STUDY ON DURABILITY CHARACTERISTICS OF HIGH PERFORMANCE CONCRETE (HPC)

by

RAED M. A. EL OTTOL

Thesis submitted in fulfillment of the
requirements for the degree
of Masters of Science
(Building Technology)

May, 2006

ACKNOWLEDGEMENTS

First and foremost, my heartfelt gratefulness goes to the Almighty, the One who has no finality for answering my prayers in many ways and blessing me with the abilities that have enabled me to achieve this success.

I would like to express my deepest gratitude to my supervisor Dr. Norizal Noordin for her invaluable guidance, advice, patience, constructive criticism and assistance given to me throughout this work. This work would have been improved with his help, concern and constant encouragement, and also sincere thanks to my co-supervisor Dr. Faisal and to Dr. EGL Tan (Dissertation Coordinator)

My sincere thanks also extend to all members of the School of Housing, Building & Planning (HBP) for their cooperation and friendly environment that help in various ways in the completion of this work. I am also grateful to University Science Malaysia (USM) for providing me a seat to pursue my higher studies.

A special word of thanks to my friends Mr. Ahmed Maher, Mohammed Ali and Adel Al-Moallem. I will always treasure the moments we spent together, your moral support is highly appreciated and your friendship is priceless. Many thanks for being caring, understanding, sharing and loving.

Last but certainly not least, I express my gratitude to my parents, brothers and sisters for their prayers and support at home. I also express my sincere thanks to my beloved wife and my little Kids whose support, encouragement and love provided me the impetus to complete this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

STUDY ON DURABILITY CHARACTERISTICS OF HIGH PERFORMANCE CONCRETE (HPC)

ABSTRACT

The recent developments in the field of high-performance concrete (HPC) represent a giant step toward making concrete a high-tech material with enhanced characteristics and durability. These developments have even led to it being a more ecological material in the sense that the components admixtures, aggregates, cementitious materials and water are used to their full potential to produce a material with a superior durability and longer life cycle.

Environmental factors, especially the climate, have significant influence on durability of concrete material. This dissertation aims to investigate the durability characteristics of High-performance concrete material which can resist the environmental factors more than ordinary concrete not only because High-performance concrete is less porous, but also because its capillary and pore networks are somewhat disconnected due to the development of self-desiccation and the effects of cementitious materials such as Fly ash, Silica Fume and Slag result reduces the water demand, improve the workability, and enhances durability to reinforcement corrosion, sulfate attack, and alkali-silica expansion.

In high-performance concrete (HPC), the penetration of aggressive agents is quite difficult and only superficial. Therefore, HPC must be cured

quite differently from ordinary concrete. Field experience in many researches has shown that if HPC is properly designed and cured, performs satisfactorily in very harsh environments.

STUDY ON DURABILITY CHARACTERISTICS OF HIGH PERFORMANCE CONCRETE (HPC)

RAED M. A. EL OTTOL

UNIVERSITI SAINS MALAYSIA

2006

Dedicated to the greatest influential
People in my life, my parents, my wife, my kids
Mr. & Mrs. Building Technology
Housing, Building and Planning

Chapter One

Introduction

1. INRODUCTION

Most of the attention in the 1970s and 1980s was directed toward high strength concrete but today the focus is more on concretes with high durability in severe environments resulting in structures with long life. (Bickley and Mitchell 2001)

High-performance concrete is definitely more durable than usual concrete and its increased use will be more often linked to its durability than its high strength. Durability will become a key issue because we will become more and more concerned with sustainable development. In that respect the use of high performance concrete is more ecological than the use of a usual concrete: less cement and less aggregates are needed to sustain a certain load, the life cycle of the concrete structure is increased due to the greater intrinsic durability of high-performance concrete and, when high-performance concrete will have to be recycled at the end of its life, it will be recycled one or two times more than usual concrete because of its higher strength.

High performance concrete (HPC) is that which is designed to give optimized performance characteristics for the given set of materials, usage and exposure conditions, consistent with requirements of durability, service life and cost. Architects, engineers and constructors all over the world are finding that using HPC allows them to build more durable structures at comparable cost. HPC is being used for buildings in aggressive environments, marine structures, highway bridges and pavements, nuclear structures, tunnels and pre cast.

High performance concrete (HPC) exceeds the properties and constructability of normal concrete. Normal and special materials are used to make these specially designed concretes that must meet a combination of performance requirements. Special mixing, placing, and curing practices may be needed to produce and handle high-performance concrete. Extensive performance tests are usually required to demonstrate compliance with specific project needs (ASCE 1993, Russell 1999, and Bickley and Mitchell 2001).

HPC can be made with cement alone or any combination of cement and mineral components, such as, blast furnace slag, fly ash, silica fume, metakaolin, rice husk ash, and fillers, such as limestone powder. Ternary systems are increasingly used to take advantage of the synergy of some mineral components to improve concrete properties in the fresh and hardened states, and to make high performance concrete more economical and ecological.

High-performance concrete almost always has a higher strength than normal concrete. However, strength is not always the primary required property. For example, a normal strength concrete with very high durability and very low permeability is considered to have high-performance properties. (Bickley and Fung, 2001)

Not all properties can be achieved at the same time. High-performance concrete specifications ideally should be performance oriented. Unfortunately, many specifications are a combination of performance requirements (such as permeability or strength limits) and prescriptive requirements (such as air content limits or dosage of supplementary cementing material (Ferraris and Lobo 1998).

High-performance concrete has been primarily used in tunnels, bridges, and tall buildings for its strength, durability, and high modulus of elasticity. It has also been used in shot Crete repair, poles, parking garages, and agricultural applications. The research and development of HPC are the most important issues relating to concrete technology today (Chang and Peng, 2001).

High-performance concretes are very sensitive to plastic and autogenous shrinkage, so that their use demands an immediate water curing. The use of a curing compound which is perfectly adequate to cure a concrete having W/B ratio greater than 0.50 is absolutely inadequate with high-performance concrete because it does not prevent the development of autogenous shrinkage when a 0.30 high-performance concrete is not water cured before setting, it can develop a 200 to 300 microstrains autogenous shrinkage during the first 24 hours, that will be added to its drying shrinkage. On the contrary when a high performance concrete is water cured during the first 24 hours, its swells slightly.

2. ISSUE

The issue to be highlighted in this study is the durability of high performance concrete in a severe environment, and to investigate the actual durability requirements which can satisfy the objectives in such environment.

A lot of experiments investigated the durability of high performance concrete but they did that separately as particles so in this dissertation trying to gather all these works will be done.

3. OBJECTIVES OF STUDY

The main objectives of this study are as follow:

1. To identify the definition and durability characteristics of High performance concrete.
2. To investigate how cementitious materials affect the durability of high performance concrete.

4. METHODOLOGY

A dissertation is only a medium through which research is reported and of course, the research itself is the most important matter. No matter how well a research report is presented, the value of the report will be dependent upon the quality of the research that is being reported.

This research methodology has been divided according to steps and procedures to ensure that the objective of the research could be achieved. It consists of two main aspects of literature review and core study.

Data is collected from communiqué of magazines, newspapers, articles, books and journals. The data which are collected will be analyzed qualitatively to determine the chapters of study.

As a conclusion, the research methodology is divided into three steps. The first step involves the discussion and collecting of data's. Discussion is done with supervisors to identify the early problems of the dissertation. A simple structure of what the dissertation is a bout is written and given to the supervisors.

The second step is to investigate deeply the durability characteristics fetchers, and conducting the reporting process.

The third step is to successfully finishing the dissertation by analyzing the research which has been done.

A simple flow chart is shown on the next page, the steps which have been taken in completing this dissertation.

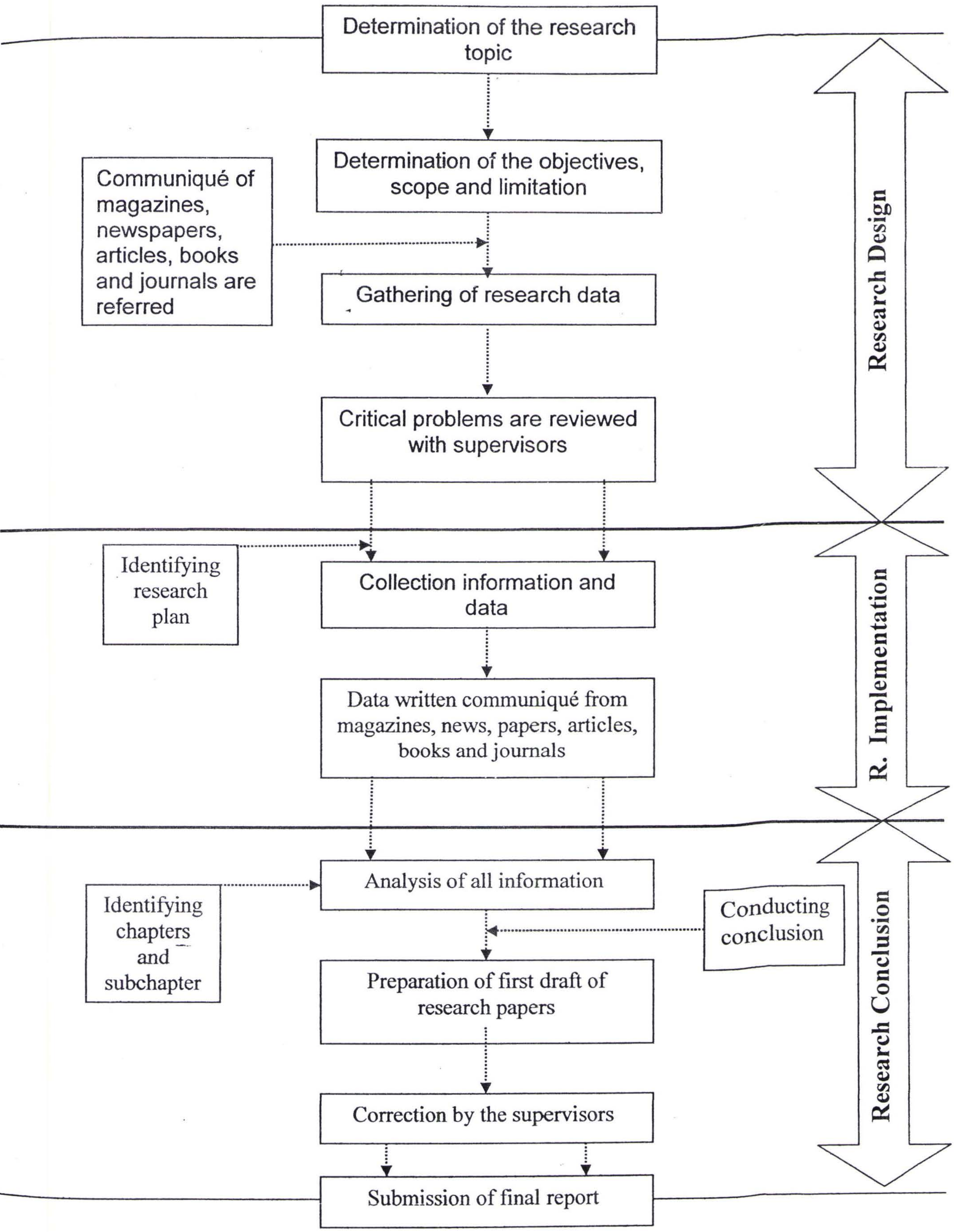

Figure 1.1 A simple flow chart of methodology

5. SCOPE OF WORK

In this dissertation the main topic is high performance concrete but the scope of work and highlighting will be done on the durability characteristics for this material, in addition to the mechanism of deterioration for each durability parameter and feature such as chemical attacks, corrosion, abrasion and alkali reaction, etc.

A simple flow chart is shown on the next page, the path of scope of work which has been taken in completing this dissertation.

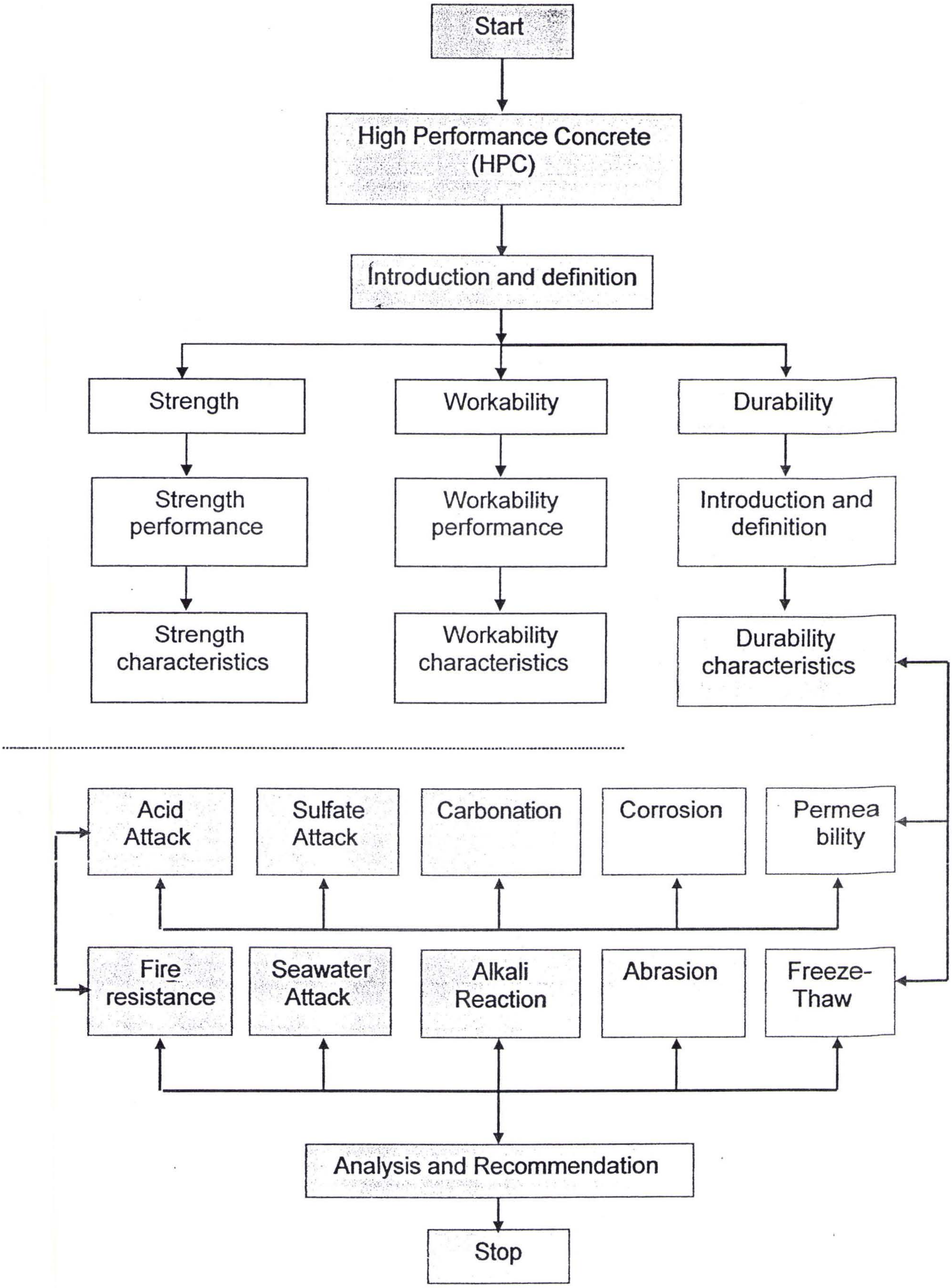

Figure 1.2 A simple flow chart of the path of scope of work

6. LIMITATION

High performance concrete is considered as a new material, and there is no many articles or books discuss about the durability in details because normally the durability tests on this material take long period of time (1- 3 years).

Also there is no one study case in Malaysia to be studied by the researcher so this dissertation depends on the others researches and developed countries projects.

7. WORKING PLAN

This dissertation has been divided to five major chapters and each chapter has been divided to subchapters (titles and subtitles) to make the explanations easier.

Chapter one (Introduction) explains a general introduction, the objectives, Methodology, the scope and also the problems and limitation of completing the dissertation in addition to working plan.

Chapter two (Understanding of high performance concrete) is about to study and examine the definition of high performance concrete , general properties of high performance concrete and cementitious materials such as fly ash , silica fume and slag.

The main objective of this chapter is to introduce the high performance concrete as a modern material, with explaining the difference between high strength concrete and high performance concrete.

Chapter three (Durability characteristics of high performance concrete) is the core of this dissertation, discusses about the basic features in durability characteristics; this includes the explanation of durability and mechanism of deterioration in each case such as corrosion, abrasion, sulfate attack, carbonation, alkali reaction, and freeze thaw. Chapter three also explains how high performance concrete can affords the severe conditions and proves the super durability of high performance concrete.

Chapter four (Analysis and conclusion) which is the final chapter, analyses and summarizes the overall dissertation by concluding the finding and recommendations.

Chapter Two

Understanding of High Performance Concrete

CHAPTER TWO
UNDERSTANDING OF HIGH PERFORMANCE CONCRETE

1. Introduction

Many recent innovations in advanced concrete materials technology have made it possible to produce concrete with exceptional performance characteristics. High performance concrete (HPC) is this concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using conventional materials and normal mixing, placing, and curing practices. The importance of HPC to structural engineering is unquestionable. However, High performance concrete is a relatively new material.(Aitcin 1997)

High performance concrete is often called "durable" concrete because its strength and impermeability to chloride penetration makes it last much longer than conventional PCC. In this chapter trying to answer the question what is the High performance concrete? And why this material needs special preparing? How to select component materials? Also main issues in High performance concrete will be focused on, such as strength, shrinkage, curing, volumetric changes and quality control. And finally we have to know at least what is the difference between ordinary concrete and high performance concrete or what is the different between autogenous shrinkage and drying shrinkage due to admixtures, proportioning, mixing, placing, curing and selection materials.(Jiang, Liu et al. 2004)

2. Historical View of HPC.

As far back as 1949, beams with a concrete strength of more than 37 mega PASCAL's (MPa) (5,400 pounds per square inch) were used in the construction of the Walnut Lane Bridge in Philadelphia. This was the first prestressed, post-tensioned concrete bridge built in North America.(Flaga 2000)

At that time and for the next four decades, engineers were concerned almost exclusively with strength. Specified concrete strength for buildings steadily increased from 35 MPa in the 1950s to 100 MPa by the end of the 1980s. The term "high-strength concrete" was frequently used. Today, the definition of High performance concrete has expanded to encompass both durability and strength.(Flaga 2000)

No single person invented High performance concrete, and no single country pioneered its use. The development of the HPC materials in use today was an incremental, combined effort involving many individuals, companies, government agencies, and countries, particularly in Canada, Europe, Japan, and the United States. Since the earliest bridges using prestressed concrete beams were only constructed about 50 years ago, not enough time has passed to confidently state a durability life span for prestressed concrete bridges.(Aitcin 2002)

For decades, the construction of very tall buildings was the driving force behind the development of high-strength concrete. Economy of construction was the goal. For example, the use of 69-MPa concrete in the Interfirst Plaza building in Dallas in 1983 provided six times more stiffness per dollar than a steel-frame building. Constructors of Two Union Square in Seattle in 1988 used 130-MPa concrete to achieve a modulus of elasticity of 49,600 MPa.(Aitcin 2000)

But As Aitcin said the Credit for the term "High Performance Concrete" must go to the French. In 1980, Roger Lacroix and Yves Malier coined this term as a first time. In 1986, the French project "New Ways for Concrete" brought together 36 researchers from France, Switzerland and Canada. Pierre-Claude Aïtcin was the leader of the Canadian group. (Aitcin 1997)

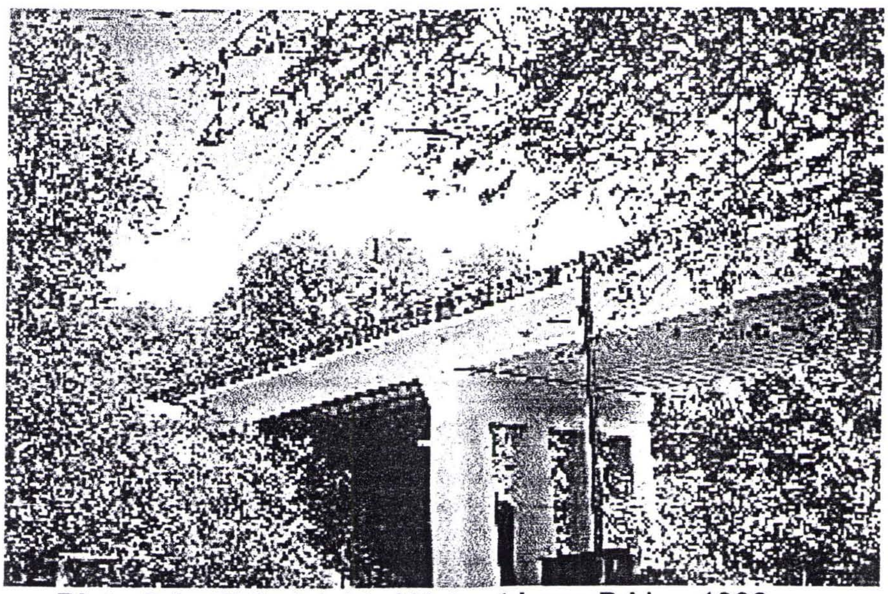

Plate 2.1 Philadelphia Walnut Lane Bridge 1988.

At the end of 1988, Pierre-Claude Aitcin, assisted by Denis Mitchell and Michael Collins, wrote the successful proposal for the Network of Centers of Excellence on High Performance Concrete, funded under the Federal Government "Centers of Excellence Program". That program started in 1990, and, in its second phase, starting in 1994, the Network became known as Concrete Canada. The researchers who comprised Concrete Canada were not the only Canadians researching and using HPC, however, a Newsletter sent to

7,000 persons world-wide, the organization of technology transfer days and seminars, and the construction of demonstration projects, So Concrete Canada played the major role in establishing HPC as a widely accepted construction material in the world.(Aitcin 1997)

In 1990 United States, the Strategic Highway Research Program (SHRP) sponsored a project on High Performance Concrete. And the first the definition which used by SHRP for HPC was as follows:

1. "It should meet one of the following criteria
   a) A 3-hour strength not less than 3,000 psi
   b) A 24-hour strength not less than 5,000 psi
   c) A 28-day strength of not less than 10,000 psi
   d) A water-cement ratio (including Pozzolans) less than 0.36
2. It should also have a durability factor not less than 80 after 300 cycles of freezing and thawing".

In 1993 the term has become a popular buzzword and in the decade 1993-2005, there has been an enormous amount of research on this subject, and thousands of Papers have been published. Most of research programs have been carried out in many countries in Europe, Asia, Australasia, Japan and North America. (Zia, 2005)

The use of HPC has recently spread rapidly. Most Provincial Highway Departments and some major cities have adopted its use, or are in the process of doing so. As a result, many consultants are specifying it, and, consequently, many contractors are winning contracts which contain innovative features.(Aitcin 1997)

3. Definitions of High-Performance Concrete (HPC).

The concrete that was known as high-strength concrete in the late 1970s is now referred to as High performance concrete because it has been found to be much more than simply stronger: it displays enhanced performance in such areas as durability and abrasion resistance. Although widely used, the expression "high-performance concrete" is very often criticized as being too vague, even as having no meaning at all. And what's more, there is no simple test for measuring the performance of concrete.(Bickley and Mitchell 2000)

Several different definitions of high-performance concrete have been proposed. Currently there is no one definition that is universally accepted either within the United States or in other countries. Some of these definitions are summarized below:

1. ***Strategic Highway Research Program (SHRP) definition*** **(Zia et al. 1991):**

a) High-performance concrete shall have one of the following strength characteristics:

- 28-day compressive strength greater than or equal to 70 MPa (10 000 psi), or
- 4-hour compressive strength greater than or equal to 20 MPa (3 000 psi), or

- 24-hour compressive strength greater than or equal to 35 MPa (5 000 psi)

b) High-performance concrete shall have a durability factor greater than 80 % after 300 cycles of freezing and thawing.

c) High-performance concrete shall have a water-cementitious materials ratio1 less than or equal to 0.35.

The SHRP definition encompasses specific strength, durability, and mixture proportioning characteristics. It should be noted that this definition was developed requirements for highway construction.(Meeks and Carino 1999)

2. *NIST/ACI Workshop definition (Carino and Clifton 1990):*

" High-performance concrete is concrete having desired properties and uniformity that cannot be obtained routinely using only traditional constituents and normal mixing, placing, and curing practices." As examples these properties may include:

1. Ease of placement and compaction without segregation.
2. Enhanced long-term mechanical properties.
3. High early-age strength.
4. High toughness.
5. Volume stability.
6. Long life in severe environments.

This is a more general definition that attempts to include a variety of concretes having special properties not attainable by ordinary concrete.

3. ***University of Tokyo definition (Carino and Clifton 1990):***

In this definition, high-performance concrete is characterized as a "forgiving concrete" that compensates for poor construction practices and structural detailing, and has the following features:

1. Ability to fill forms with little or no external compactive effort.
2. Cohesive mixture with low segregation.
3. Minimum cracking at early ages due to shrinkage and thermal strains.
4. Sufficient long-term strength and low permeability.

This definition is a reflection of the Japanese emphasis on constructability as well as strength and durability of concrete.

4. ***Prestressed Concrete Institute definition (PCI Committee on Durability 1994):***

High-performance concrete is concrete with or without silica fume having a water/cement ratio of 0.38 or less, compressive strength at or above 55.2 MPa (8 000 psi) and permeability 50 % lower (by AASHTO T-259 or T-277 methods) than that of conventional mixtures.

5. ***Civil Engineering Research Foundation definition (CERF Technical Report 1994):***

Unlike conventional concrete, high-performance concrete meets one or more of these requirements:

1. Places and compacts easier.
2. Achieves high strengths at early ages.

3. Exhibits superior long-term mechanical properties such as strength, resistance to abrasion or impact loading, and low permeability.
4. Exhibits volume stability and thus deforms less or cracks less.
5. Lasts longer when subjected to chemical attack, freezing and thawing, or high temperatures.
6. Demonstrates enhanced durability.

This definition is an outgrowth of the earlier NIST/ACI workshop definition.

According to Aitcin the definition can be technically refined by stating that a high-performance concrete is: "a concrete in which autogenous shrinkage can develop due to a phenomenon called self desiccation when the concrete is not water cured'. But the technical jargon, however, does little to clarify things because very few people are familiar with the terms self-desiccation and autogenous shrinkage.(Aitcin 2002)

Since there is no single best definition for the material that is called high-performance concrete, So Aitcin prefers to define it as a low water/binder concrete with an optimized aggregate/binder ratio to control its dimensional stability and which receives an adequate water curing. (Aitcin 2002)

Now HPC is defined by the American Concrete Institute (ACI) as concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices. HPC is a concrete in which certain characteristics are developed for a particular application and environment Characteristics that may be considered critical for an application are ease of placement, compaction without segregation, early age strength, long-term mechanical properties, permeability, density, heat of hydration, toughness, volume stability, and long life in severe environments. In most applications, the water-cementing materials ratio will not exceed 0.40. HPC has a very broad definition and is not restricted to just strength. (Aitcin 2002)

4. High-Performance Concrete (HPC) and High-Strength Concrete (HSC)

HSC is defined by ACI as concrete that has a specified compressive strength for design of 6,000 psi (41 MPa) or greater Therefore, HSC is an HPC in which the critical characteristic is a specified strength of 6,000 psi (41 MPa) or greater. Consequently, an HSC is always an HPC but not all HPC is HSC, because the durability property according to the previous definition of High performance concrete can be achieved with high strength or without. (Tumidajski and Chan 1996)

5. Main Characteristics of High-Performance Concrete.

Durability of high-performance concrete is one of very important feature but high-performance concrete has also many features such as high compressive strength, resulting from a very compact matrix. Other characteristics also include almost no paste/aggregate transition zone; a higher modulus of elasticity than conventional concrete made with the same aggregates that can be in the best cases almost equivalent to that of aluminum; very low impermeability, quite frequently lower than that of many natural rocks; exceptional abrasion resistance, rivaling that of the hardest rocks; outstanding resistance to freeze-thaw cycles and deicing salts; very low creep; and high flexural strength.(Aitcin 1994)

Until now there is no much studies dealing with the long-term behavior of high-performance concrete, but the high performance concrete is so compact and impervious that it remains practically unaffected by its external environment, with the possible exception of skin concrete. However, as for any kind of concrete, curing may influence this last aspect.(Aitcin 1994)

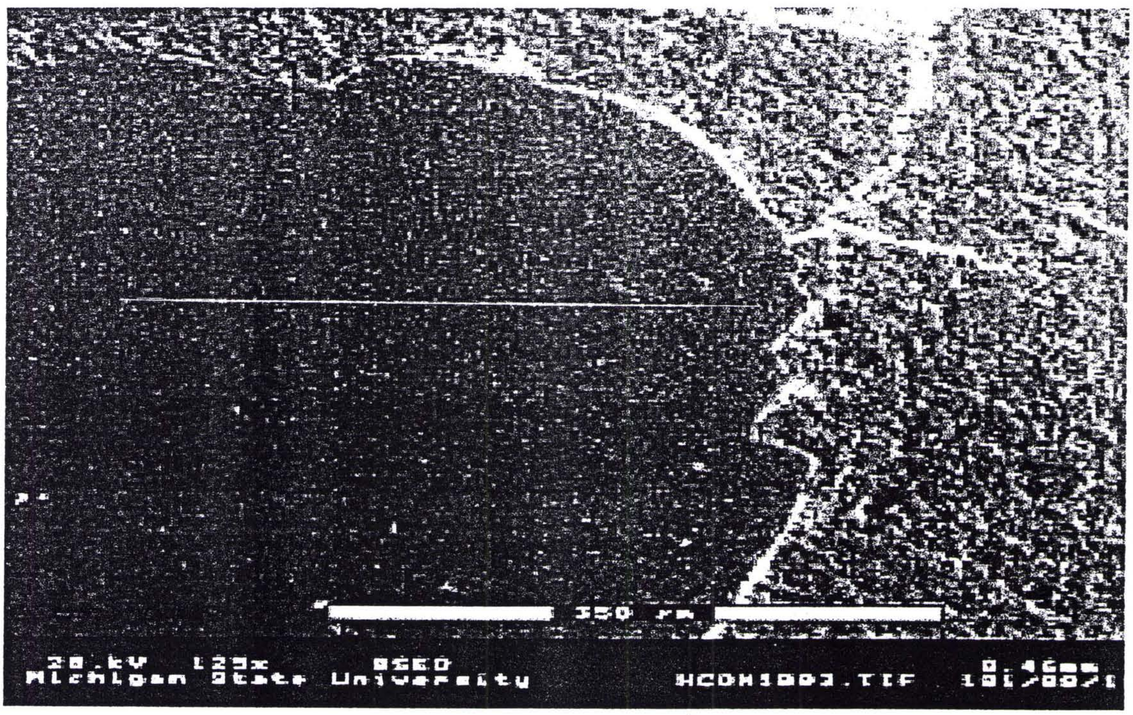

Plate 2.2: Scanning Electron micrographs for high Performance concrete: (Soroushian and Elzafraney 2003)

Table 2.1 Grades of performance characteristics for high performance structural concrete (http://www.fhwa.dot.gov/bridge/hpcdef.htm)

Performance characteristic	Standard test method	HPC performance characteristic grade		
		1	2	3
Freeze-thaw durability (F/t=relative dynamic modulus of elasticity after 300 cycles)	AASHTO T 161 ASTM C 666 Proc.A	70%≤F/T<80%	80%≤F/T<90%	90%≤F/T
Scaling resistance (SR=visual rating of the surface after 50 cycles)	ASTM C 672	3.0≥SR>2.0	2.0≥SR>1.0	1.0≥SR>0.0
Abrasion resistance (AR=avg. depth of wear in mm)	ASTM C 944	2.0>AR≥1.0	1.0>AR≥0.5	0.5>AR
Chloride penetration (CP=coulombs)	AASHTO T 277 ASTM C 1202	2500≥CP>1500	1500≥CP>500	500≥CP
Alkali-silica reactivity (ASR=expansion at 56 d)(%)	ASTM C 441	0.20≥ASR>0.15	0.15≥ASR>0.10	0.10≥ASR
Sulfate Resistance (SR=expansion)(%)	ASTM C 1012	SR≤0.10 at 6 months	SR≤0.10 at 12 months	SR≤0.10 at 18 months
Flowability (SL=slump,SF=slump flow)	AASHTO T 119 ASTM C 143,and proposed slump flow test	SL>190mm (SL>7-1/2 in),and SF<500 mm (SF<20 in)	500≤SF≤600 mm (20≤SF≤24 in)	600 mm<SF (24 in<SF)
Strength (f=compressive strength)	AASHTO T 22 ASTM C 39	55≤f<69 MPa (8≤f<10 Ksi)	69≤f<97 MPa (10≤f<14 Ksi)	97MPa<fc (14 Ksi<fc)
Elasticity (E=modulus of elasticity)	ASTM C 469	34≤E<41 GPa (5≤E<6x10 psi)	41≤E<48 GPa (6≤E<7x10 psi)	48 GPa ≤Ec (7x10 psi≤Ec)
Shrinkage (S=microstrain)	AASHTO T 160 ASTM C 157	800>S≥600	600>S≥400	400>S
Creep (C= microstrain/pressure unit)	ASTM C 512	75≥C>55/MPa (0.52≥C>0.38/psi)	55≥C>30/MPa (0.38≥C>0.21/psi)	30/MPa≥C (0.21/psi≥C)

- This table does not represent a comprehensive list of all characteristics that good concrete should exhibit. It does list characteristics that can quantifiably be divided into different performance groups. Other characteristics should be checked. One characteristic is sufficient for classification as an HPC.

- In the FHWA publication located at

  (http://www.fhwa.dot.gov/bridge/hpcdef.htm)

On the negative side it should be pointed out that high-performance concretes develop explosive failure that results in spalling of the skin of the concrete in reinforced columns, so provisions should be taken for this in codes. Finally, the fire resistance of high-performance concrete is still a very controversial issue.(Aitcin 1994)

Finally According to (Flaga 2000) all characteristics of high performance concrete can be summarized as follow:

(i) High compression strength;

(ii) Greater brittleness (and lower tensile strength in relation to compression strength);

(iii) Very low porosity and absorbability (about 3% by weight);

(iv) High durability and freeze resistance due to high tightness;

(v) Adhesion to the reinforcement increased by 40%;

(vi) Shrinkage and creep reduced by 50%; being completed to 70% as soon as the 7th day of curing;

(vii) Increased heat of cement hydration and

(viii) Reduced ®re resistance because of high tightness, which makes it impossible for the water contained in the hardened concrete to get out and causes its transformation into high-pressure steam during a fire. (Flaga 2000)

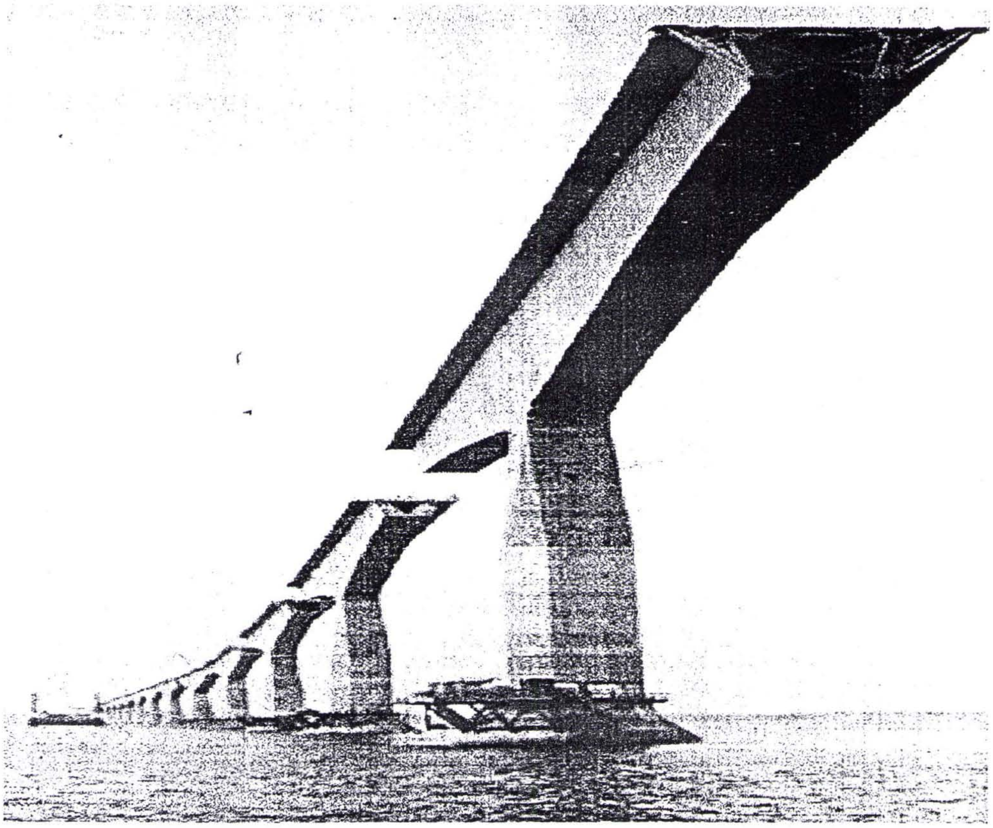

Plate 2.3 High performance concrete Confederation Bridge P.E.L

5.1. The properties of freshly mixed high performance concrete

(Zain, Safiuddin et al. 1999) showed that the properties of freshly mixed high performance concrete were determined in respect of slump, slump flow, V-funnel flow, air content, unit weight, and concrete temperature. These are given in Table 2.2. It was observed that the properties of fresh composite are interrelated, especially the two characteristic flows and the air content. The relationships between the two characteristic flows and the air content are shown in Figure 2.1 the average slump of different mixes was maintained between 23 and 25 cm by adjusting the mix proportions and dosages of superplasticizer and air entraining admixture. The average slump flow of the mixes was in the range