is maximum particle packing and the inter-particle space and pores have been eliminated”. In line with this theory, coarse aggregate in RPC is replaced by fine sand (<600μm) preferably silica or quartz based.

This replacement in combination with further refined silica or quartz powders leads to the formation of a relatively more homogenous material having the following benefits (Richard and Cheyrezy, 1995):

1. Increase in granular packing leading to an increase in the density of RPC.
2. Increase in the pozzolanic reaction during heat curing providing a corresponding increase in early age strength.
3. Reduction in micro cracking between the aggregate and paste interface.

The elimination of coarse aggregate in the mix design of RPC leads to a mix resembling mortar rather than a concrete, hence it is also referred to as Reactive Powder Mortar (RPM) (Coppola et al., 1997). The addition of the above mentioned filler powders (refined silica or quartz sand) provides added benefits to the packing density of RPC by filling the voids between the fine granular particles (cement and silica fume) and coarse fine sand. Figure 2 below illustrates the typical powder materials used in RPC.

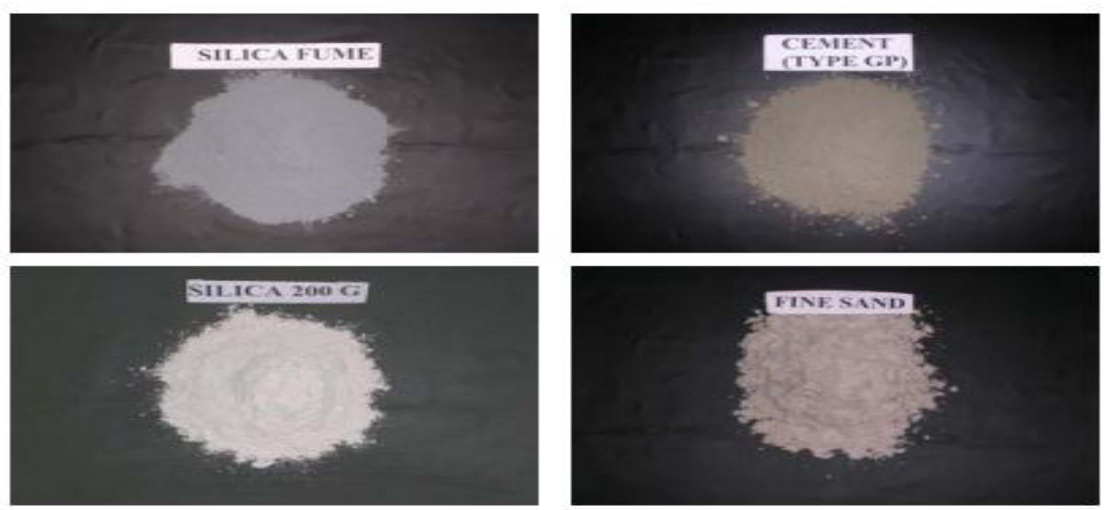


Figure 2 Binding and filling materials used in RPC mix

2.1.3. Water and Admixture Dosage

The requirements that always governs the water cement ratio of a concrete mix are workability, strength, and durability. Usually, the amount of water provided should be just enough to produce adequate hydration. Too much water increases the residual capillary porosity with adverse implications on concrete durability and strength. Normal water-cement ratio for standard concrete applications range between 0.35 and 0.7 while RPC has low water-cement ratios that ranges between 0.10 and 0.25 (Menefy, 2007).

The water cement ratio of a normal concrete adopted is mainly dependent on the water demand of the mix and the dosage rate of superplasticizer used, but for RPC mix is mainly due to large surface area of the constituent materials used. A report on the effect of three different types of superplasticizer by Coppola et al. (1997) on water-cement ratio and compressive strength, showed that an acrylic polymer mixture performs better than naphthalene or melamine based superplasticizers.

This is because the acrylic polymer has a lower water demand and hence a lower water cement ratio was required which led to a higher compressive strength after three days.In comparison to this project, the water cement ratio is expected to be above the typical value of water-cement ratio in RPC due to the use of naphthalene based superplasticizer, the grade of silica fume and also use of river sand instead of find quartz or silica sand.

2.1.4. Steel Fibers

The combination of ultra-fine materials in RPC leads to an extremely brittle matrix generally not suitable for structural use. Steel fibers are added in RPC to provide the much needed ductility and enhanced post cracking performance. The steel fibers used in RPC exhibit a high tensile strength as shown in Figure 3 (c) and similar to those shown in Figure 3(a). The fibers are brass coated which serves to protect the base metal from corrosion. When used in RPC, the coating breaks down and generally is not noticeable at casting (Graybeal, 2006). In the case of this study, 20mm±1mm length steel fiber is used with diameter of 0.2mm±0.05mm.

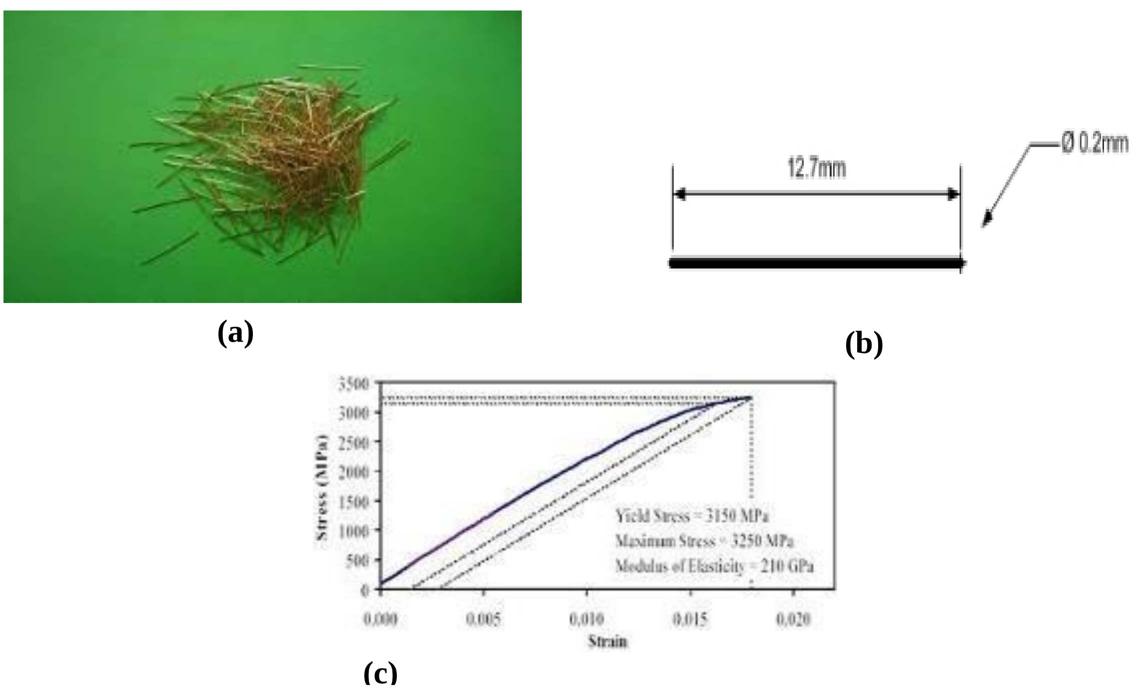


Figure 3 (a) Steel fibers used in FR-RPC (b) Steel fiber dimensions (c) Typical stress-strain characteristics (Graybeal, 2006)

Dugat et al. (1996) reported on optimum content which was determined through the measurement of fracture energies (i.e. toughness, ductility) at differing fiber contents. An optimum volumetric percentage between 2 and 3 percent (6% and 7% of total mix weight) was reported as sufficient to enable significant improvement in the ductile behavior of RPC. In this study, a content of 1% and 2 % of steel fibers of the binder content are used in the mixes.

A number of researches have investigated the effect of fiber type on the mechanical performance of RPC. Collepardi et al., (2003) investigated the use of fibers with aspect ratio's (L/Ø) ranging between 45 and 72 and concluded that the type of fiber did not significantly affect workability. Further, steel fibers with an aspect ratio of 72 exhibited the highest flexural strength. Growripalan et al. (1999) similarly reported earlier on the comparative investigation carried out on RPC mixed with either steel, polypropylene or carbon fibers. It should be noted here that the polypropylene or organic fibers are currently used in a commercial RPC mix (DUCTAL-AF) in which a cocktail mix of steel and polypropylene fibers are used to mitigate fire induced stresses within the concrete matrix.

2.2 Mix Designs from Previous Research

Mix designs developed for RPC from previous literature are outlined in Table 10, Appendix A below. Most mix designs for RPC are based on the original mix design developed by Richard and Cheyrezy (1994). Cement contents range between 28 % and 38% of the total mix weight which equates to a mass greater than 650 kg/m^3 of RPC mix. The 10% variation in cement content between mix designs arises due to the use of fine powders (silica flour or ground quartz which enable a reduction in the cement content. The use of either silica flour or ground quartz is dependent on local materials available. Silica fume contents vary between 8% and 10% of the total mix weight (about 20 to 30 percent of cement content) which corresponds to masses of approximately 200 kg/m3 of RPC mix. Similarly, a reduction in silica fume content is enabled through the use of silica fume or ground quartz.

The type and quantity of superplasticizer used is highly dependent on the water demand of the binding materials and desired flow of the RPC mix. High range superplasticizer (polycarboxcylic ether polymer) at high dosage rates (6 to 7 percent of cement content) are used in RPC.

Also indicated in Appendix A, Table 10, are the characteristic strengths obtained from individual RPC mixes. In summary:

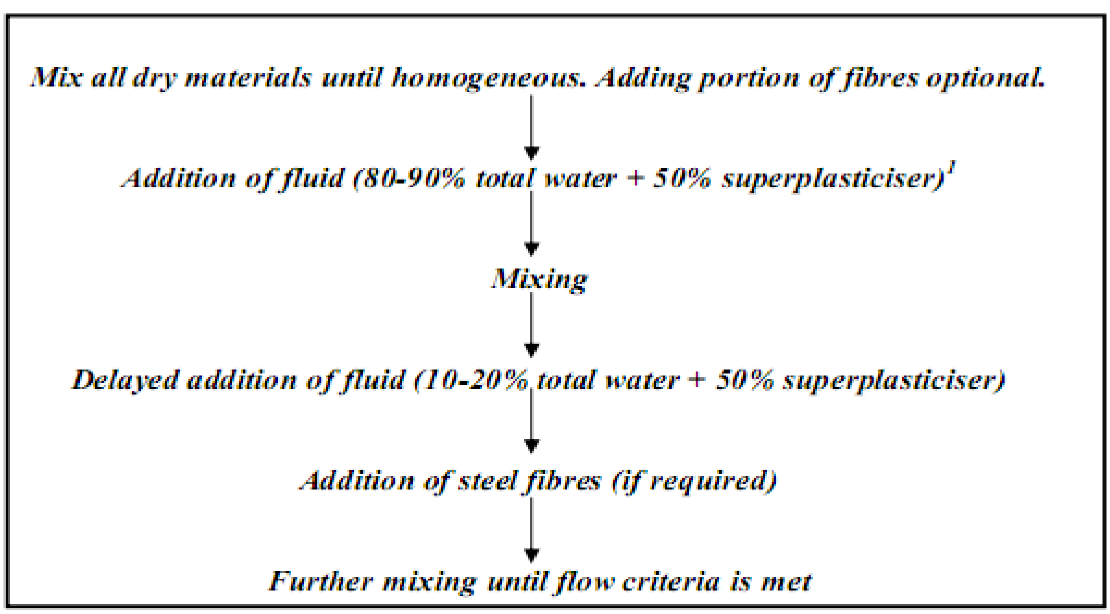
- Compressive strengths achieved varied between 160 and 197 MPa.
- Flexural strengths achieved varied between 25 and 50 MPa.
- Indirect tensile strengths achieved varied between 12 and 21 MPa
- Elastic moduli achieved varied between 44 and 62 GPa.

2.3 Mixing Regime

2.3.1 Rationale

In regards to the nature of the raw materials comprising RPC and the high mix quality required, standard mixing procedures outlined in AS1012.2 (1994) are not entirely sufficient. Bonneau et al. (1997) listed a typical mixing approach for the production of RPC as shown in Figure 4 below. Variations in the mix procedures are generally governed by the type of mixer used.

High energy mixers are predominantly used to ensure a highly effective distribution of reactive ingredients in the RPC mix. For this reason, the production of RPC is primarily suited to the precast owing to the nature of the constituents' materials and meticulous



production processes required (Menefy, 2007).

Figure 4 Controlled mixing procedures (Bonneau et al., 1997)

Steel fibers are added during dry mixing or before the “breakpoint” of the mixing process. The “breakpoint” is defined as the point at which superplasticizer and water is adequately dispersed throughout the mix, and flow characteristics appears of a viscous nature (Graybeal and Hartmann, 2003). Adding steel fibers to the dry mix alleviates pallets that form when fluid is added (Bonneau et al., 1996).

2.3.2 Mixer Type

Limited studies have investigated the effects of different mixer types on the performance of RPC. Bonneau et al. (1997) investigated ready-mix application in both ready mix trucks and a central mixer in a precast plant. The mixing time in the central mixer found to be less than the ready mix truck. Generally, higher energy mixers will require less mixing time.

Hence, in this research, the incline drum rotary mixer in the testing Laboratory is used because the quantity of production of RPC per mix is not significant compared to mixes required to be transported to the site immediately.

2.3.4 Curing Regime

Research by Roy and Gouda (1973) investigated the effects of high temperature and high pressure curing on cement pastes. The results indicated that the heat curing speeds up cement hydration and pressure application decreases porosity. Hence, the temperature effect is greater on strength and pressure application is greater on density. However, Cheyrezy et al. (1995) recently reported that heat treatment greatly affects the hydrated microstructure and in turn porosity of RPC. Gilbert et al. (2000) reported that without heat treatment, RPC suffers endogenous shrinkage occurring over a considerable period of time. So heat treatment will catalyze this shrinkage over a shorter period of time. However, the practicality of heat and pressure treatments on a commercial level is questionable in term of time and cost required for the full production of RPC. The issue was raised by Cheyrezy (1999) who reported that the use of the above curing regime would depend on the application required and budget constraints at the time of design. In any case, the cumulative porosity without heat treatment is approximately 9% which is still far superior to most concretes on the market today.

In contrast to the above sentiments, this study will use the conventional way of concrete curing in water tank at room temperature for specified period of time (3, 7, 28, 56 days).

2.4 Compressive Strength

According to research by Price (2009), the first RPC produced by Richard and Cheyrezy (1995) has a compressive strength of 170 MPa after curing it for 28 days at an ambient temperature but obtained a compressive strength of 230 MPa curing it at 90℃ for 6-12 hours after curing it for 2days at ambient temperature. They found that the fracture energies varied from 15000 J/m^2 to 40000 J/m^2 depending on the amount of steel added to the mix. This study is focusing on achieving a similar strength by curing the concrete in water at 25℃.

Fehling (2004) also studied the compressive and tensile properties of hardened Ultra High Performance Concrete (UHPC). The observation indicates that the compressive strength of UHPC lied in the range of 150 to 220 MPa. Furthermore, till 70 to 80% of the UHPC compressive strength showed a linear elastic behavior while the failure is explosive for those without fibers, with no descending branch in the stress- strain diagram.

Benjamin Graybeal and Marshall Davis (2008) investigated an experimental study to determine alternative methodology for computing compressive strength of an ultra-high-performance fiber-reinforced concrete (UHPFRC) in the strength range from 80 to 200 MPa. The lack of appropriate testing facilities provoked him to provide empirical factors between varying cubes and cylinder size.

2.5 Flexural Strength

The same author above also observed that direct flexural strength test on UHPC without fibers yielded a brittle failure with flexural strength values between 7 and 10 MPa. On the other hand, those with fibers had a ductile failure with strength values between 7 and 15 MPa.

Price (2009), also indicated that the ductile behavior of RPC in the study of Richard and Cheyrezy (1995), is obtained by the addition of up to 10% volume of steel fibers, which resulted in the increase of flexural strength from 28MPa to approximately 100 MPa with required fracture energy of 50 J/m^2 to 40000 J/m^2, depending on the curing condition and the amount of fibers added. Fracture energies this high indicate a very ductile behavior.

2.6 Application of RPC in Construction Industry

1. Construction of prestressed structure without any steel reinforcement. The foot and bicycle bridge in Sherbrooke, Canada as shown in Figure 5 below, was the first structure to be built using RPC with mix design developed by University of Sherbrooke (Adeline et al., 1998).

Figure 5 Foot and Bicycle Bridge in Sherbrook Canada (Adeline et al., 1998)

2. Pipe products for the conveyance of water, sewage and other liquids under pressure or gravity flow provide an opportunity to utilize many of the enhanced properties of RPC (Dowd & Dauriac, 1998). The USA Army Corps of Engineers has developed (1994-1997) pipe prototypes which exhibit greater overall value than pipes fabricated from other materials.
3. According to Soutsos et al., the mechanical properties of RPC appeared to be attractive for construction of security enclosures, such as safes and computer centers, nuclear waste containment vessels, and defense structures.

With the mentioned applications of RPC already in existing, this study is aiming at achieving the targeted strength so that it can be used in the construction industry of most developing country, especially in South East Asia and Africa.

2.7 Comparing RPC to Conventional High Performance Concrete.

Lee N. P. & Chisholm D. H (2005), compared the properties of RPC to that of conventional HPC in terms of strengths, loading and ductility. They reported that while RPC is arguably more expensive to produce than regular concrete, its isotropic nature and ductility make it competitive with steel, over which it has a significant cost advantage for many structural application. Table 2 below shows the comparison they made between RPC and HPC.

Table 2 Properties of RPC vs. conventional high performance concrete

(Lee N. P. & Chisholm D. H., 2005)

Property	**HPC**	**RPC**
Compressive strength (MPa)	60 - 100	180 - 200
Flexural strength (MPa) [central- point loading]	6 - 10	40 - 50
Fracture Energy (J/m^2) [ASTM C293]	140	1,200 – 40,000

Young's modulus (GPa)	23 - 37	50 - 60

2.8 Summary

From the review of relevant literatures above, it is observed that the superior material performance of RPC is attributed to its combination of low water cement ratio, high silica fume content, particle grading optimization and the inclusion of steel fibers (Menefy, 2007). A proper mixing rationale is required for the production of RPC. It is predictable that a proper mix design and curing in this study will produce RPC with the required or targeted strengths.

CHAPTER 3: METHODOLOGY

3.1 Mix Design

The first mix design of RPC was formulated by Richard and Cheyrezy in 1995. Similarly, the constituents of RPC used in this research are cement, silica fume/MIRHA, superplasticizer, water and steel fibers, with exception of river sand instead of fine quartz sand, and fly ash instead of quartz powder. This is because quartz or silica materials are expensive and scarce in Malaysia. The basic philosophy of using the above materials lies in complete elimination of coarse aggregate to impart greater homogeneity, with mineral and chemical admixture to heighten stronger gel formation during hydration. Enhancing compacted density by optimizing granular mixture and providing ductility by addition of steel fibers.

Therefore, the mix design for this research is similar to the original mix design by RPC inventors, Richard and Cheyrezy (1995), as shown in Table 3 below, although the quantities of water and superplasticizer was discovered to be less during mixing and adjusted as shown in Table 4. Also, in the current research, silica fume is replaced by MIRHA for mixes M4 - M6 but of the same quantities as indicated in Table 4.

Table 3 Typical RPC Mix Design (Richard & Cheyrezy, 1995)

Constituent Material	Quantity	Unit	Sizes
Cement (ASTM Type I)	955	kg/m^3	7.5 - 31μm
Silica Fume/MIRHA (proposed)	229	kg/m^3	0.1 – 1μm
Fly ash	10	kg/m^3	10μm
River Sand	1051	kg/m^3	300 - 800μm
Super plasticizer (sika)	13	L/m^3	
Water	153	L/m^3	
Steel Fiber	0,1%,2% of Cementitous content (proposed)	kg/m^3	$L=20\pm1mm$ d_o =0.2mm±0.05mm
W/C	0.16		
Volume of mix used	0.023 m^3		

Table 4 Applied Mix Proportion to obtain RPC

Mix No.	OPC (Type 1) **kg/m^3**	Silica Fume **kg/m^3**	Silica Powder/Fly ash **kg/m^3**	Fine Silica Sand **kg/m^3**	Water **L/m^3**	Super plasticizer (viscocrete) **L/m^3**	Steel Fiber		W/C
							% F	Wt. F **kg/m^3**	
M1	955	229	10	1051	282	19.13	0	0	0.295
M2	955	229	10	1051	282	19.13	1	12	0.295
M3	955	229	10	1051	282	24.34	2	24	0.295
Using MIRHA in the place of silica fume									
M4	955	229	10	1051	282	24.34	0	0	0.295
M5	955	229	10	1051	282	24.34	1	12	0.295

M6	955	229	10	1051	282	24.34	2	24	0.295

3.1.1 Material properties

Ordinary Portland cement (OPC) - Ordinary Type I Portland cement complying with ASTM C 150 or MS: 522 is used. It is mostly used in the general construction work where special properties are not required. It is also characterized with fairly high C_3S content for good early strength development. The estimated initial setting time of Type I OPC is greater than 45 minutes while its final setting time is about 375 minutes. The normal consistency being 28% and the particle size ranges from 7.5μm to 31μm.

Silica Fume - The silica fume used in the experiment conforms to ASTM C1240 – 97b. The specific gravity being 2.25, percentage passing through 45μm sieve in wet sieve analysis is 92% and the particle size range lies between 1.8 μm – 5.3 μm.

MIRHA – This is used as a replacement for the silica fume in the mix design for the last 3 mixes. The particle size of MIRHA is assumed to be the same as that of the silica fume for the purpose of filling in the concrete. A combination of burning temperatures of 500℃, 600℃ and 700℃ MIRHA is used to optimize the mix.

Silica Powder/ Fly ash – At least particle size of 10 μm is required for the silica powder. Unfortunately, silica powder was not used in this research due to the difficulties of sourcing it locally within Malaysia. It is also expensive to import from outside the country as this study requires only about 4 kg to complete the project. In respond to this situation, the author decided to use fly ash as a replacement material for the silica powder.

River Sand – The sand used for this experimental work to replace the fine quartz/silica sand is river sand of size range 300 – 800 μm. The sand is locally sourced within Malaysia from the local suppliers. With consultation from the supervisor, the author has decided to use river sand as an alternative to silica sand because the latter is expensive and scarce within Malaysia.

Superplasticizer – Sika Viscocrete 2044 superplasticizer is used for this experiment.

Steel fibers **-** To enhance the RPC ductility, 1% and 2 % of steel fibers were added in mixes, M2 and M3 respectively while using silica fume as pozzolanic material. Similarly, as the silica fume is replaced with MIRHA, the same percentage of steel fibers were added in mixes, M5 and M6 respectively. Steel fibers conforming to BS EN 14889-1:2006 are used with length of 20mm ($\pm$1mm) and diameter of 0.2mm ($\pm$0.05mm).

This type of fiber is quiet stronger than the steel fibers used by Richard and Cheyrezy (1994) due to the difference in the length despite the similarity in the diameter. However, the quantity used determines how much strength effect it could have on the RPC compared to 7.3 kg used by Richard and Cheyrezy.

3.2 **Mixing**

3.2.1 Material preparation

The above materials are prepared ready in the Laboratory before the commencement of mixing. This involves using sieve analysis where necessary to characterize the material sizes, measuring the quantities and quality control by storing in a dry place and room temperature before usage.

3.2.2 Mixing procedures

Mechanical inclined drum (ID) rotary concrete mixer is used in the mixing. The mixing procedures follows the same time interval as conventional concrete mixing, although the addition of the materials varies from one item to another as indicated in Table 5 below. The procedures are as described below:

Table 5 Mixing procedures

Mixing Protocol	**Elapsed Time (minutes)**
Lightly grind cement and silica fumes to break up agglomerates	-
Pre-mixing of the silica sand and the steel fiber is carried out	5
All the dry powders and pozzolanic materials are added to the rotary mixing drum and mixed with the silica sand and steel fiber.	10

87% of water and 50% of super plasticizer is added to the dry materials.	5
The remainder of water and super plasticizer is also added.	5
Then high speed mixing is carried out.	5
Stop mixing and cast test specimens	30

3.2.3 Workability of RPC concrete

Normally it is observed that the addition of fibers will not improve the compressive strength but it only increases the flexural strength (Maroliya, 2012). When we add fiber, the workability is reduced and it requires higher water/cement ratio or dosage of super plasticizers. So after readjusting W/C ratio and dosage of super plasticizers, a flowable mix is obtained.

But the steel fibers because of their higher strength as compared to matrix, act as a reinforcement and confines the matrix helping in improving the compressive strength of the concrete.

At the conclusion of the mixing period, the workability of the mix was tested by carrying out slump flow test (ASTM C 1611). This aims at investigating the filling ability of SCC. It measures three parameters of the fresh concrete; flowability (d_{max}), viscosity (T50) and stability of the concrete (VSI). The VSI determines the segregation and bleeding behavior of the fresh concrete.

Equipment used

- Base plate of size at least 900mm x 900mm with smooth surface and clearly marked with circles of 200mm and 500mm diameter respectively.
- Abram cone
- Measuring tape
- Stop watch
- Rag for cleaning spilled concrete and moist towel for wetting the Abram cone.

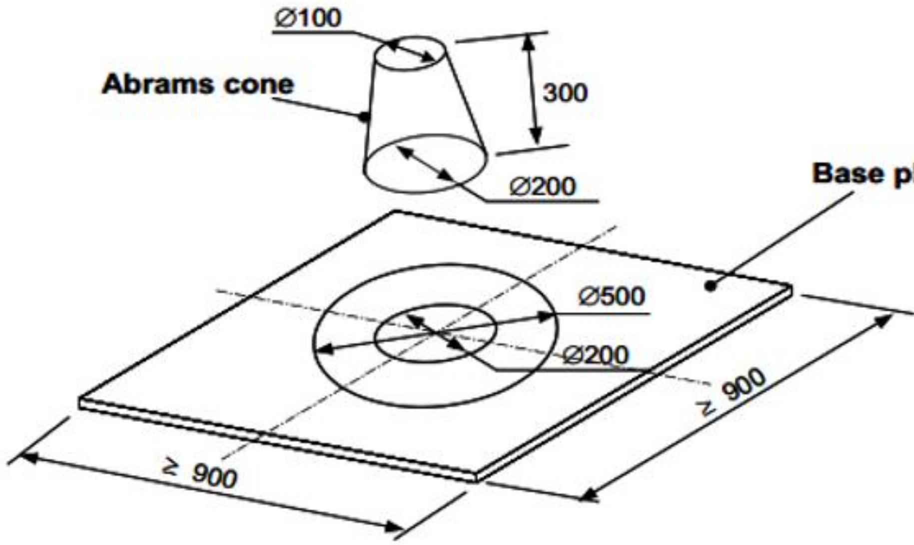


Figure 6 Slump flow test equipment and measurement

Test Procedure

1. The base plate is placed on a stable and leveled position.
2. The inner surface of the Abrams cone and the test surface of the base plate is wetted with moist towel. The cone is placed at the 200 diameter center of the base plate.
3. The cone is then filled with fresh concrete without compacting or vibrating. The surplus concrete above the top of the cone is struck off, and any concrete remaining on the base plate is removed.
4. After a short rest (no more than 30 seconds for cleaning and checking the moist state of the test surface), the cone is lifted perpendicular to the base plate in a single movement, in such a manner that the concrete is allowed to flow out freely without obstruction from the cone, and the stopwatch is started the moment the cone loses contact with the base plate.
5. The stopwatch is stopped when the front of the concrete first touches the circle of diameter 500 mm. The stopwatch reading is recorded as the T50 value. The test is completed when the concrete flow has ceased.

6. The largest diameter of the flow spread, d_{max}, and the one perpendicular to it, d_{perp}, is measured using the measuring tape.
7. The visual stability index (VSI) is assigned where necessary to the nearest 0.5 based on the criteria in Table 6 below.
8. The base plate and the cone were cleaned up after testing.

Table 6 Visual stability index Rating (ASTM C 1611)

VSI	Criteria
0 = Highly Stable	No evidence of segregation or bleeding
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass.
2 = Unstable	A slight mortar halo ≤0.5 in. and/or aggregate pile in the concrete mass.
3 = Highly Unstable	Clearly segregation by evidence of a large mortar halo > 0.5 in. and/or a large aggregate pile in the center of the concrete mass.

Expression of results

1. The slump flow spread S is the average of diameters d_{max} and d_{perp}, as shown in Equation (1). S is expressed in mm to the nearest 5 mm.

$$S = \frac{dmax + dperp}{2} \quad \ldots\ldots (1)$$

2. The slump flow time T50 is the period between the moment the cone leaves the base plate and SCC first touches the circle of diameter 500 mm. T50 is expressed in seconds to the nearest 1/10 seconds.
3. Visual stability index (to the nearest 0.5)

3.3 **Casting**

After the necessary workability test is conducted, the fresh concrete is casted in form of cubes and beams. 12 cubes are casted in 100mm x 100mm x 100mm size mold and 2 beams in 100mm x 100mm x 500mm size mold. For all the mixes after mixing, the fresh RPC concrete was transferred into steel molds with the ability to compact itself. The specimens were given a proper finishing ensuring uniformity and perfect appearance. The specimens are allowed to harden in their mold for 24 hours before it is removed and subjected to curing.

3.4 **Curing**

The curing method of conventional concrete is adopted. This is done by immersing the casted concrete in water at 25℃ until the day of testing. After 24 hours of hardening, the cubes and beams were removed from the mold. Markings, such as the date of casting, top or bottom surface, and day of testing is done for testing and indication purpose. The specimens are then immersed in a water tank at 25℃ waiting for their dates of testing.

3.5 Testing

A. *<u>Compressive strength</u>*

The compressive strength testing of the RPC cubes is tested using the 3000 KN testing machine as shown in Appendix D. A total of 3 cubes (100 x100 x 100) mm of each mixes were tested to get the average compressive strength for the specified days of 3, 7, 28 and 56 days. The load is applied at a pace rate of 3 KN/sec. The ultimate strength is recorded when the specimen failed to resist any more loads. Theoretically, the compressive strength can be calculated using the equation below;

$$\text{Compressive strength} = \frac{\text{Load (P)}}{\text{Cross sectional Area (A)}} \qquad (2)$$

B. *<u>Flexural strength</u>*

For the flexural strength, the beam will be tested using 1800 KN flexural testing machine at a pace rate of 0.2 KN/sec, according to the standard test method ASTM 1609. A total of 2 beams of each mixes were tested after the 28th day of curing to get the average flexural strength.

3.6 **Flow Chart of Methodology**

The flow chart below describes the overall project work flow and methodology carried out by the author. The author adjusted the project work flow where necessary based on advice from the supervisor.

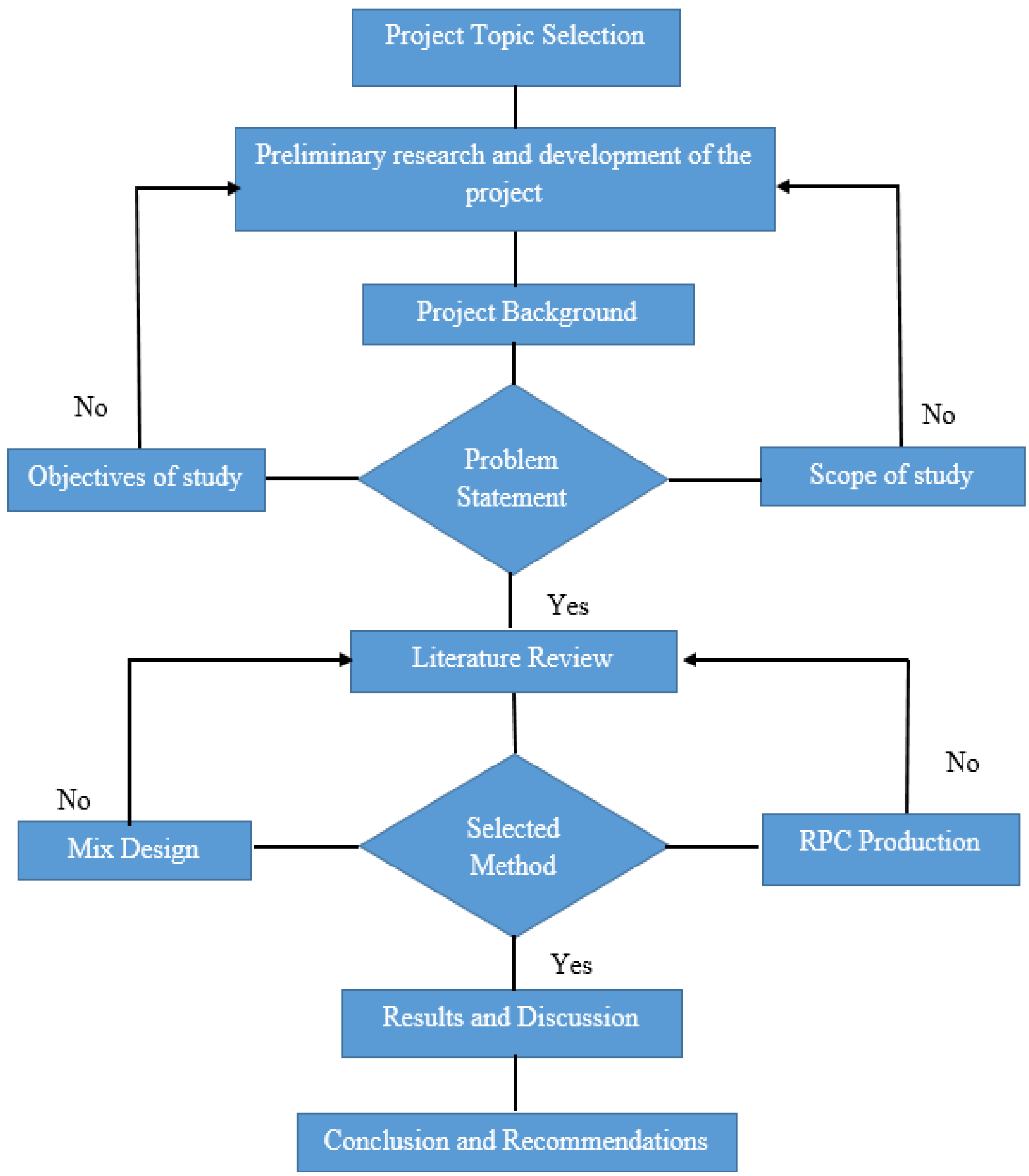


Figure 7 General research methodology flow chart

3.7 **Gantt chart**

		Weeks														
No.	**Scope of Work (FYP 1)**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1	Selection of project topic							**Mid-**								
2	Preliminary															

No:	Scope of Work	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	research		■	■	■	■										
3	Submission of extended proposal						▲									
4	Proposal defense								■	■						
5	Detail research										■	■	■	■	■	■
6	Mixing, casting and testing											▲				
7	Project works continue												■	■	■	■
8	Submission of interim draft report													▲		
9	Submission of interim report														▲	
No:	**Scope of Work (FYP 2)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Works continue	■	■	■	■	■	■	**Mid – Semester Break**								
2	Progress report submission								▲							
3	Works continue								■	■	■	■	■			
4	Pre – SEDEX (Poster presentation)											▲				
5	Submission of draft report												▲			
6	Submission of dissertation (Soft bound)													▲		
7	Submission of technical paper													▲		
8	Viva presentation														▲	
9	Submission of project dissertation (hard bound)														▲	

■ **Project work progress** ▲ **Suggested Key milestone**

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Slump flow test

The slump flow test was conducted as described in the workability test method above segregation or non-segregation of the fresh concrete. The flowability is measured by the diameter of the flow, the viscosity is measured by the T50 (as define in part 3.2.3) and the segregation is measured using the Visual Stability Index (VSI). Figure 8 below shows the measurement of the diameter after the fresh concrete has stop flowing and as observed there is no segregation or bleeding, hence VSI = 0.

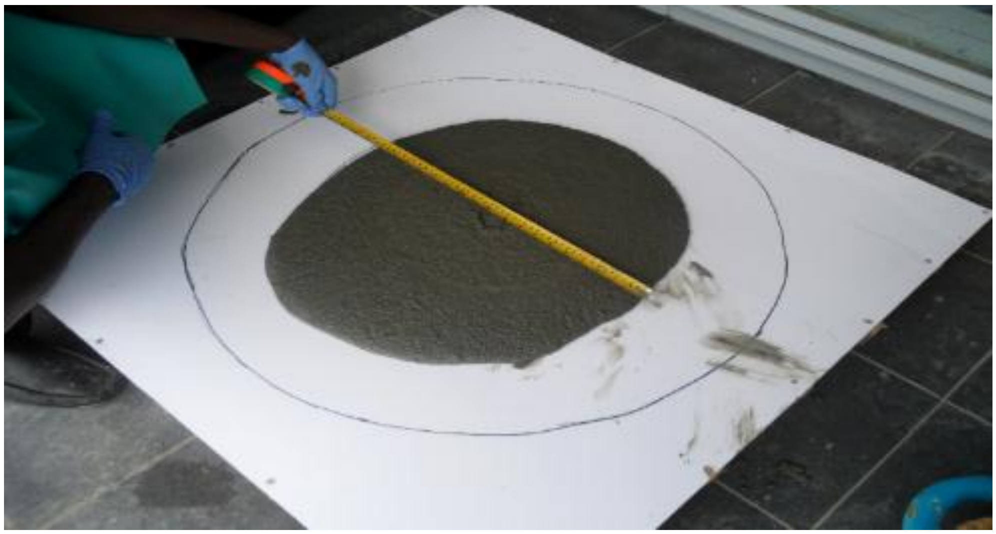


Figure 8 Measurement of fresh concrete flow diameter

a) <u>Flow</u>

Based on the result in Table 7 below, the spread diameter of the flow increases as the flow becomes more workable. In other words, in this experiment, as the quantity of the superplasticizer was increased, the flowability increases and the amount of water is kept constant. Typical SCC mixes have slump flow in the range of 457mm to 800mm. The result below shows an average flow spread diameter ranging from 465mm to 800mm, which lies in the requires range of slump flow.

Table 7 Slump flow Results

Mix ID	Slump Flow			T50 (s)	VSI
	d_{max} (mm)	d_{perp} (mm)	d_{avg} (mm)		

M1	470	460	**465**	Not reach d_{500} mm	0
M2	520	480	**500**	12	0
M3	590	500	**545**	11	0
M4	880	750	**815**	05	0
M5	830	720	**775**	07	0
M6	860	740	**800**	06	0

b) Viscosity

The time it takes the fresh concrete to reach the 500mm diameter of the base plate (T50) indicates the viscosity. A T50 between 3 and 6 seconds indicates low viscosity. From the result in Table 7 above, the viscosity reduces as the flow diameter increases and this all depends on the amount of the superplasticizer added. Mix 1 (M1) didn't reach the 500mm diameter circle on the base plate with an average flow of 465mm, and this shows that it is highly viscous than the other mixes.

When the T50 is plotted against the flow of the fresh concrete as in Figure 9 below, the relationship shows that, the lesser the time, the higher the flowability and vice versa. Therefore less time (T50) shows low viscosity and high flow, while the more time the fresh concrete takes to reach the 500mm diameter, the higher the viscosity and the lower the flow.

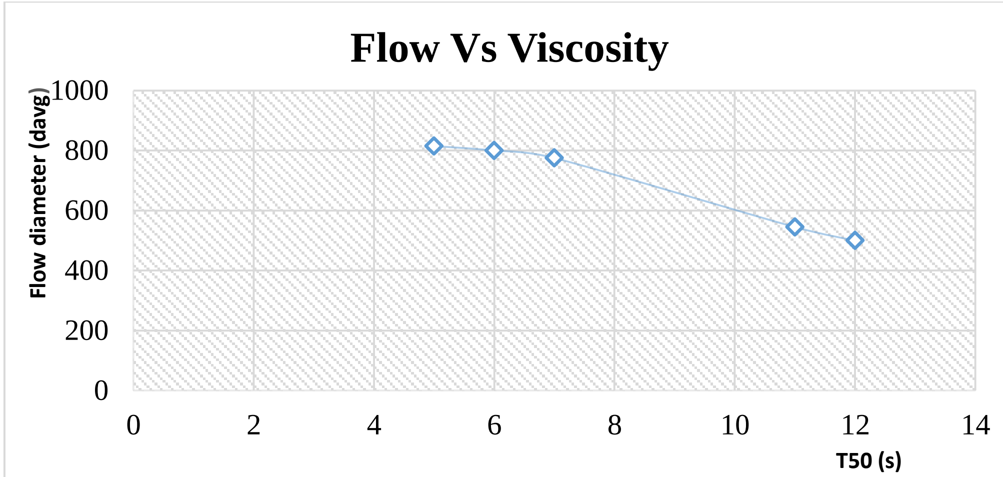


Figure 9 Plotted graph of relationship between the flow and viscosity of fresh RPC concrete.

c) <u>Segregation/Bleeding</u>

The Visual Stability Index (VSI) is a purely subjective test that rates the fresh concrete as indicated in Table 6 above as highly stable, stable, unstable and highly unstable. The author observe the concrete as it spreads out in the slump flow test. A VSI of 0 depicts a highly stable fresh concrete. This means that there is no observable segregation and bleeding. From the result in the Table 7 above, a VSI=0 is observed for all the mixes, hence the mixes in this experiment are highly stable with no observable segregation and bleeding.

As observed in this workability test, the author concluded that the mixes were workable and able to yield the recorded tested strengths.

4.2 Compressive Strength

Average compressive strengths of cube samples produced from each mix are presented in Table 8 below. To achieve a comprehensive results, testing was conducted on three specimens cast from each of the six (6) different mixes and the average results were recorded. The compressive strengths were measured at 3, 7, 28, and 56 days of curing in water at room temperature (25℃). It is observed that the specimens attained over 70% of the compressive strength at the age of 7 days and 20% increment at the end of 28 days. For both category of the mixes using silica fume and MIRHA, the non-fibered mix has indicated higher strength than 1% addition of steel fibers.

However, increment to 2% steel fibers increased the strength much higher than the non-fibered mixes. The result showed that increment of compressive strength does not totally depend on incorporation of steel fibers but the quantity used can increase the strength. Another observation from the result is the fact that the MIRHA mixes (M4 – M6) produced slightly higher strength than the silica fume mixes (M1 – M3). The result clearly shows that the materials characteristics used has effect on the strength, especially the change of silica fume to MIRHA after three mixes. This is because each of them have different degree of pozzolanic reaction with the rest of the composition materials. After 28 days, the strengths increased by 10% for both silica fume and MIRHA mix categories.

Table 8 Average Sample weight and Compressive Strength evaluated at 3, 7, 28, and 56 days

Mix ID	Description	Average Compressive Strength (MPa)				Average Wt. of Samples (Kg)
		3 Days	7 Days	28 Days	56 days	
M1	NF-RPC	70	88	111	117	2.18
M2	F-RPC (1%)	73	86	101	110	2.14
M3	F-RPC (2%)	86	99	112	125	2.20
MIRHA replaced silica fume						
M4	NF-RPC	83	88	114	127	2.27
M5	F-RPC (1%)	82	91	109	110	2.25
M6	F-RPC (2%)	85	97	117	129	2.28

Graphs in Figure 10 and 11 below, illustrates the rate at which the strength is gain in all the mixes. The trend shows a sharp increase for 3 and 7 days for all the mixes. After which the strength gain from 7 days to 28 days slowed down with an increase of about 20 % and 10% for 28 - 56 days. Mix 2 and 5 containing 1% steel fibers in both category records the lowest strength of all the mixes after 56 days but addition of 2% steel fibers in Mix 3 and 6, increases the strength higher than the non-fibred samples (M1 and M4).

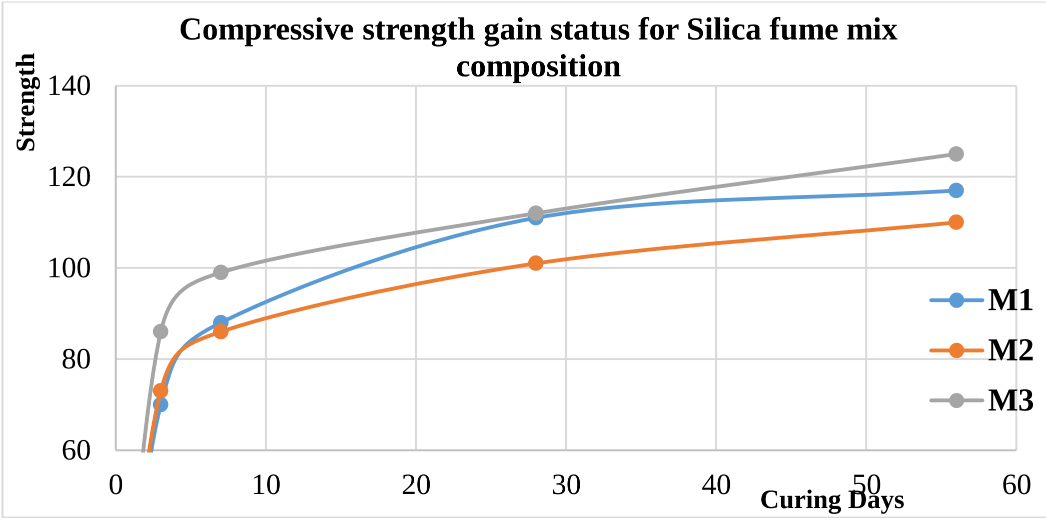


Figure 10 Mode of compressive strength gain at 3, 7, 28, 56 days

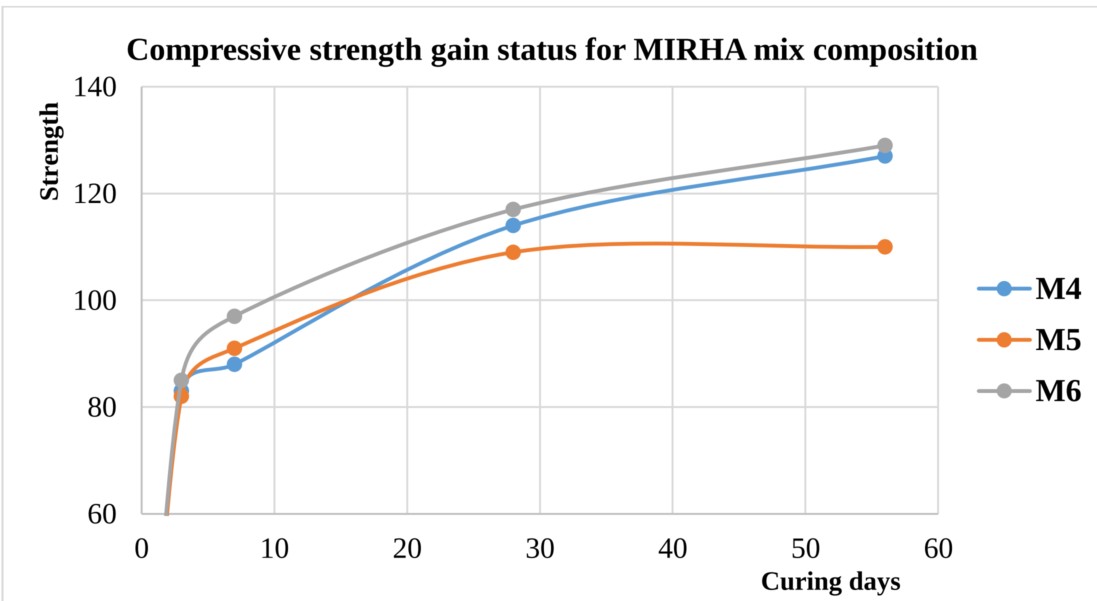


Figure 11 Mode for compressive strength gain at 3, 7, 28, 56 days

Significantly, Figures 12 and 13 below, shows graphs illustrating the 28th days mean compressive strength of M1 - M3 and M4 - M6 using Silica fume and MIRHA respectively. The two graphs shows similarity in strength gain where the Non-fibred Mixes (M1 and M4) produced slightly higher compressive strength compared to the 1% fibred Mixes of M2 and M5 respectively.

As the steel fiber content was increased to 2% in M3 and M6, the compressive strength gained increases higher than the rest of the Mixes. It therefore follows that, the addition of steel fiber does not guarantee the increase in strength of RPC, however it can be deduced from the result above that, the higher the fiber content, the higher the compressive strength.

The results also showed that the pozzolanic reaction of MIRHA as a replacement material for silica fume with the other composition materials of RPC, produces a relatively higher strength than using silica fume. At least a difference in strength ranging between 3 – 7MPa is observed in mixes containing MIRHA and Silica fume. In general, the performance of MIRHA is observed to be significant than silica fume because of its very strong pozzolanic reaction considering its very high fineness and amorphous structure which is similar to the behavior of silica fume.

Hence, cutting down the cost of producing the Ultra-high concrete when MIRHA is used since it can be sourced locally within Malaysia and is also cheaper. It also confirms previous research observations that MIRHA performs better in normal concrete than silica.

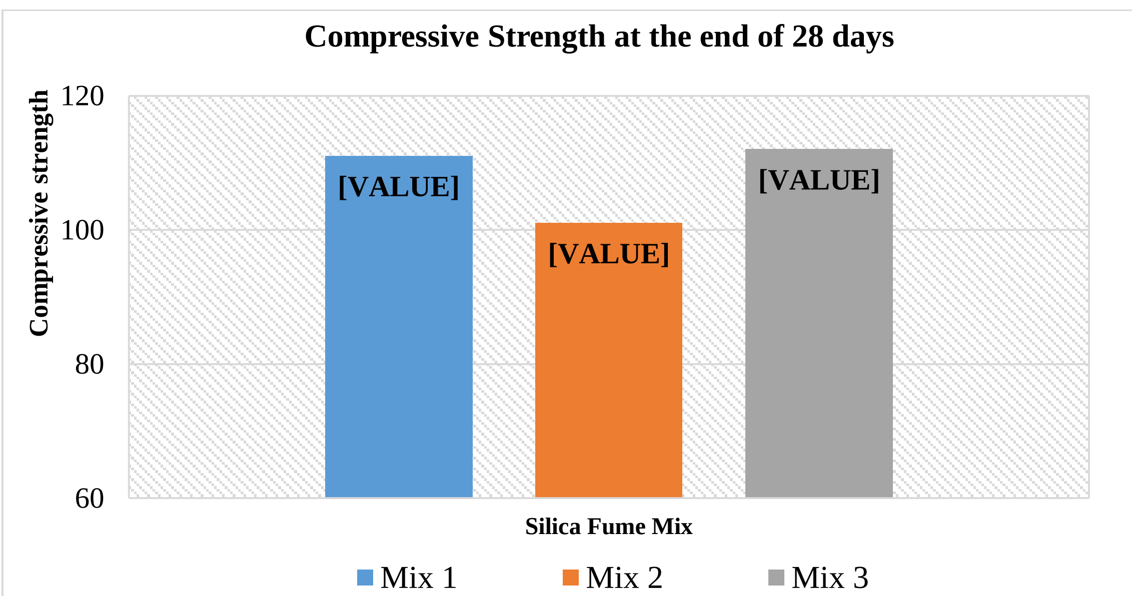


Figure 12 Silica fume pozzolanic Mix Compressive strength

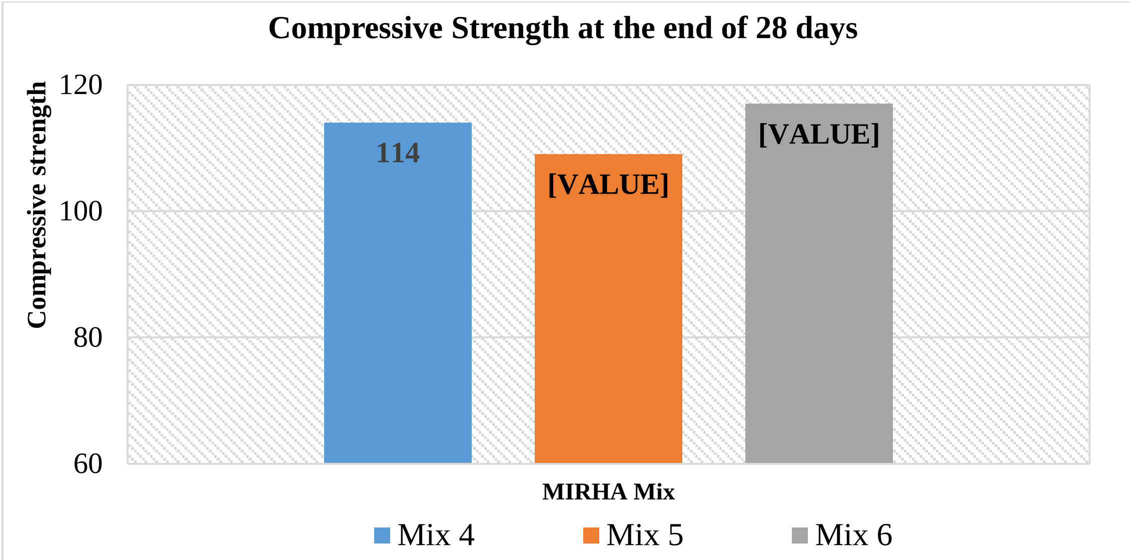


Figure 13 MIRHA pozzolanic Mix Compressive strength

4.3 Flexural Strength

Beam of size 100 x100 x 500mm were used for determination of flexural strength in accordance with AASHTO T 97. The samples were tested after curing in 25ºC water for 28 days. The test was carried out under two symmetrical loadings at a pace rate of 0.2 KN/sec as shown in appendix D. The result were recorded as shown in Table 9 below.

Table 9 Average Weight and Beam flexural strength evaluated after 28 days

Mix ID	**Flexural Strength (MPa) at 28 days**	**Beam weight**
	Average Strength	**Average wt.**
M1 (NF-RPC)	8.23	11.04
M2	7.24	10.78
M3	9.34	11.01
MIRHA replaced Silica fume		
M4 (NF-RPC)	8.4	11.53
M5	7.5	11.38
M6	9.8	11.44

Similarly to the gain of compressive strengths above, the flexural strength of the non-fibred mixes (M1 and M4) and 2% steel fibred mixes (M3 and M6), has relatively higher flexural strength than the 1% steel fibred mixes (M2 & M5). Although the results indicate relatively same level of results for all the mixes but the performance of MIRHA as a pozzolan is yet deduced to work well in this project.

4.4 Weight of Samples

Although the weight of the samples increased as the quantity of steel fibers increased, the result from Table 8 and 9 above shows that the average weight of both the cubes and prism samples of the non-fibred concrete has higher weight than the steel fibred samples. This proves the fact that using steel fibers is valuable in producing light weight, durable and ductile concretes although the strength seems to increase with weight. It is also observed that the weight of the samples after curing is observed to be $\pm$ 0.03kg higher than the weight before curing. Hence putting the concrete under water at a normal room temperature had less impact on the weight of the samples. However, with adverse exposure condition of weather especially on building structures, any possible impact can be expected.

4.5 Failure mode of the Samples.

a. Cube Samples

The cube samples tested for compressive strength in this research had different failure pattern depending on whether or not they contained steel fibers. When a compressive force was applied to samples without steel fibers, the failure would be sudden and unexpected. The samples are observed to fail along one failure plane as seen in Figure 14(a) below. Samples without steel fibers but with higher ranges of strength failed in explosive manner. A loud cracking noise could be heard when observing failure in the samples without steel fibers. Failure of non-fibred concrete is mostly undesirable in structural members because it lacks ductility.

(a) Without steel fibers

(b) Contain steel fibers

Figure 14 Failure mode of non-fibred and fibred cube samples under loading

On the other hand when steel fiber is incorporated into the mix, the failure pattern is as shown in Figure 14(b) above. Small cracking noise could be heard when testing the samples. The final failure occurs over several failure planes and the cracks are distributed at random over the sample surfaces as observed in Figure 14(b) above. This kind of failure is more desirable in the structure as indicates the ductility of the structural members.

b. *Beam samples*

Figure 15 Failure mode of non-fibred beam sample

The extent to which steel fibers enhance the ductile behavior of RPC is seen when testing beam samples for flexural strength. From Figure 15 above, beam sample without steel fibers failed in a sudden brittle manner with no cracks detected before failure. It is completely broken into two parts after failure. While for the beam samples containing steel fibers, the failure was not sudden but small cracks were created at the start of the loading and as the loading increased, the cracks widened. After failure, the samples stills hold itself together as shown in Figure 16 below. This is the reason why steel fibers were incorporated into the mix to provide ductility to the samples.

Figure 16 Failure mode of beam sample containing 1% steel fiber

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Depending on the result of this investigation on the strength properties on RPC, the following conclusions were drawn;

1. It is feasible to produce reactive powder concrete from local materials such as river sand and fly ash while using silica fume as the pozzolanic admixture. Likewise, MIRHA can also be used as a replacement for silica fume, as it has proven to perform better in this research.
2. Reactive Powder Concrete (RPC) with a compressive strength of about 115 to 125 MPa were achieved at the end of 56 days after curing in water at room temperature. A flexural strength of about 7 – 9 MPa was also attained. However, the result did not reach the target strength similar to the ones achieved by Richard and Cheyrezy (1994). This is attributed to the fact that certain composition materials such as silica sand and powder were difficult to source within Malaysia and has to be replaced by local materials like river sand and fly ash. These replacement materials has different water adsorption properties. Hence they required higher water – cement ratio which affects the outcome of the results.
3. The addition of steel fibers does not necessarily increase the strength but it definitely improve the ductility and reduce the weight of the concrete. With ductile and light weight properties, we conclude that RPC is suitable for construction of high strength concrete structures.

5.2 Recommendations

1. For further improvement on this thesis, other available local materials and their quantification, is desirable to achieve the target strength.
2. A proposed 3% addition of steel fibers can also be used in the next study.
3. To increase the homogeneity of the mix, reduce the river sand size to 150µm - 500µm from the original size used in this research. This is in case the same materials is used.

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APPENDICES

Appendix A: Mix Designs

Table 10 Mix design for RPC from past literature

Material	Richard and Cheyrezy (1994)	Dugat et al. (1996)	HDR Inc. (2002)	Bonneau et al. (1997)	Graybeal (2006)	Roux et al. (1996)	Matte and Moranville (1999)	Gowripalan et al. (1999)	Collepardi (2003)	Campbell et al. (1998) (a)	Campbell et al. (1998) (b)	Cavill (1999)	Aitcin et al. (1998)	Gowripalan et al. (2003)	Voo et al. (2001)	Dallaire et al. (1998)
Cement (C)	36.7	37.6	36.9	27.9	28.5	39.3	27.9	35.6	35.5	36.9	30.6	28.1	27.4	28.2	36	29.9
Silica fume (S)	8.8	9.4	9.3	9	9.3	9.82	9.1	8.9	8.9	9.25	10.0	9.15	8.9	8.5	8.7	9.7
Silica flour	0.4	-	-	-	-	-	-	-	-	-	9.2	-	-	8.5	5.7	-
Ground quartz	-	-	-	8.4	8.4	-	8.4	-	-	-	-	8.4	8.2	-	-	8.9
Fine sand	40.4	39.5	40.6	39.7	40.8	43.2	39.8	41	39.1	40.6	44.4	40.2	39.3	40.4	35.8	42.8
Super-plasticiser	0.5	0.7	1.6	1.5	2.4	0.58	1.7	1.1	0.5	1.6	1.3	1.1	0.7	1.8	2.5	0.7
Steel fibres	7.3	5.8	6.3	5.6	6.2	-	7.7	7.1	7.3	6.3	6.8	7.6	7.4	6.5	6.8	8
Water (W)	5.9	7.1	5.3	7.8	4.4	7.1	5.6	6.3	8.9	5.3	4.6	5.6	7.6	6.2	4.5	8.3
*W/C	0.16	0.19	0.14	0.28	0.19	0.18	0.20	0.18	0.25	0.14	0.15	0.20	0.28	0.22	0.13	0.28
*W/(C+S)	0.13	0.15	0.11	0.21	0.14	0.14	0.15	0.14	0.20	0.12	0.11	0.15	0.21	0.17	0.10	0.21
f'_c (MPa)	170	194	180	197	193	170	191	189	180	214	-	170	192	160	177	-
f'_{cf} (MPa)	25	32	30	-	-	-	-	35	50	-	-	30	40	24	24	-
f'_{ct} (MPa)	-	-	-	-	12	-	-	-	-	-	-	-	-	16	21	-
E_c (GPa)	54	62	-	49	52	-	-	50	60	57	-	50	50	47	44	-

Appendix B: General Results

Table 11 Slump flow test result

Mix ID	**Slump Flow**			**T50 (s)**	**VSI**
	d_{max} (mm)	**d_{perp} (mm)**	**d_{avg} (mm)**		
M1	470	460	465	Not reach d_{500} mm	0
M2	520	480	500	12	0
M3	590	500	545	11	0
M4	880	750	815	05	0
M5	830	720	775	11	0
M6	860	720	790	06	0

Table 12 Compressive Strength test results

Mix ID	Descrip-tion	Compressive Strength (MPa)															
		3 Days				7 Days				28 Days				56 days			
		S 1	S 2	S 3	**Avg**	S 1	S 2	S 3	**Avg**	S 1	S 2	S 3	**Avg**	S 1	S 2	S 3	**Avg**
M1	NF-RPC	69.06	70.35	69.5	**69.64**	85.75	76.33	90.95	**88.35**	108.2	95.0	113.3	**111**	108.3	121.9	111.1	**116.5**
M2	F-RPC (1%)	71.07	72.5	75.07	**72.88**	78.53	83.78	89.09	**86.44**	101.1	101.3	95.79	**101.2**	110.4	107.7	106.5	**110**
M3	F-RPC (2%)	86.47	85.21	80.55	**85.84**	98.64	96.83	99.94	**98.47**	112	109	108	**110.5**	119.8	125.8	124.9	**125.35**
M4	NF-RPC	83.41	83.26	83.76	**83.48**	85.97	89.87	87.67	**87.84**	116	107	111	**113.5**	128.8	125.8	125.2	**127**
M5	F-RPC (1%)	76.96	81.67	83.27	**82.47**	89.09	92.00	92.96	**91.35**	110	107	105	**108.5**	113.3	106.4	104.0	**110**
M6	F-RPC (2%)	80.79	82.19	81.59	**81.52**	87.96	98.73	94.37	96.55	116	113	118	**117**	128.5	125.1	128.9	**129**

Table 13 Weight of Cube samples

Mix ID	Cubes Sample Weight (kg)															
	3 Days				7 Days				28 Days				56 Days			
	S 1	S 2	S 3	**Avg**	S 1	S 2	S 3	**Avg**	S 1	S 2	S 3	**Avg**	S 1	S 2	S 3	**Avg**
M1	2.16	2.07	2.21	**2.15**	2.22	2.24	2.09	**2.18**	2.16	2.16	2.19	**2.17**	2.18	2.08	2.17	**2.14**
After curing	2.17	2.09	2.23	**2.16**	2.25	2.25	2.11	**2.20**	2.15	2.18	2.20	**2.18**	2.20	2.11	2.20	**2.17**
M2	2.19	2.05	2.16	**2.13**	2.01	2.19	2.17	**2.12**	2.11	2.12	2.17	**2.13**	2.14	2.19	2.21	**2.18**
After curing	2.20	2.08	2.18	**2.15**	2.02	2.22	2.18	**2.14**	2.14	2.13	2.19	**2.15**	2.17	2.21	2.23	**2.20**
M3	2.24	2.24	2.16	**2.21**	2.21	2.16	2.23	**2.20**	2.22	2.12	2.16	**2.17**	2.24	2.25	2.26	**2.25**
After curing	2.25	2.25	2.16	**2.22**	2.22	2.17	2.24	**2.21**	2.23	2.13	2.17	**2.18**	2.26	2.27	2.28	**2.27**
M4	2.24	2.19	2.27	**2.23**	2.25	2.28	2.28	**2.27**	2.29	2.23	2.30	**2.27**	2.32	2.29	2.29	**2.30**
After curing	2.26	2.20	2.30	**2.25**	2.27	2.29	2.30	**2.29**	2.32	2.25	2.32	**2.30**	2.34	2.32	2.32	**2.33**
M5	2.21	2.24	2.22	**2.22**	2.31	2.24	2.23	**2.26**	2.29	2.23	2.19	**2.24**	2.23	2.22	2.18	**2.21**
After curing	2.22	2.26	2.23	**2.24**	2.33	2.25	2.31	**2.30**	2.31	2.26	2.21	**2.26**	2.26	2.25	2.20	**2.24**
M6	2.22	2.31	2.25	**2.26**	2.24	2.23	2.14	**2.20**	2.27	2.25	2.33	**2.28**	2.23	2.24	2.30	**2.26**
After curing	2.24	2.32	2.27	**2.28**	2.26	2.25	2.15	**2.22**	2.28	2.29	2.36	**2.31**	2.26	2.27	2.33	**2.28**

Note: The difference in weight of cube samples before and after curing ranges between 0.01 – 0.03 kg

Table 14 Beam samples weight and Flexural strength result

Mix ID	Flexural Strength (MPa) at 28 days			Beam weight		
	B1	B2	**Average Strength**	B1	B2	**Avg wt.**
M1	7.3	8.23	**8.23**	11.01	11.05	**11.03**
				11.02	11.08	**11.05**
M2	6.97	7.5	**7.24**	10.65	10.71	**10.68**
				10.86	10.88	**10.87**
M3	8.905	9.34	**9.1225**			
				11.32	11.16	**11.24**
M4	8.35	8.422	**8.4**			
				11.42	11.64	**11.53**
M5	8.497	9.081	**8.7899**			
				11.44	11.32	**11.38**
M6	7.856	7.511	**7.6835**			
				11.42	11.46	**11.44**

Appendix C: Typical staged mixing Procedure

Stage mixing procedures

Appendix D: Strength Testing

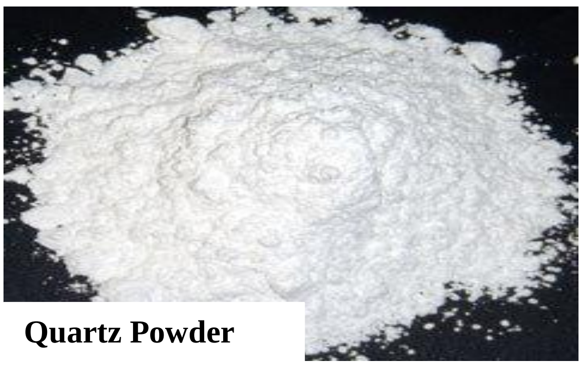
Compressive Strength Test

Flexural Strength test

Appendix E: Some materials used in RPC

Hooked steel fibre

Type 1 OPC

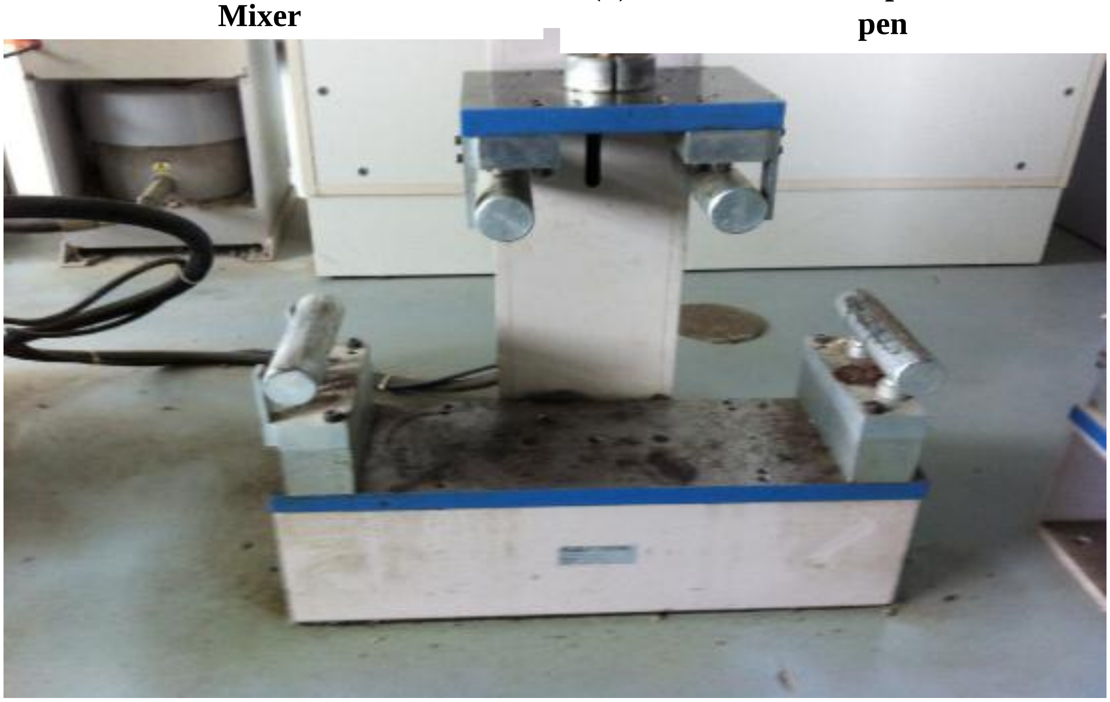


Quartz Powder

APPENDIX F: Some of the Equipment used in the Experiment

(a)Inclined Drum rotary concrete Mixer

(b)Abram cone, Base plate, Meter, Marker pen



(c) Flexural strength testing machine

(d) Compressive strength testing machine

(e) Measuring Cylinder

(f) Measuring container

Appendix G: Failure Modes of the Tested Samples

Non-fibered cube sample

Fibered cube sample

Non-fibered prism sample

Fibered prism sample