COMPARISON OF CONCRETE DURABILITY AS PRODUCED BY VARIOUS CEMENTS MANUFACTURED IN ETHIOPIA

BY

BIRHANU BOGALE

ADVISOR: DR.-ING. SURAFEL KETEMA

A thesis submitted to
the School of Graduate Studies of Addis Ababa University
in partial fulfillment of the requirements for the Degree of
Master of Science in Construction Technology and Management

February 2007

COMPARISON OF CONCRETE DURABILITY AS PRODUCED BY VARIOUS CEMENTS MANUFACTURED IN ETHIOPIA

BY
BIRHANU BOGALE

ADVISOR: DR.-ING. SURAFEL KETEMA

A thesis submitted to
the School of Graduate Studies of Addis Ababa University
in partial fulfillment of the requirements for the Degree of
Master of Science in Construction Technology and Management

February 2007

Addis Ababa University
School of Graduate Studies

COMPARISON OF CONCRETE DURABILITY AS PRODUCED BY VARIOUS CEMENTS MANUFACTURED IN ETHIOPIA

MSc Thesis

By

Birhanu Bogale

Approved by the Board of Examiners

Dr.-Ing. Surafel Ketema
(Advisor)
Surafel K. Dest

Dr.-Ing. Abebe Dinku
(Internal Examiner)
Abebe Dinku

Dr.-Ing. Adil Zekaria
(External Examiner)

Mr. Daniel Shawul
(Chairman)

ACKNOWLEDGEMENTS

First of all, I would like to thank my advisor **Dr.-Ing. Surafel Ketema** for his kind cooperation and constant encouragement. I am very grateful for his continual support starting from inception to the final completion of the work. I am also very pleased to thank Dr.-Ing. Abebe Dinku for visiting my laboratory works and giving me constructive suggestions. I am highly indebted to the steady assistance of the Department of Civil Engineering, Addis Ababa University.

In addition, I am extremely thankful to Varnero Construction PLC for providing me Mugher OPC for free in spite of its sheer shortage in the market then. I am also grateful to my friend Melesse Mamo and his colleague Solomon G/Mariam for their cordial support in facilitating the purchasing and transport of Dire Dawa PPC for this research work.

My profound gratitude also goes to the following people for their invaluable material as well as technical support which was extremely essential to my work.

- Ato Daniel Kifle and Ato Demessew Melaku - Department of Civil Engineering, Faculty of Technology, Addis Ababa University
- Ato Hintsaselassie Seifu and Ato Asteray Tsegaye - Department of Chemical Engineering, Faculty of Technology, Addis Ababa University
- Ato Sintayehu Chala and Ato Girum Ketema - Department of Electrical and Computer Engineering, Faculty of Technology, Addis Ababa University
- Ato Tesfaye Tefera - Department of Mechanical Engineering, Faculty of Technology, Addis Ababa University
- Dr. Ariaya Hymete and Ato Tadesse Gebregiyorgis - Department of Pharmachemistry, School of Pharmacy, Addis Ababa University

I would also like to thank all my friends especially Tadesse Yemane, Tewodros Alemu and Abel Shawel for their encouragement and supportive ideas. Last but not least, I am pleased to acknowledge the effort of my helpful and understanding family. I always thank God.

Birhanu Bogale
Addis Ababa, February 2007.

TABLE OF CONTENTS

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This research is intended to furnish comparative analysis on the effects of the different types of cements produced in Ethiopia on the durability characteristics of concrete prepared from the same. Several laboratory tests are conducted on concrete samples prepared from the various cements available in the country from different sources by keeping all the other ingredients the same. The methods of specimen preparation like mixing time and compaction effort and the subsequent curing condition are also kept identical for the different specimens. Therefore, in essence the study attempts to relate any variation in the durability characteristics of the samples to be obtained after testing only to the type of cement originally used in their preparation.

Critical review of related researches undertaken in the area reveals that under the same external environmental conditions, durability characteristics of concrete are affected by its microstructure. Concrete microstructure, which is its fundamental internal structure, in turn affects the transport phenomena taking place inside it. Hence, quantitative analysis of the various transport mechanisms in concrete is a direct lead to its ability to resist deterioration over time, which is its durability. Consequently, considering the capability of the laboratory and the available funding, three of the major transport mechanisms were selected and testing was conducted on concrete samples prepared from five cements obtained from three different sources to assess their level of variability. The results are then correlated with the possible influence of the different cements on the internal structure of the concrete samples and comparative analysis is carried out.

In addition, to illustrate the effects of varying cement content on each concrete sample, two types of mixes were prepared from each cement type, for normal and intermediate ranges of compressive strength, and the tests were also conducted twice at two different ages of the concrete specimens, 60 and 90 days. Besides, compressive strength measurements were taken alongside the durability tests at the ages of 56 and 91 days, in addition to, of course, the standard 28 days compressive strength test.

The results indicate that in some cases, there is a significant variation in some of the most critical factors which affect durability within samples prepared from the different cements from which reasonable proximity is expected. While anticipating exactly identical results is not rational, it's alarming to find variation of magnitude as high as 100% which reflects the need for more stringent quality checking and rigorous product standardization at the national level. It’s also imperative to seek ways of improving performance of such cements.

Key words: *Hydration, Permeability, Diffusion, Sorption, Porosity, Resistivity*

CHAPTER ONE
INTRODUCTION

1.1. Rationale for the research

Concrete has been and continues to be one of the most widely used construction materials throughout the world. The fact that it is economical and has several desirable engineering properties like high compressive strength which continues to grow with age, very good fire, chemical and radiation resistance, and reasonable water tightness, has made it an indispensable part of the construction industry at present. Although it has numerous advantages over other similar construction materials, it is not immune from failure and a combination of several factors can lead to its premature failure. And it is obvious that if it fails to satisfy either or both of the performance and serviceability requirements over the intended period, it entails a huge cost. The ability of concrete to withstand deterioration over time is called durability.

In earlier days, a number of researches have focused towards the development of better compressive strengths of concrete. However, huge financial losses have been witnessed in the world because of the fact that high strength concrete may not necessarily withstand deterioration resulting from exposure to aggressive environments and/or malicious internal reactions inside the concrete itself. Therefore, concrete durability is also becoming an essential element to be considered in the performance criteria of concrete recently.

In view of the above stated facts, researches undertaken in the country have been consulted and it was found out that recent study has been carried out on comparing the different properties of concrete prepared from various cements produced in Ethiopia (1). The study compares the compressive strengths of different concrete samples prepared from the various cements by conducting rigorous laboratory tests, and it suggests conducting durability testing as an area of further study. There is no any other study what so ever which attempts to assess the durability of concrete prepared from locally manufactured cements.

Furthermore, in recent years, concrete construction is intensifying in the country and unless the performance criteria for specifying concrete fulfill both the compressive strength and durability requirements, it's apparent that there will be dire repercussions. This makes the need for making scientific researches in the area coupled with practical viewpoints even more crucial.

It is with these underlying facts in mind that this topic has been selected for research. The study attempts to conduct actual laboratory investigations on concrete specimens prepared in the laboratory and analytical assessment of the major factors affecting concrete durability from the perspective of the test results.

1.2. Research goals

The study is aimed at conducting comparative analysis on the major factors affecting concrete durability as it is produced by the various cements manufactured in Ethiopia. Thus the main objective of the research is to arrive at the comparative effects each cement type imparts on durability characteristics of concrete prepared from that specific cement.

In fact specifically, the research tries to assess the different transport mechanisms in each concrete sample and therefore, primary data on the effects of cement type on the transport phenomena in concrete can be obtained from it. However, categorical assessment of the transport mechanisms leads to an understanding of the internal structure of concrete which in turn can be correlated with its long term durability behaviors. Therefore, the study is expected to yield the relative effect of each cement type on concrete durability as its title suggests.

1.3. Methodology of the research

To attain the stated objectives, the research basically focuses on laboratory investigations of concrete samples prepared from each cement source. The specimens are prepared in such a way that virtually everything other than the cement is kept identical for all the samples. This includes the types of coarse and fine aggregates and water to be used in the preparation of the mixes, the condition of the aggregates prior to mixing, the mix proportions, duration of mixing the ingredients, compaction effort during casting and the subsequent curing conditions. Also to keep the external conditions during mixing and casting the same, the activities were conducted at specific time of the day everyday.

The British DOE method was used in determining the mix proportions after all the required parameters have been obtained a priori. These include the sieve analysis of both the fine and coarse aggregates and their specific gravity. Normal (C-25) and intermediate (C-40) strength concretes were selected and trial mixes were prepared. Trial mixes were conducted in such a way that if the compressive tests were satisfied by at least one type of cement, the same cement content will be used for all the other mixes and their subsequent compressive strengths reported alongside. In preparing the trial mixes, it was attempted to avoid the use of admixtures and slump and compressive strength adjustments were made by varying the aggregate gradation instead. Normal tap water was used for all the mixes of course. All this is done to emulate the practice in the field as much as practicable, so that the results could closely signify what the actual practice yields.

Subsequent curing was carried out in a curing tank for 28 days to avoid minor discrepancies from the shortening of the curing period. The specimens are then kept inside the laboratory till the tests are conducted.

Parallel to preparing the specimens and conducting the laboratory tests, background study was also conducted in the form of literature reviews so as to correlate the expected results with their actual physical significance. In view of this, a number of textbooks and researches conducted in related areas have been reviewed.

1.4. Research contents

The research is organized in such a way that it can systematically convey the works undertaken and be clear and consistent in flow simultaneously, so that the reader can easily grasp the required targets.

The subsequent topics discuss literatures reviewed from different sources which are selected to be of paramount importance to interpret the final results. They are believed to provide the link between the quantitative results expected from the laboratory tests and their real physical implications. They are classified in three chapters to systematically guide the reader from the basic concepts to the fundamental hypotheses in understanding the nucleus of the problem.

The next chapter discusses the laboratory tests undertaken starting from material preparation for making the samples, to making ready and preconditioning of the samples required for the durability tests. This will be immediately followed by the test results and their analysis.

Finally the thesis discusses the results of the analysis by incorporating the theoretical concepts reviewed in the literature survey. Conclusion and suggestions for further study are also forwarded at last.

CHAPTER TWO
CEMENT AND CONCRETE

2.1. General

It is believed that concrete has been used as a construction material for more than 2000 years now. Although the use of other construction materials like steel and various hybrid materials is increasingly being practiced nowadays, concrete still continues to be one of the most widely used material in the construction industry. Especially in developing countries where alternative construction materials are in short supply and incur heavier costs, it is likely that concrete will remain to be the integral part of the construction sector. In such countries, as the construction sector constitutes a major part of their developing economy and consumes substantial portion of their budget, due emphasis should be given to the sector so that its benefits are properly exploited.

Concrete is prepared by mixing cement, coarse aggregate, fine aggregate and water in measured proportions. Depending on the need, air may be entrained in concrete and different admixtures may also be added to improve one or more of its engineering properties. Because concrete has a very low tensile strength, it is almost always reinforced with steel, and the two act in a collaborative manner to form what is known as reinforced concrete. The cement binds the different ingredients together and keeps them in plastic state until it hydrates progressively to such a level that the mixture completely turns to a solid state. Therefore, it can be said that cement is the fundamental component in the making of concrete and hence, it is essential to understand the properties of cement to properly comprehend and predict the behaviors of concrete associated with it.

2.2. Cement as concrete making material

As stated above, cement plays a central role in concrete by providing an inert medium (the cement paste) in the plastic state and by ensuring proper bonding between the different ingredients, and also with the reinforcement, after hardening. It is primarily prepared by combining predetermined proportions of calcareous material such as limestone or chalk and silica and alumina commonly found as clay or shale. These raw materials are ground into a very fine powder and burnt in a large rotary kiln at about $1400^{o}C$ temperature where they fuse and form clinker. The clinker is then cooled and ground to a very fine powder by adding gypsum to result in what is called Portland cement. The mixing and grinding of the raw materials can be carried out either in water or in a dry condition, accordingly, the processes are termed wet and dry processes respectively.

During manufacturing of Portland cement, the raw materials interact with one another in the kiln to form a series of more complex compounds. Four compounds are regarded as the major constituents in cement (2). These compounds are listed in Table 2.1 along with their commonly used abbreviated symbols.

Table 2.1. Main Compounds in Portland cement (2)

Name of Compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

The silicates C_3S and C_2S are the most important compounds which are responsible for the strength of hydrated cement paste. The presence of C_3A in cement is undesirable as it contributes little or nothing to the strength of cement except at early ages. Moreover, when hardened cement paste is attacked by sulphates, the formation of calcium sulphoaluminate (ettringite) may cause disruption. However, C_3A is beneficial in the manufacture of cement as it facilitates the combination of lime and silica. Compared to the other three compounds, C_4AF is present in cement in small quantities and it doesn't affect behavior of the cement significantly. However, it reacts with gypsum to form calcium sulphoferrite and its presence may accelerate the hydration of the silicates.

In addition to the main compounds listed in Table 2.1, there exist minor compounds in cement which amount to not more than a few percent of its mass, like MgO, TiO_2, Mn_2O_3, K_2O and Na_2O. Two of these compounds, Na_2O and K_2O, also known as the alkalis, are of interest as they affect the rate of gain of strength of the cement. Moreover, they have been found to react maliciously with certain types of aggregates at later ages of concrete forming expansive products which are capable of disintegrating the concrete.

By varying the proportion of the raw materials during the manufacture of cement and thus the resulting compound composition, and/or by using additives, it is possible to manufacture different types of cements which exhibit different properties. In fact there are several types of Portland cements available commercially and additional cements can also be produced for special purposes. Moreover, although they cannot be used as cements by themselves, some industrial products, notably ground granulated blast furnace slag (GGBS) and pulverized fuel ash (PFA) are also used to partially replace Portland cement during concrete making resulting in substantial improvements in the properties of concrete (3).

2.3. Hydration of cement

The development of microstructure of concrete is closely related to hydration of the cement. Hydration is the chemical combination of the different compounds in cement with water to form new compounds which, as time goes on, produce a firm and hard mass - the hardened cement paste. Although cement hydrates faster initially, the rate of hydration of cement decreases continuously so that even after a long time, appreciable amount of unhydrated cement remains in the concrete. Moreover, hardening of concrete will hardly continue after having been interrupted once and therefore, curing measures must start immediately after casting and should never be interrupted (2,4).

The two calcium silicates, C_3S and C_2S, which are the main cementitious compounds in cement, hydrate to form the compounds calcium hydroxide and calcium silicate hydrate (previously called tobermorite gel). Hydrated Portland cement contains 15% to 25% calcium hydroxide and about 50% calcium silicate hydrate by mass. It is the calcium silicate hydrate that primarily determines the strength and other properties of hydrated cement. C_3A reacts with water so rapidly that it leads to flash set, which is actually prevented by adding gypsum to the cement clinker. It thus reacts with water and calcium hydroxide to form tetracalcium aluminate hydrate. And C_4AF reacts with water to form calcium aluminoferrite hydrate. Hydration of cement is a complicated process and these reactions represent only the basic compound transformations. They are summarized in Table 2.2, and Figure 2.1 shows estimates of the relative volumes of the compounds in hydrated Portland cement pastes (4).

Table 2.2. Portland cement compounds hydration reactions (4)

$2(3CaO.SiO_2)$ Tricalcium silicate	$+ 11H_2O$ Water	$= 3CaO.2SiO_2.8H_2O$ Calcium silicate hydrate (C-S-H)	$+ 3(CaO.H_2O)$ Calcium hydroxide
$2(CaO.SiO_2)$ Dicalcium silicate	$+ 9H_2O$ Water	$= 3CaO.2SiO_2.8H_2O$ Calcium silicate hydrate (C-S-H)	$+ CaO.H_2O$ Calcium hydroxide
$3CaO.Al_2O_3$ Tricalcium aluminate	$+ 3(CaO.SO_3.2H_2O)$ Gypsum	$+ 26H_2O$ Water	$= 6CaO.Al_2O_3.3SO_3.32H_2O$ Ettringite
$2(3CaO.Al_2O_3)$ Tricalcium aluminate	$+ 6CaO.Al_2O_3.3SO_3.32H_2O$ Ettringite	$+ 4H_2O$ Water	$= 3(4CaO.Al_2O_3.SO_3.12H_2O$ Calcium monosulphoaluminate
$3CaO.Al_2O_3$ Tricalcium aluminate	$+ CaO.H_2O$ Calcium hydroxide	$+ 12H_2O$ Water	$= 4CaO.Al_2O_3.13H_2O$ Tetracalcium aluminate hydrate
$4CaO.Al_2O_3.Fe_2O_3$ Tetracalcium aluminoferrite	$+ 10H_2O$ Water	$+ 2(CaO.H_2O)$ Calcium hydroxide	$= 6CaO.Al_2O_3.Fe_2O_3.12H_2O$ Calcium aluminoferrite hydrate

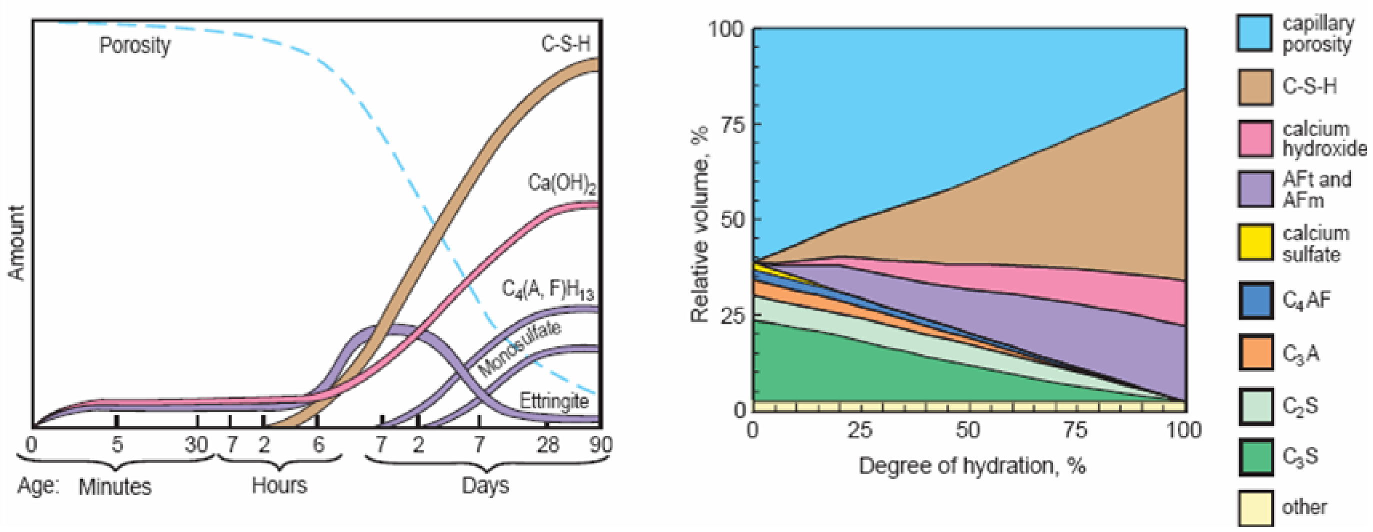


Figure 2.1. Relative volumes of the major cement compounds in the microstructure of hydrating Portland cement pastes as a function of time and the degree of hydration (4)

Hydration of cement compounds is an exothermic reaction and the quantity of heat evolved upon complete hydration at a given temperature and per unit gram of unhydrated cement is called the heat of hydration. For the usual range of Portland cements, about one half of the total heat is liberated between 1 and 3 days, about three quarters in 7 days, and nearly 90% in 6 months (2). Table 2.3 shows the heat of hydration of pure cement compounds.

Table 2.3. Heat of hydration of pure compounds (2)

Compound	**Heat of hydration**	
	J/g	**Cal/g**
C_3S	502	120
C_2S	260	62
C_3A	867	207
C_4AF	419	100

It has to be noted that fineness of cement affects the rate of heat development but not the total amount of heat liberated, which can therefore be controlled by the quantity of cement in the concrete mix. In general, by reducing the proportions of C_3A and C_3S in cement, it is possible to reduce the rate as well as the total heat of hydration.

2.4. Cement production in Ethiopia

Due to the rise in concrete construction in Ethiopia, the demand for cement has been steadily growing over the past few years. There are however only three cement factories in the country operating at full capacity at present. Mugher and Messobo cement factories produce both Ordinary Portland and Portland Pozzolana cements (OPC and PPC) while the Dire Dawa cement factory produces only PPC. With the exception of their sheer scarcity, the Mugher and Messobo cements are distributed in the market here in Addis Ababa, but the Dire Dawa cement is distributed only in Dire Dawa and nearby localities and it is totally not available in the central market.

The annual production of both Mugher and Messobo cements nears 1.5 million tons, with Mugher slightly on the upperhand, while that of Dire Dawa is only around 100,000 tons. Of the total production of Mugher cement factory, about 15% is OPC and the rest PPC while Messobo produces OPC amounting to about a third of its total production. The pozzolan type in both the Mugher and Dire Dawa cements is predominantly pumice obtained from their respective nearby localities, but the Messobo factory employs mainly volcanic basalt which is in abundant supply in its vicinity (5,6). The other physical and chemical composition of the cements is summarized in Table 2.4.

Table 2.4. Composition and properties of cements produced in Ethiopia (1)

Cement Source	**Mean Chemical Oxides of Clinker (%)**					
	CaO	**SIO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**
Mugher	65.61	21.26	5.76	3.79	0.95	1.08
Messobo	66.36	21.50	5.21	4.03	1.26	0.68
Dire Dawa	65.81	22.31	4.95	4.03	1.84	0.70
Cement Source	**Mean Chemical Compounds of Clinker (%)**					
	C_3S	**C_2S**	**C_3A**	**C_4AF**	**Total**	**% of Silicates**
Mugher	58.3	17.0	8.9	11.5	95.7	75.3
Messobo	64.0	13.3	7.0	12.3	96.6	77.4
Dire Dawa	57.4	20.7	6.3	12.3	96.6	78.1
Cement Source	**Mean Chemical Oxides of OPC (%)**					
	CaO	**SIO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**
Mugher	63.38	21.36	4.89	3.92	1.27	2.54
Messobo	63.94	20.50	4.75	3.70	1.31	2.41
Cement Source	**Mean Chemical Compounds of OPC (%)**					
	C_3S	**C_2S**	**C_3A**	**C_4AF**	**Total**	**% of Silicates**
Mugher	50.04	23.48	6.32	11.91	91.76	73.52
Messobo	60.41	13.19	6.32	11.27	91.20	73.61
Cement Source	**Mean Chemical Oxides of Pozzolana (%)**					
	SIO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**
Mugher	64.58	2.27	0.97	4.04	15.17	0.00
Messobo	54.80	8.83	10.55	8.14	6.22	0.03
Dire Dawa	68.10	11.32	4.82	1.50	0.63	0.00

Cement Source	**Mean of Pozzolana included in PPC (%)**	**Mean gypsum content in cement (%)**	**Pozzolana type**	**Cement type produced**	**Specific Gravity**
Mugher	28.3	4 - 5	Pumice	OPC	3.15
				PPC	N/a
Messobo	25.0	5	Volcanic basalt	OPC	3.15
				PPC	2.75
Dire Dawa	25.0	5	Pumice	PPC	N/a

CHAPTER THREE
MICROSTRUCTURE OF CONCRETE

3.1. General

Durability of hydraulic cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Durable concrete will retain its original form, quality, and serviceability when exposed to any environment.

Concrete durability is closely associated with the transport of aggressive species across it and such transport occurs through a network of openings that exist in the cementitious matrix, the aggregate cement interface and even the aggregates themselves. The nature of the voids determines the rate of intrusion as well as the magnitude of aggressive species that can enter and cause potential disruption of the mass. Therefore, it is essential to study microstructure of concrete to predict its capability of transporting those destructive agents and predict its long term durability behaviors.

Concrete is a composite material and hence its microstructure is random over a wide range of magnitudes. Concrete can be generally considered as a mortar-rock composite and mortar itself as cement paste-sand composite. Thus, the degree of randomness in the internal structure of concrete is in the order of centimeters, typical size of a coarse aggregate, and that in mortar is in the order of millimeters.

Cement paste can also be considered as a composite material made up of unreacted cement, calcium silicate hydrate (C-S-H), calcium hydroxide (CH), the voids inside and other chemical phases. The randomness in the structure of cement paste is on the order of micrometers. And a close examination of the C-S-H phase itself reveals that it is a complex material with a random structure, the randomness being on the order of nanometers. Hence characterization of the microstructure of concrete is a large and difficult task (7).

Microstructure development in concrete is a direct result of a series of complex processes taking place during mixing and placing including the hydration reactions. Once the anhydrous cement phases are mixed with water, the developing hydrates fill the space between the solids, which was originally occupied by the water. And the amount of space occupied by the water is related to the original water-cement ratio (w/c). For example, assuming the density of cement to be 3.3g/cc and that of water to be 1.0g/cc, a Portland cement paste with a w/c of 0.5 contains 62% by volume of water and therefore has 62% by volume of original porosity. Similarly, a paste with a w/c of 0.3 has 50% by volume of original porosity. It is therefore obvious that the less space to fill and the denser the microstructure, the stronger the resulting product would be.

As it is discussed in the previous chapter, as the hydration reaction continues, the developing hydration products become denser, porosity decreases, and physical and mechanical performance properties increase. However, the picture becomes more complicated at the interfacial zones in concrete and the interaction of hydrates with non-reactive aggregates found in mortars and concrete is also not well understood.

The interfacial zone occupies as much as one third to one half of the total volume of hardened cement paste in concrete and is known to have a different microstructure from the bulk of the hardened cement paste. It is also the probable location for early microcracking. For these reasons, the interfacial zone is expected to contribute significantly to the transport processes in concrete. However, as continuity of the pores is essential to allow movement, the bulk of the hardened cement paste also controls the transport phenomena as it is the only continuous phase in concrete (2). Therefore, all transport mechanisms are a function of the pore structure and crack configuration, and are determined by the same processes. Moreover, the rate, extent and effect of the transport processes are also dependent on the microclimate at the concrete surface.

3.2. Pore structure of concrete

For a characterization of the open pore structure with regard to the transport of substances into and within porous building materials, two parameters will be of importance: open porosity and pore size distribution (2,8,9).

Open porosity means pores which are interconnected so that transport of liquids or gases and/or the exchange of dissolved substances is possible. It corresponds to the maximum reversible water content and, in the case of cement paste, lies in the region of 20-30%.

The pore size distribution particularly influences the rate of the transport. The sizes of pores in the cement paste range over several orders of magnitude. According to origin and characteristics, the pores are described as compaction pores, air pores, capillary pores or gel pores. Expressed in more general terms, it appears to be convenient to classify them as macropores, capillary pores and micropores. Schematic representation of pore size distribution is shown in Figure 3.1.

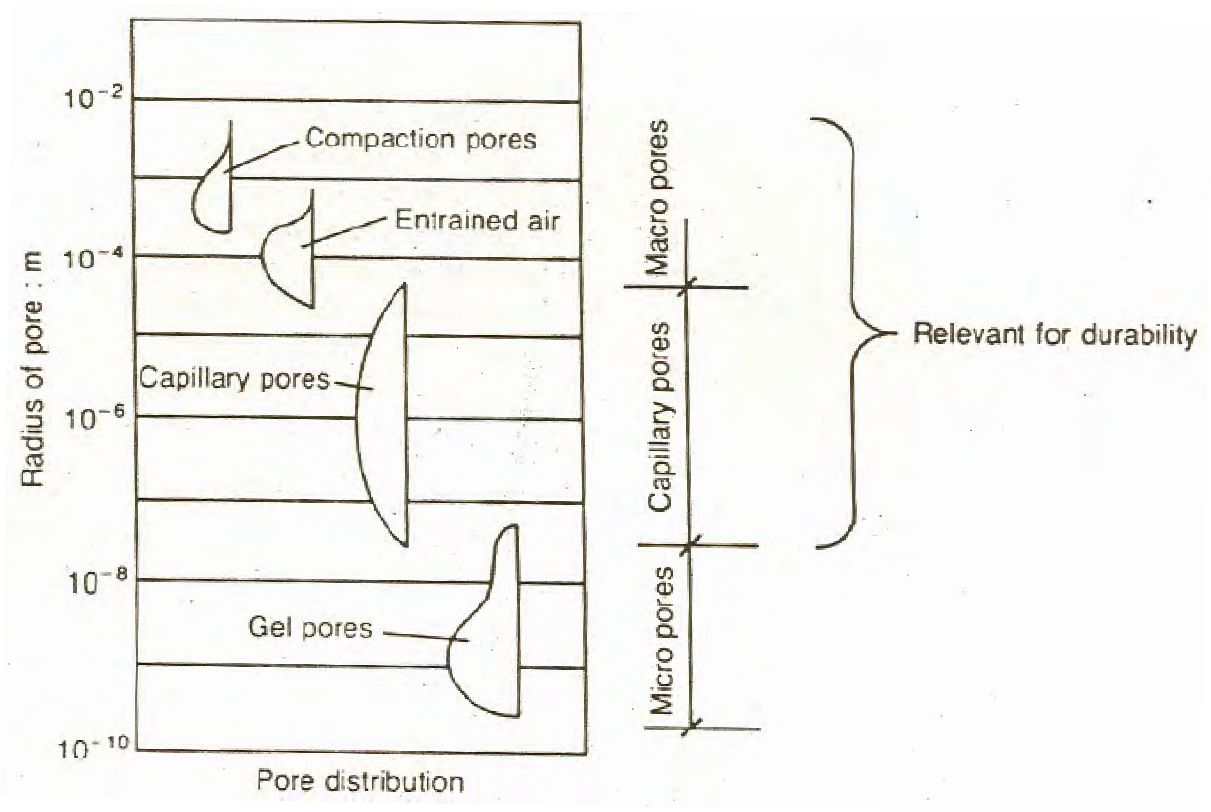


Figure 3.1. Pore size distribution in a cement paste (7)

3.3. Categorization of pores

Even though the degree varies, virtually every concrete contains some amount of pores. Leaving other factors aside, the hardened cement paste formed as a result of the hydration reactions itself always contains interconnected pores of different sizes. As discussed in the preceding section, the pores can be divided into macropores, capillary pores and micropores (gel pores).

Micropores are the interlayer spaces within the calcium silicate hydrate (C-S-H) gel, which have a volume equal to about 28% of the gel. Their dimension ranges between 0.5nm and 2.5nm. These pores have very little impact on the durability of concrete and its protection of the embedded reinforcement because they are too small to allow significant transport of aggressive agents. However, they can influence transport of ions by diffusion, and other properties of concrete like shrinkage and creep (3,8,10).

It is estimated that anhydrous Portland cement requires a space of approximately twice its volume to accommodate the hydration products. Capillary pores are thus the voids left unoccupied by the solid products of hydration in hardened cement paste. In well hydrated cement paste produced using low water-cement ratio, capillary pores have a dimension ranging from 10nm to 50nm; however, for higher water-cement ratio and if the cement paste is not well hydrated, their dimension can reach up to 3-5μm.

Macropores are larger pores of dimension up to a few millimeters and are the result of air entrapped during mixing and not removed by compaction of fresh concrete. Air bubbles with diameters of about 0.05-0.2mm may also be introduced in the cement paste intentionally by means of air entraining admixtures so as to improve some properties of the concrete like resistance to freeze-thaw action.

The capillary pores and macropores are particularly relevant with regard to durability, and in general, the resistance of concrete to chemical and physical influence is considerably reduced with increasing quantity of capillary pores. Summarized categorization of the different pores is shown in Table 3.1. Figure 3.2 shows the development of hydration products of concrete in relation to porosity as hydration progresses and for varying water-cement ratios.

Table 3.1. Pores in hardened Portland cement paste (3)

Designation	Diameter	Description	Origins
Macropores	10,000-50nm (10-0.05μm)	Large capillaries Interfacial pores	Remnants of water filled space
Mesopores	50-10nm 10-2.5nm	Medium capillaries Small, isolated capillaries	Remnants of water filled space Part of outer product C-S-H
Micropores	2.5-0.5nm <0.5nm	 Interlayer spaces	Intrinsic part of C-S-H Intrinsic part of C-S-H

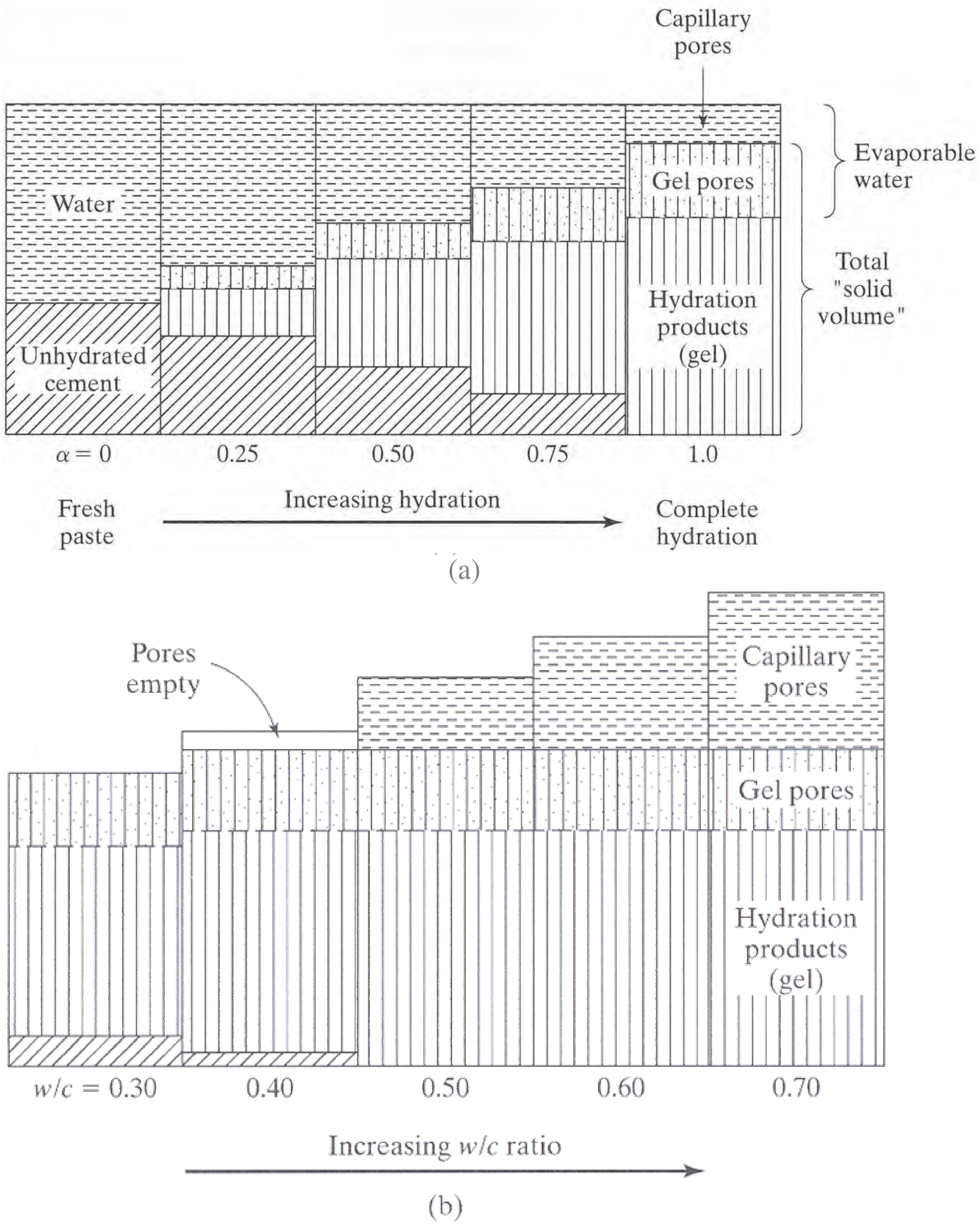


Figure 3.2. Volume relationship among constituents of hydrated cement pastes (a) constant water-cement ratio = 0.5 (b) Changing water-cement ratio (α = 1.0) (8)

3.4. Water-cement ratio and curing on porosity development

During the hydration of cement paste, the gross volume of the mixture practically does not change, so the initial volume, equal to the sum of the volumes of mixed water (V_w) and cement (V_c) is equal to the volume of the hardened product. As shown in Figure 3.3, this consists in the sum of the volume of cement that has not yet reacted (V_{uc}), the hydrated cement ($V_p + V_{gw}$), the capillary pores that are filled with water (V_{cw}) or with air (V_{ec}). As discussed earlier, the volume of the hydration products can be assumed to be roughly double that of the cement and therefore, if the cement is kept moist (curing), the hydration proceeds and the volume of the capillary pores decreases and will reach a minimum when the hydration of cement has completed.

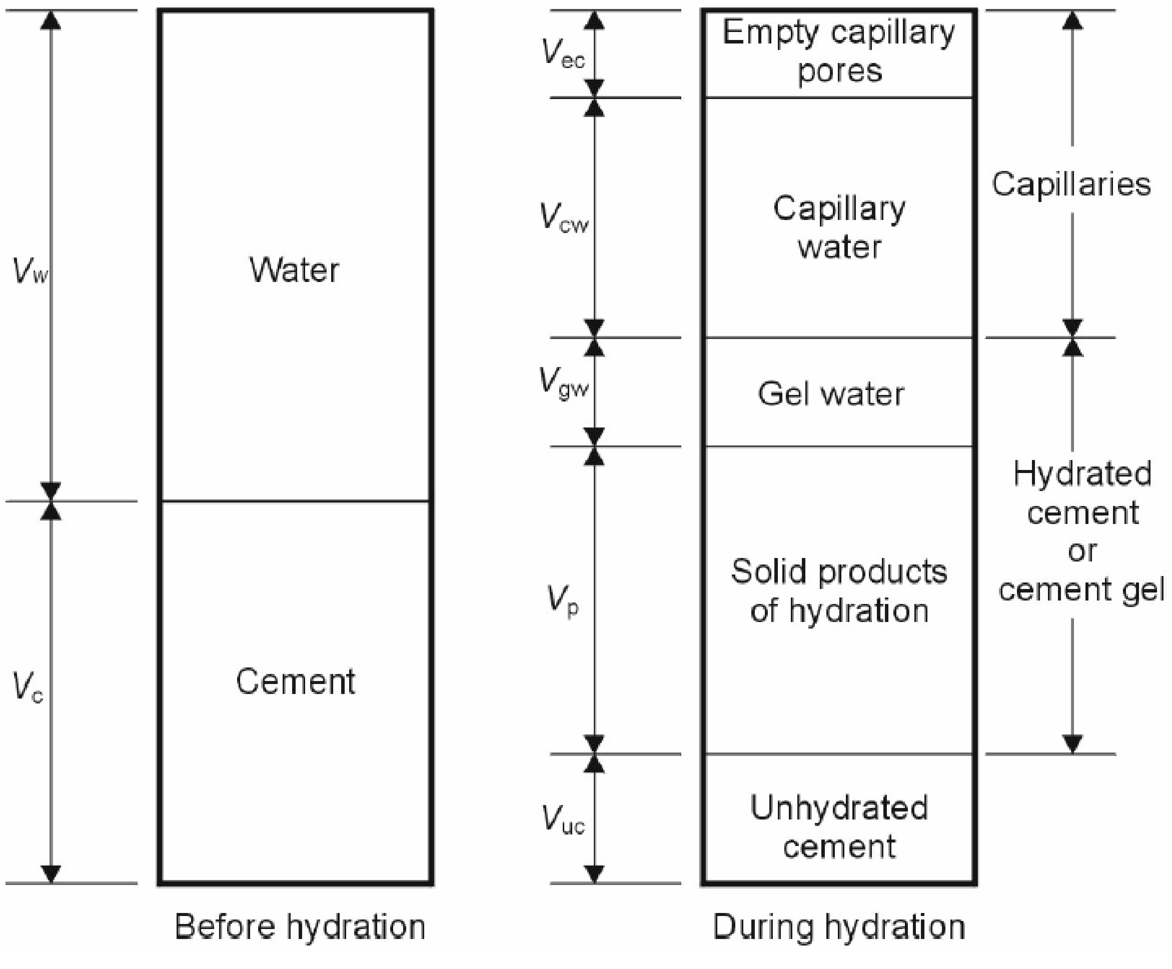


Figure 3.3. Schematic representation of the volumetric proportions in cement paste before and during hydration (9)

In general, the volume of the capillary pores in the cement paste increases with the amount of water used in the paste and thus with the water-cement ratio, and decreases with the degree of hydration. As the water-cement ratio decreases or as the curing time, and thus the degree of hydration, increases, the reduction of porosity is mainly due to the reduction in pores of larger dimensions that have been filled by C-S-H gel or have been connected only by C-S-H gel pores.

When concrete is considered instead of cement paste, the water-cement ratio and the degree of hydration remain the main factors that determine the capillary porosity. Nevertheless, concrete is more complex because of the presence of aggregates and the transition zone between aggregates and the cement matrix, where the structure of cement paste tends to be more porous.

3.5. Interaction between pores and water

Due to lack of binding components to the adjacent molecules, free surfaces of solids exhibit a surplus of energy. Thus, in cement paste pores, the surface energy on their outer layer causes the water vapor molecules entrapped with in the pores to adsorb onto the pore surface, the thickness of the water film depending on the degree of humidity within the pores. Due to the fact that the surface area to volume ratio of the pores increases with decreasing pore radius, the quantity of water adsorbed relative to the pore volume will also increase until, at a certain limit value of the pore radius, the pores with smaller radii are completely filled with water. This process is called capillary condensation. The limit value of the pore radius depends primarily on the water content of the air in the pore which, other factors being constant, is proportional to the humidity of the air surrounding the concrete.

As a result of the high proportion and small radii of the gel pores, concrete exhibits comparatively high water content even when the humidity of the surrounding air is relatively low. Increasing the humidity of the air will cause the larger pores to be filled with water, thus reducing the pore space available for the diffusion of gases. Consequently, the permeability of the concrete with regard to gases will decrease considerably with growing water content and, in the case of an almost water saturated concrete, the diffusion of gases like carbon dioxide and oxygen becomes practically negligible. Figure 3.4 illustrates the water binding phenomena in a simplified pore model.

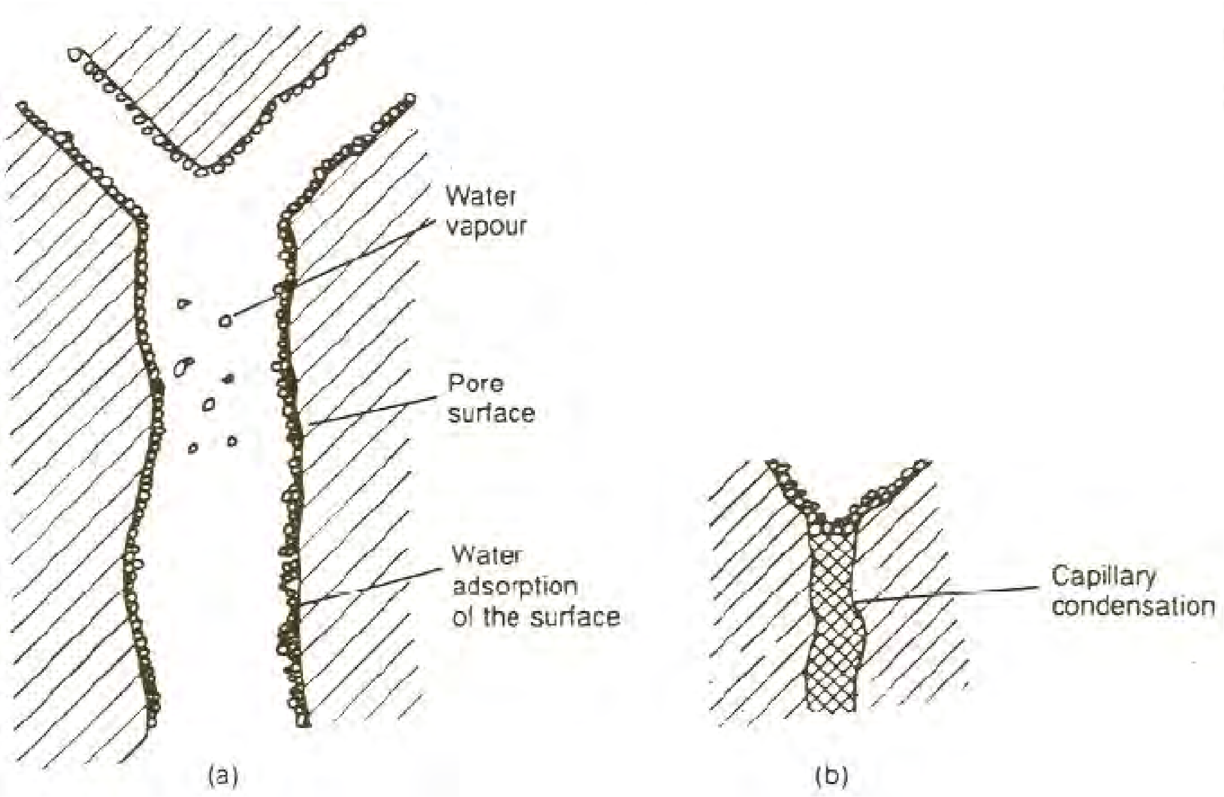


Figure 3.4. Simplified pore model showing binding phenomena: (a) water adsorption; (b) capillary condensation (7)

CHAPTER FOUR
TRANSPORT MECHANISMS IN CONCRETE AND THEIR MEASUREMENT

4.1. General

Concrete is a composite material and as discussed in the previous chapter, the complexity in its microstructure always makes it difficult to correlate microstructure and transport properties theoretically for concrete, even more challenging is to take the conceptual frameworks through to specific applications. Therefore, a thorough understanding of the major transport mechanisms is essential to outline how the spatial geometry of the microstructure affects the transport properties. In the end, it is these transport properties that significantly determine the service life and utility of concrete exposed to its natural environment.

A variety of transport mechanisms play an important role in the degradation of concrete. Although concrete is commonly thought of as inert or unchanging material, the ingress of potentially deleterious substances from the environment like chlorides, sulfates and even water, can cause considerable deterioration over its service life. It has to be noted here that in addition to the pore structure of concrete, pore radius or width of micro-cracks, a number of physical and/or chemical mechanisms may govern the transport of these agents into the concrete like the nature of the substance flowing and its local concentration, the environmental conditions, the degree of saturation of the pore system and the temperature. Hence, considering the possibility of variation of these factors over a wide range for different climatic exposure conditions, the transport of media into concrete in most cases is not due to one single mechanism and several mechanisms may act simultaneously. For experimental evaluation of the transport characteristics however, it is assumed that the movement is attributed to one single transport mechanisms in order to derive transport coefficients according to established theoretical models for the different transport mechanisms (7,9).

In this chapter, transport mechanisms that significantly affect the durability of concrete, mainly permeability, diffusion and capillary absorption are presented. Mathematical models and test methods pertinent to these transport phenomena are also discussed alongside. First though, the different forms of existence of water in concrete are discussed as water is the most important media for transport of the different species.

4.1. Water in concrete

Water may be present in the hydrated cement paste in many forms that may be classified on the basis of the degree of difficulty with which it can be removed (9).

Capillary water - is the water contained in capillary pores which accounts for the greatest part of water in concrete. As the pore water is composed of different ionic concentrations of a range of species, the aqueous solution contained in pores of larger than about 50nm diameter can be considered free of bonding forces with the solid surface. This water will evaporate without causing any significant shrinkage in the cement paste if the relative humidity of the air falls below 100%. Moreover, this free solution has transport properties analogous to those of a bulk solution. Water held by capillary tension in pores of diameter less than 50nm will evaporate at lower values of relative humidity; typically, values ranging from 95% to 60% are required as the diameter of the capillary pores decreases from 50nm to 5nm. In this case, evaporation can cause significant shrinkage and the mobility of ions is affected by chemical and physical interactions between the liquid and the solid and is therefore lower than that of a solution of the same composition.

Adsorbed water - is the water that remains adsorbed to the inner surfaces of capillary pores in the form of a very thin layer, even after water has evaporated from them. This water can be removed if the external relative humidity falls below 30% and it contributes little to transport phenomena. However, its removal causes shrinkage of the cement paste and influences creep behavior.

Interlayer water - is the water retained between the C-S-H layers which is removed if the external humidity falls below 11%. This water does not affect transport processes, nor does it influence shrinkage and creep.

Chemically combined water - is the water that is an integral part of the C-S-H gel or other hydration products which is not lost on drying. It can only be released when the hydrates decompose on heating to higher than 1000^{o}C and it does not contribute to any transport phenomena.

With regard to capillary pores, as discussed in section 3.5, water is first adsorbed on their surface and then, as the relative humidity increases, it condensates and fills up the pores, starting with the smallest and moving to those with larger dimensions. As shown in Figure

4.1, inside concrete that is exposed to the atmosphere of a certain relative humidity, pores whose diameters are below a given value turn out to be filled with water, while those with diameters above this value are filled with air.

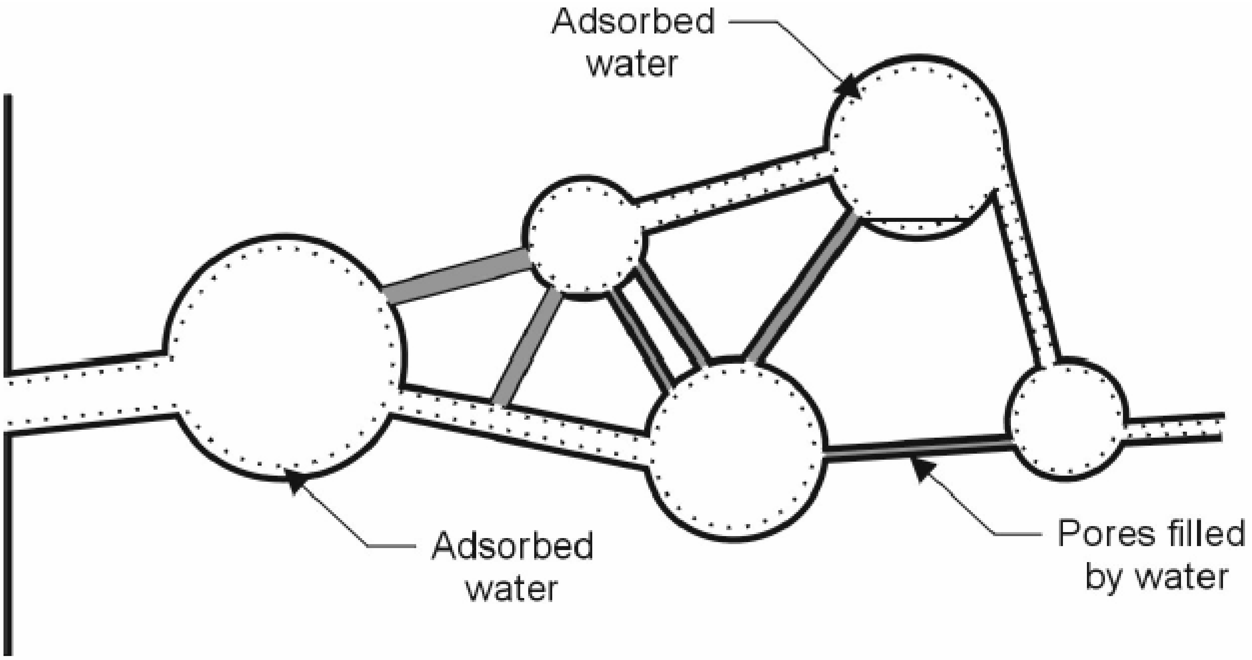


Figure 4.1. Representation of water present in capillary pores in concrete in equilibrium with non-saturated atmosphere (9)

4.2. Permeability

Permeability is the movement of fluids across a porous medium as a result of pressure gradient. Thus concrete permeability refers to its ability to transmit fluids through it caused by pressure head. It applies to the transport of both gases and liquids.

4.2.1. Gas permeability

For gases, both the viscosity as well as the compressibility of the gas affect coefficient of permeability. For the case of laminar flow, the coefficient of permeability is given by Equation 4.1 (2,7).

$$K_g = \eta \cdot \frac{Ql}{tA} \cdot \frac{2p}{(p_1 - p_2)(p_1 + p_2)} \quad \text{---------------------------- [4.1]}$$

Where K_g = *coefficient of permeability (m^2)*

η = *viscosity of the gas (Ns/m^2)*

Q = *volume of gas flowing (m^3)*

l = *thickness of penetrated section (m)*

A = *penetrated area (m^2)*

p = *pressure at which volume Q is measured (N/m^2)*

p_1 = *pressure at entry of gas (N/m^2)*

p_2 = *pressure at exit of gas (N/m^2)*

t = *time (s)*

The condition of laminar flow however does not necessarily prevail for the transport of gases through the pore system of the hydrated cement paste because of the wide range of pore diameters. Therefore, the coefficient of gas permeability has also been defined as shown in Equation 4.2. In this case, K_g is no longer a materials characteristic but depends on the transported medium.

$$\overline{K}_g = \frac{Q}{t} \cdot \frac{l}{A} \cdot \frac{p}{p_1 - p_2} \quad \text{-- [4.2]}$$

Where $\overline{K}_g$ = *coefficient of permeability (m^2/s)*

4.2.2. Water permeability

Water represents the most important liquid among those penetrating through concrete. Permeability of concrete is not a simple function of its porosity but depends also on the size, distribution, shape, tortuosity, and continuity of the pores. Thus, although cement paste has a porosity of 28% as discussed previously, its permeability is only about 7×10^{-16} m/s. This is due to the extremely fine texture of hardened cement paste. The pores and the solid particles are very small and numerous of course, but in rocks, the pores, though fewer in number, are much larger and lead to a higher permeability (it's worth mentioning here that the permeability of granite is almost the same as that of mature cement paste with a water-cement ratio of 0.7!). For the same reason, water can flow more easily through the capillary pores than through the much smaller gel pores. The cement paste is as a whole 20 to 100 times more permeable than the gel itself. Thus it follows that the permeability of hardened cement paste is mainly controlled by its capillary porosity.

Permeability in a fresh cement paste is controlled by the shape, size and concentration of the original cement particles and it decreases as hydration progresses with the gels filling the originally water filled space. Thus in a mature paste, the permeability depends on the continuity of the capillary pores and the size, shape and concentration of the gel particles.

Keeping other factors the same, permeability of a cement paste decreases with increasing cement content (i.e. decreasing water-cement ratio) and the reduction is even more substantial in concrete. Moreover, increasing the wet curing duration of concrete from 1 day to 7 days reduces its water permeability by a factor of 5.

The properties of cement also affect water permeability. For the same water-cement ratio, coarser cement tends to produce a hardened cement paste with a higher porosity than a finer one. The compound composition of the cement affects permeability in the same manner as it does the rate of hydration, the ultimate porosity and permeability remain unaffected however. As there are aggregates in concrete, the permeability of the aggregate itself affects permeability of the concrete as compared to a cement paste of the same water-cement ratio. If the aggregate has a very low permeability, its presence reduces the effective area over which flow can take place. Moreover, as the aggregate intercepts the flow, the effective path becomes considerably longer and therefore the presence of aggregates tends to reduce permeability of the concrete significantly. In a well compacted concrete, the cement paste envelops the aggregate particles and the interface zone does not contribute much to the flow. Therefore, the influence of the aggregate is small and generally it is the permeability of the hardened cement paste that has the greatest effect on that of the concrete (2).

Permeability of concrete is of concern in relation to water tightness of liquid retaining and other similar structures. It is also related to the problem of hydrostatic pressure in dams. Moreover, the ingress of moisture into concrete affects its thermal insulation properties. In the laboratory, permeability of concrete can be evaluated under both steady state and non-steady state conditions.

Steady state water permeability

In this case, water is allowed to move across the specimen until steady state flow is attained. This is done by subjecting the specimens to specific pressures and recording the penetrated water until constant flow of water is obtained. The coefficient of permeability is then calculated by using Darcy's law as shown in Equation 4.3 (11,12).

$$K_w = \frac{Q}{t} \cdot \frac{l}{A} \cdot \frac{1}{\Delta p} \quad \text{-- [4.3]}$$

Where K_w = *coefficient of water permeability (m/s)*

Q = *volume of water flowing* (m^3)

t = *time (s)*

l = *thickness of penetrated section (m)*

A = *penetrated area* (m^2)

Δp = *pressure head (m)*

Non-steady state water permeability

In this case, the depth of water penetration is measured without the water flow necessarily reaching steady state. Figure 4.2 below shows the setup for running this test. A succession of water pressure is applied across the specimen as follows (ISO/DIS/7031) (12):

- 0.3MPa (3Bar) for the first 24 hours,
- 0.5MPa (5Bar) for the next 24 hours, and
- 0.7MPa (7Bar) for the last 24 hours.

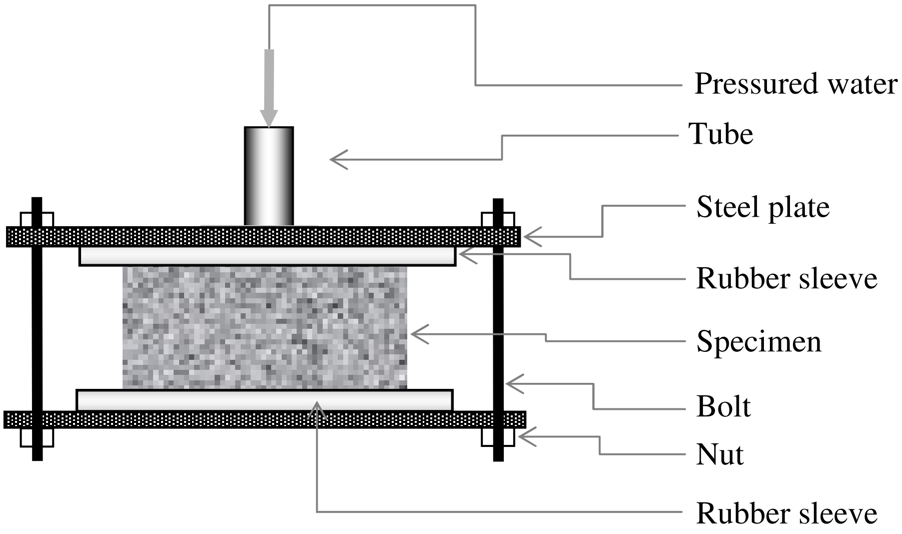


Figure 4.2. Setup for water penetration test

At the end of the 72 hours period, the specimens are removed from the rig and split at the center as shown in Figure 4.3. Just after splitting, the maximum and average depths of penetration are visually observed and measured (11,12).

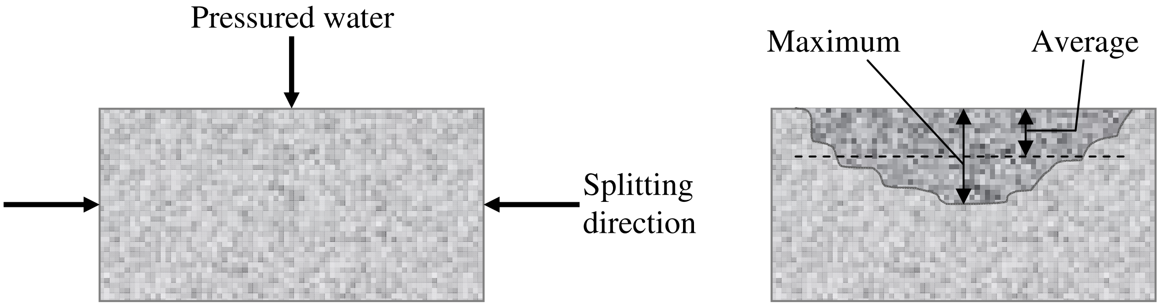


Figure 4.3. Splitting and measurement of penetration depth

4.3. Capillary absorption

Capillary absorption, also known as capillary suction or sorption, is the transport of liquids in a porous medium due to surface tension acting in capillaries. The transport of liquids by sorption is influenced by the viscosity, density as well as surface tension of the liquid. The characteristics of the medium like pore structure (size and continuity of capillaries), surface energy and the angle of contact between the liquid and the pore walls also affect capillary absorption. The local capillary force is inversely proportional to the pore diameter with smaller pores exerting a larger capillary force, although the rate of ingress into a smaller pore will actually be less than that into a larger one due to increasing friction. In general, under normal range of compositions, a more porous concrete absorbs more water and faster than a dense concrete (9,13).

Capillary absorption is an important mechanism by which the ingress of chlorides into concrete can take place. Non-saturated concrete in contact with a salt solution will take up the salt solution by capillary forces, thus chlorides can penetrate into the concrete much faster than by diffusion alone. Simultaneously, chlorides are transported by diffusion consequently increasing the depth of penetration. This is a typical example of mixed mode of transport which takes place by the simultaneous action of diffusion and capillary suction, notably more effective than the single transport process alone.

Parameters obtained from the water suction test are widely used as a general indicator of concrete quality. In general, a relationship between absorbed amount of water and square root of time exists even though the relationship varies for high strength concrete. Moreover, in concrete with low water-cement ratio, the square root relationship is changed to a power relationship with exponent lower than 0.5 (9,11,12).

The capillary suction test is conducted in the laboratory on 25mm thick concrete disks cut from cylindrical specimens (Nordtest method – NT BUILD 368). Initially, the slices are dried at 105°C for 24 hours to constant weight and then kept in desiccator for another 24 hours to naturalize the moisture distribution inside them. Then the specimens are exposed to water on one side as shown in Figure 4.4 and the surface dry weights were recorded at regular intervals for a couple of days until constant weight is approached (11,12).

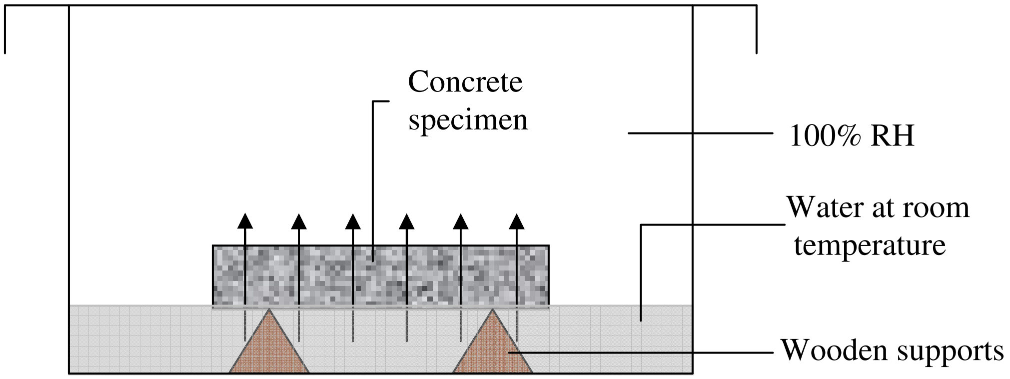


Figure 4.4. Exposure of a test specimen for capillary absorption test

Depending upon quality of the concrete, the time required for the water to reach the top surface of the samples varies. The weight gained at scheduled time intervals per unit cross sectional area of the specimens is calculated from the recorded data and then plotted against square root of time. A typical capillary absorption versus square root of time plot is shown in Figure 4.5.

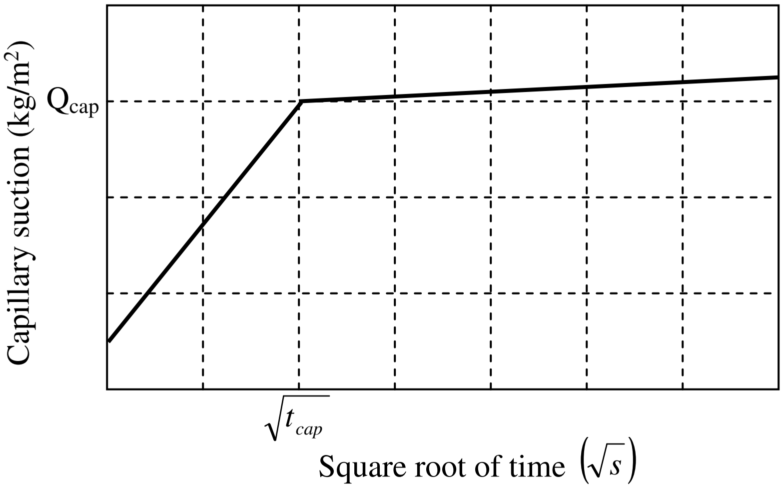


Figure 4.5. Relationship between capillary suction and square root of time

The crossing point of the two lines, which are obtained by regression analysis, represents the time t_{cap}, when the capillary pores are filled and the waterfront reaches the top, and Q_{cap}, the amount of water absorbed per unit area in a period of time t_{cap}, after which a distinct change in the rate of water absorption occurs. This is because, after t_{cap} is reached, water is successively sucked up through the smaller voids.

In the first phase of water absorption up to the nick point as shown in Figure 4.5 the amount of water absorbed follows the general equation of capillary rise. The capillary number (k) which is the rate of capillary absorption is then calculated as the slope of the first linear regression line as shown by Equation 4.4 (11,12).

$$k = \frac{\partial M / A}{\sqrt{\partial t}} = \frac{Q_{cap}}{\sqrt{t_{cap}}} \quad \text{--} \ [4.4]$$

Where k = *capillary number (kg/m$^2\sqrt{s}$)*

M = *mass of absorbed water (kg)*

A = *sample surface area exposed to water (m^2)*

t = *time (s)*

Q_{cap} = *rate of capillary absorption (kg/m^2)*

t_{cap} = *the time when the capillary pores are filled and the waterfront reaches the top (s)*

In addition, another parameter called the capillary resistance number (m), which is given by Equation 4.5, describes the relative time that the waterfront needs to reach the top of the specimen.

$$m = \frac{t_{cap}}{h^2} \quad \text{--} \ [4.5]$$

Where m = *capillary resistance number (s/m²)*

h = *height of the specimen (m)*

The capillary number and the resistance number practically convey the same type of information for a typical concrete quality. Both are related to the time for a very well defined change in the rate of water absorption (t_{cap}), and in general reflect the size, distribution and continuity of the capillaries. However, since the capillary number depends on the pore volume of the concrete and thereby the portions of the cement paste, the resistance number is a more consistent parameter to describe concrete quality (12).

Another qualitative measurement of the concrete quality is its porosity or the percentage of space in the concrete which is occupied by pores and thus can absorb water. It is usually expressed in percent. If the porosity is high and the pores are interconnected, they contribute to the transport processes, however, if they are discontinuous or otherwise (blind pores), they are ineffective with respect to the transport phenomena.

The same measurements that are used for the water suction test could be used to get information on the porosity of the concrete. After taking the last measurement for the water suction test, the specimens are immersed under water for further 3 days to ensure complete saturation and their weight is taken at the end under saturated and surface dry (SSD) condition. Then the specimens are further saturated under a pressure of 5MPa for 24 hours and again their SSD weights are recorded. The volume of the specimens is also determined finally by measuring their weight suspended in water.

Thus, besides the parameters obtained previously, the suction porosity, total porosity and air porosity of the samples can also be calculated using Equations 4.6, 4.7 and 4.8 respectively (11,12).

$$\varepsilon_{suc} = \frac{W_1 - W_0}{V} \cdot 100 \quad \text{--} \ [4.6]$$

$$\varepsilon_{tot} = \frac{W_2 - W_0}{V} \cdot 100 \quad \text{--} \ [4.7]$$

$$\varepsilon_{air} = \frac{W_2 - W_1}{V} \cdot 100 \quad \text{--} \; [4.8]$$

Where ε_{suc} = *suction porosity (%)*

ε_{tot} = *total porosity (%)*

ε_{air} = *air porosity (%)*

W_0 = *weight of oven dry specimen at 105^{o}C (kg)*

W_1 = *weight after three days immersion in water (kg)*

W_2 = *weight after pressure saturation (kg)*

V = *volume of the specimen (lt)*

It should however be noted here that the actual values obtained from the capillary suction test depend on various factors, the main one being the degree of drying to which the samples have been subjected at the start of the test. If the concrete specimens are only partially dried before testing, it has been found out that it would be too difficult to control both the initial moisture content, and the distribution of the moisture. And if the initial moisture content varies from one concrete sample to the other, the resulting suction parameters may not be comparable. In addition, if the initial moisture content is too high, investigations have shown that the capillary absorption may not necessarily follow the square-root-of-time-law discussed earlier. This is the reason for drying the specimens at 105^{o}C to constant weight. Nevertheless, oven drying at such a high temperature may modify the water content in the hydration products, thus altering the microstructure of the C-S-H and other phases, and may also cause microcracks that favor capillary absorption. Yet, it's generally accepted that the coarser capillary pores which mainly control the water absorption up to the nick-point will not be significantly affected by such drying.

Other methods of drying may give results that more closely reflect real behavior of concrete, but they require much longer times. For instance, a procedure designed to resemble atmospheric exposure of concrete in practice as much as possible, involves four weeks of drying in a climate room with air of 20^{o}C and 65% relative humidity before commencement of the test. Another procedure for tests on repair materials suggests oven drying at 40^{o}C. This method of drying is probably the best compromise between establishing a well-defined and low-moisture condition and avoiding damage to the microstructure. In any case, should microcracking be unavoidable, this effect by itself can as well be considered as a general quality assessment (9,11).

4.4. Diffusion

Diffusion is the transport of aggressive species through concrete as a result of concentration gradient. Several ions and gasses diffuse through pores from the surface where they are present in higher concentrations, to internal zones where their concentration is normally lower. These include mainly O_2, CO_2, Cl^- and/or $SO_4^=$ and the like. The rate of diffusion of gases through open pores is higher than that through water-saturated pores. In water, gas diffusion is 4-5 orders of magnitude slower than in air (2,9). On the other hand, chloride and sulfate ions diffuse only when dissolved in pore water and their diffusion is more effective in saturated than in partially saturated pores.

The diffusion of carbon dioxide and oxygen in concrete has remarkable effect in terms of concrete durability. Carbon dioxide causes the carbonation of hydrated cement paste, where as oxygen is responsible for the progress of corrosion of the embedded steel reinforcement. The intrusion of chloride ion is also the cause of chloride attack of the steel inside. Sulfate attack of concrete is the result of ionic diffusion of sulfates into it.

Similar to permeability, diffusion is lower at lower water-cement ratio, but the influence of water-cement ratio on diffusion is much smaller than that on permeability. There are several methods to measure diffusion in the laboratory. Most commonly, diffusion of chloride ions is considered because chloride ions are classified as being most mobile, and it is one of the reasons for relatively rapid concrete corrosion when the material is in contact with chloride containing water (3). Diffusion of chloride ions can be measured by using the ponding test or other accelerated test methods. Ponding test however requires 90 days, often taking several months and even years to obtain the results. Therefore, rapid chloride penetration test is conveniently used to get a quick indication of the resistance of the concrete to the penetration of chloride ions under non-steady state condition (15).

The test is carried out by using concrete specimens of 60mm height cut from cylindrical samples. The actual test setup used in this study is shown in Figure 4.6. The samples are first saturated in water for 24 hours and then assembled in a rubber sleeve and tightened. Leakage through the rubber sleeve is checked by filling it with water prior to commencement of the test. The assembled specimens are then suspended inside a catholyte reservoir filled with 2N NaCl solution. The sleeve is then filled with a volume of approximately 300ml of anolyte solution of 0.3N NaOH. The anode is immersed in the anolyte solution and the cathode in the catholyte solution. Then the cathode is connected to the negative pole and the anode to the positive pole of the power supply and 30V potential was applied. The temperature, electrical resistance of the concrete specimens and current flow were recorded at the beginning and completion of the test.

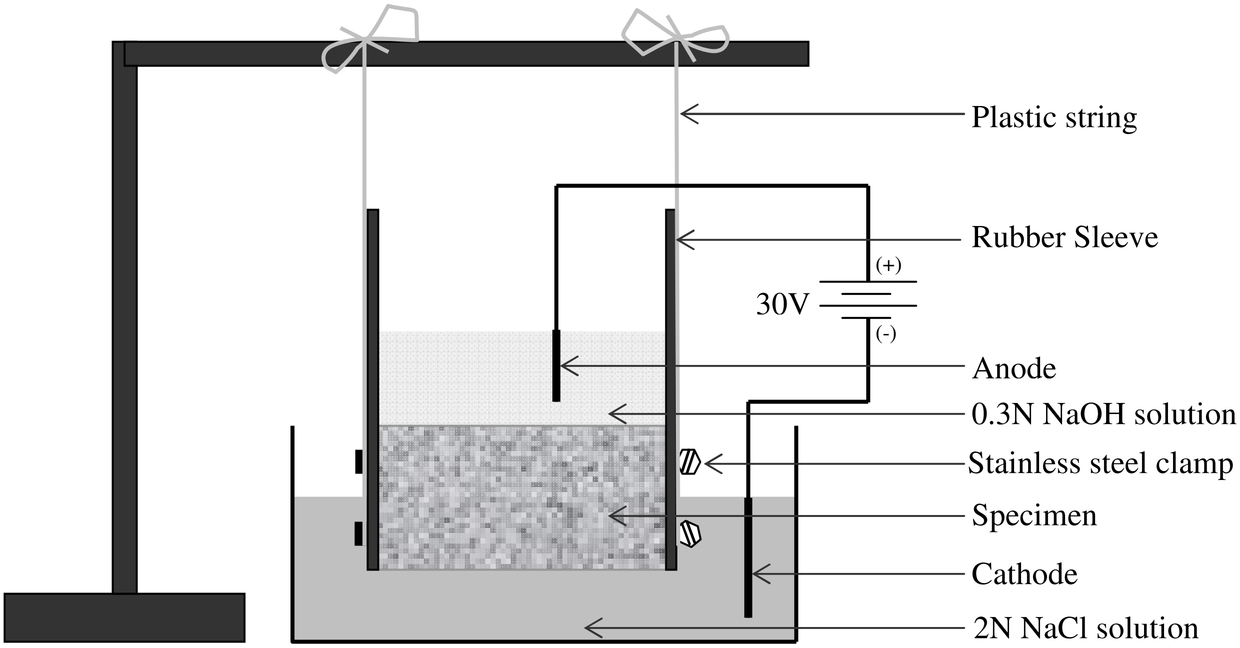


Figure 4.6. Setup for chloride migration test

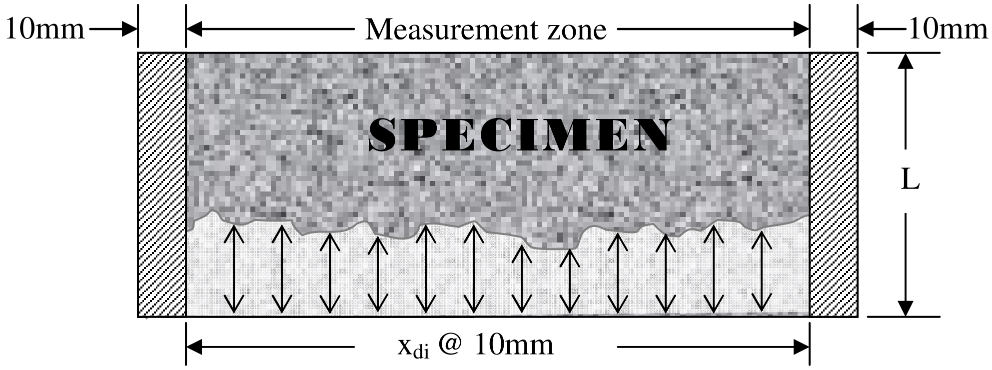


Figure 4.7. Measurement of chloride penetration depths

The specimens are normally kept for 6hr duration and at the end of the test period, they are removed from the rubber sleeve and rinsed with tap water. The excess water from the surface of the specimens is wiped off and the surface dry specimens are then split at the center into two pieces. A 0.1M $AgNO_3$ solution is then sprayed on the freshly split surface. When a silver nitrate solution is sprayed on a concrete containing chloride ions, a chemical reaction occurs. The chlorides bind with the silver to produce silver chloride, a white colored salt. In the absence of chlorides, the silver instead bonds with the hydroxides present in the concrete, creating a brownish color. Therefore, when the white precipitate is clearly visible, normally after a period of about 15 minutes, the depth of penetration is measured using slide caliper as shown in Figure 4.7. The average value of the depth measurements is then calculated.

The calculation of diffusivity is then carried out using Equation 4.9 based on the average observed depth or profile of chloride penetration in the concrete specimens (11,12).

$$D_{nssm} = \frac{RT}{zFE} \cdot \frac{x_d - \omega\sqrt{x_d}}{t} \qquad \text{------------------------------------} \; [4.9]$$

Where

$$E = \frac{U-2}{L} \qquad \text{--} \; [4.10]$$

$$\omega = 2\sqrt{\frac{RT}{zFE}} \cdot erf^{-1}\left(1 - \frac{2C_d}{C_o}\right) \qquad \text{---------------------------} \; [4.11]$$

D_{nssm} = *non-steady state migration coefficient (m^2/s)*

z = *absolute value of ion valence (for chloride, $z=1$)*

F = *Faraday's constant ($F=9.648x10^4 J/(V.mol)$)*

U = *absolute value of the applied potential (V)*

R = *gas constant ($R=8.314J/(K.mol)$)*

T = *average value of the initial and final temperatures in the anolyte solution (K)*

L = *thickness of the specimen (m)*

t = *test duration (s)*

erf^1 = *inverse error function*

C_d = *chloride concentration at which the color changes ($C_d \approx 0.07N$ for OPC concrete)*

C_o = *chloride concentration in the catholyte solution ($C_o \approx 2N$)*

Inserting the values of C_d and C_o in the inverse error function and simplifying gives:

$$erf^{-1}\left(1-\frac{2x0.07}{2}\right) \quad = \quad 1.28$$

Furthermore, combining Equations 4.10 and 4.11 and inserting the value of the inverse error function into equation 4.9 gives:

$$D_{nssm}=\frac{0.0239(273+T)L}{(U-2)t}\left(x_d-0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right) \quad \text{---- [4.12]}$$

Where D_{nssm} = *non-steady state migration coefficient (x10^{-12} m^2/s)*

U = *absolute value of the applied potential (V)*

T = *average value of the initial and final temperatures in the anolyte solution (^{o}C)*

L = *thickness of the specimen (mm)*

x_d = *average value of the penetration depth (mm)*

t = *test duration (h)*

Besides the non-steady state migration coefficients, the electrical resistivity of the specimens can also be calculated from the same data using Equation 4.13 (12).

$$\rho=\frac{RA}{H} \quad \text{-- [4.13]}$$

Where ρ = *electrical resistivity (Ω.m)*

R = *initial electrical resistance measured just at the start of the test (Ω)*

A = *cross-sectional area of the specimen (m^2)*

H = *average height of the specimen (m)*

While this test generally gives a very good estimate of the chloride diffusivity in concrete, it still has minor sources of error. For instance, the total current measured can not be taken as totally due to only the chloride ions because there may be several other current carriers as well. If for example a more conductive ionic species like calcium nitrite is present, the current will be carried by the highly ionically mobile nitrite ions instead of the chloride ions. Thus, the chloride ions would effectively experience a lower potential gradient, reducing the distance they would travel. Hence, the transference number for chloride must be known to better interpret experimental results.

In addition, any reactions of the chloride ions with the compounds present in the cement paste, for example aluminate hydrates (chlorides bind with the aluminate phases or are adsorbed on the C-S-H gel), need to be considered as well. The test might also induce a minor change in the pore structure of the concrete as a result of temperature rise by polarization which accelerates hydration thus modifying resistivity of the specimens too. Ohmic heating may also disturb the local flow of current and ion diffusion. The initial moisture content of the samples also affects the current measured at the start of the test. All these factors make it difficult to attribute any difference in measured chloride diffusion only to differences in microstructures of different concrete samples, although it gives a reasonable estimate (15,16,17).

CHAPTER FIVE
MATERIAL PREPARATION AND MIX PROPORTIONING

5.1. General

As discussed in the previous chapters, concrete is a mixture of cement, coarse aggregate, fine aggregate, water and when necessary, admixtures and air. These ingredients are mixed in carefully determined proportions to yield the required results. However, the raw materials themselves have to be properly selected, prepared and handled in such a way that they can contribute effectively towards satisfying the desired targets. In this respect, there are standard methods of preparing, testing and handling concrete making raw materials before carrying out the mixing.

Apart from this, there are also standard procedures for mixing, compaction, casting, troweling and subsequent curing of the concrete, which ultimately determine its quality and utility in the field. It has to be noted here that all these factors do have a significant impact on the overall performance of the concrete.

In this research, the material requirements were first determined and then they were prepared in such a way that they won't have a major impact on the parameters to be assessed later. No admixtures and air entraining were used so as to limit the variables, and also to resemble ordinary concrete work practiced widely. Normal tap water was used in the mix and equal amount of the different cements was employed in each concrete grade. The aggregates used in the mix are all obtained from the laboratory as it was not possible to buy because of the limited funding. Following is a discussion of the tests undertaken to determine the values to be used in mix proportioning and the results obtained.

5.2. Fine aggregate

Normal river sand which was available in the laboratory was used to prepare the samples and according to the laboratory personnel, it is obtained from around Mojo area. The following tests were conducted on the fine aggregates.

5.2.1. Silt content

The material in fine aggregates which is finer than 75μm is generally regarded as silt. The presence of silt in sand which is used to make concrete has severe impact on the quality of the resulting product. Mainly, it affects the workability and therefore, water-cement ratio of the mix and it is also responsible for eventual concrete cracking. Silt content of the sand to be used in the mix was determined using the following steps (18).

A sample of fine aggregate was taken and it was dried in an oven at 105°C for 24 hours. It was then sieved on a 1.18mm sieve, the material passing was weighed and its mass was found to be 482gm (m_1). It was then thoroughly washed on a 75µm sieve until clear water comes out, and again dried in oven at 105°C for another 24 hours. Its final mass was then taken and it was found to be 423gm (m_2). The silt content was then calculated as:

$$Silt\ content = \frac{m_1 - m_2}{m_1}.100\% = \frac{462-423}{462}.100\% = 8.44\%$$

This value is obviously high and according to Ethiopian Standard, the silt content of sand to be used for construction shall not exceed 6% (19). Therefore, the sand is thoroughly washed and dried to saturated surface dry (SSD) condition.

5.2.2. Sieve analysis

Approximately 2kg of fine aggregate was taken and it was dried in oven at 105°C for 24 hours. The sample was then quartered using riffle box and 509gm of sample was taken for sieve analysis. The results obtained are shown in Table 5.1.

Table 5.1. Sieve analysis of fine aggregate

Sieve size (mm)	**Wt. of sieve (gm)**	**Wt. of sieve and retained (gm)**	**Wt. retained (gm)**	**Percentage retained (%)**	**Cumulative coarser (%)**	**Cumulative passing (%)**
9.5	586	586	0	0	0	100
4.75	567	587	20	3.94	3.94	96.06
2.36	521	594	73	14.37	18.31	81.69
1.18	538	642	104	20.47	38.78	61.22
0.6	507	630	123	24.21	62.99	37.01
0.3	478	604	126	24.80	87.80	12.20
0.15	481	529	48	9.45	97.24	2.76
Pan	423	437	14	2.76	100.00	0.00
Total			508	100	309.06	

Fineness modulus of the fine aggregate was then computed as:

$$FM = \frac{\sum Cumulative\ Coarser}{100} = \frac{309.06}{100} = 3.09$$

The gradation of the fine aggregate is shown in Figure 5.1 along with the grading requirements for fine aggregate prescribed by Ethiopian standard.

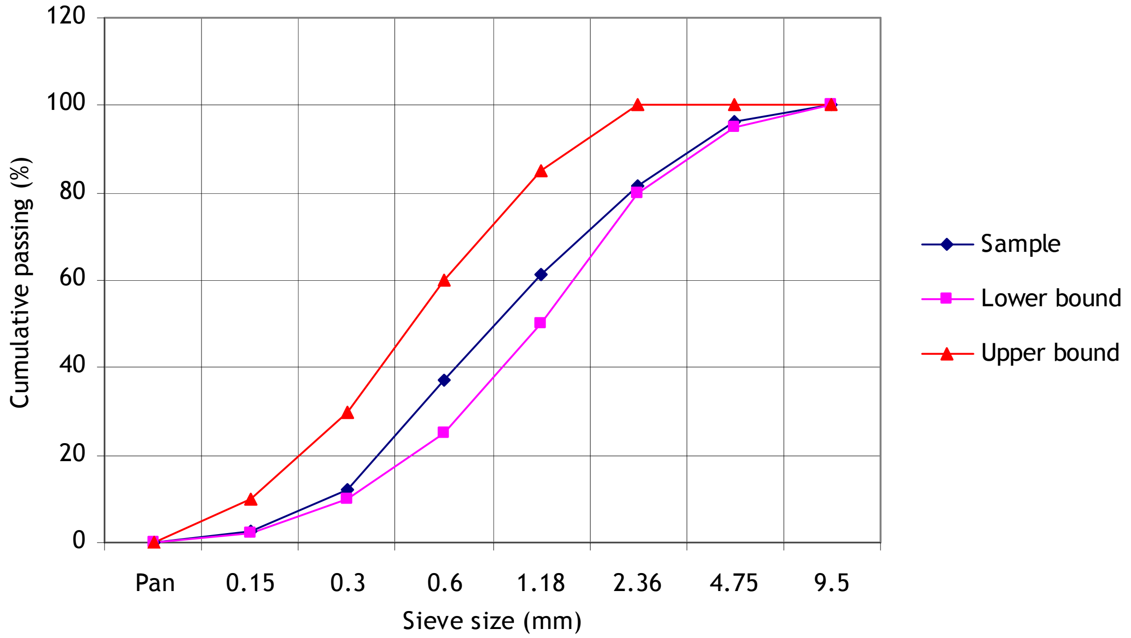


Figure 5.1. Fine aggregate gradation chart

5.2.3. Specific gravity

The specific gravity of the fine aggregate was determined using 3 different pycnometers so that the average can be taken. For each test, 500gm of oven dried fine aggregate was used. The result is presented in Table 5.2.

Table 5.2. Specific gravity determination for fine aggregate

Trial no	**Mass of dry sand sample in gm (A)**	**Mass of pycnometer + water in gm (B)**	**Mass of pycnometer + water + sand in gm (C)**	**Specific gravity [A/(A+B-C)]**
1	500	1283	1571	2.36
2	500	1290	1571	2.28
3	500	1288	1576	2.36
			Average	2.33

5.3. Coarse aggregate

The coarse aggregates used are also determined from the laboratory which are reportedly bought from Tikur Abay Construction Materials Supplier. Because the aggregates have been stored in the laboratory for a while, visual examination reveals that there is a dust film on their surface and therefore, the aggregates were washed thoroughly and dried to saturated surface dry (SSD) state before any test was carried out.

5.3.1. Sieve analysis

There were two types of coarse aggregates available in the laboratory of which upon physical inspection, one looks coarser and the other finer. Therefore, sieve analysis was carried out on both types so as to exploit any blending options later. The results are shown in Table 5.2 and the corresponding gradation charts along with the recommendations of the Ethiopian standard are shown in Figure 5.2.

Table 5.2. Sieve analysis of coarse aggregate (a) Sample 1 (b) Sample 2

Sieve size (mm)	Wt. of sieve (gm)	Wt. of sieve and retained (gm)	Wt. retained (gm)	Percentage retained (%)	Cumulative coarser (%)	Cumulative passing (%)
37.5	1084	1084	0	0	0	100
19	1419	4010	2591	57.26	57.26	42.74
12.5	1166	3004	1838	40.62	97.88	2.12
9.5	1189	1281	92	2.03	99.91	0.09
4.75	1195	1199	4	0.09	100.00	0.00
Pan	873	873	0	0	100.00	0.00
Total			4525			

(a)

Sieve size (mm)	Wt. of sieve (gm)	Wt. of sieve and retained (gm)	Wt. retained (gm)	Percentage retained (%)	Cumulative coarser (%)	Cumulative passing (%)
37.5	1084	1084	0	0	0	100
19	1419	1846	427	26.52	26.52	73.48
12.5	1166	1826	660	40.99	67.52	32.48
9.5	1189	1475	286	17.76	85.28	14.72
4.75	1195	1432	237	14.72	100.00	0.00
Pan	873	873	0	0	100.00	0.00
Total			1610			

(b)

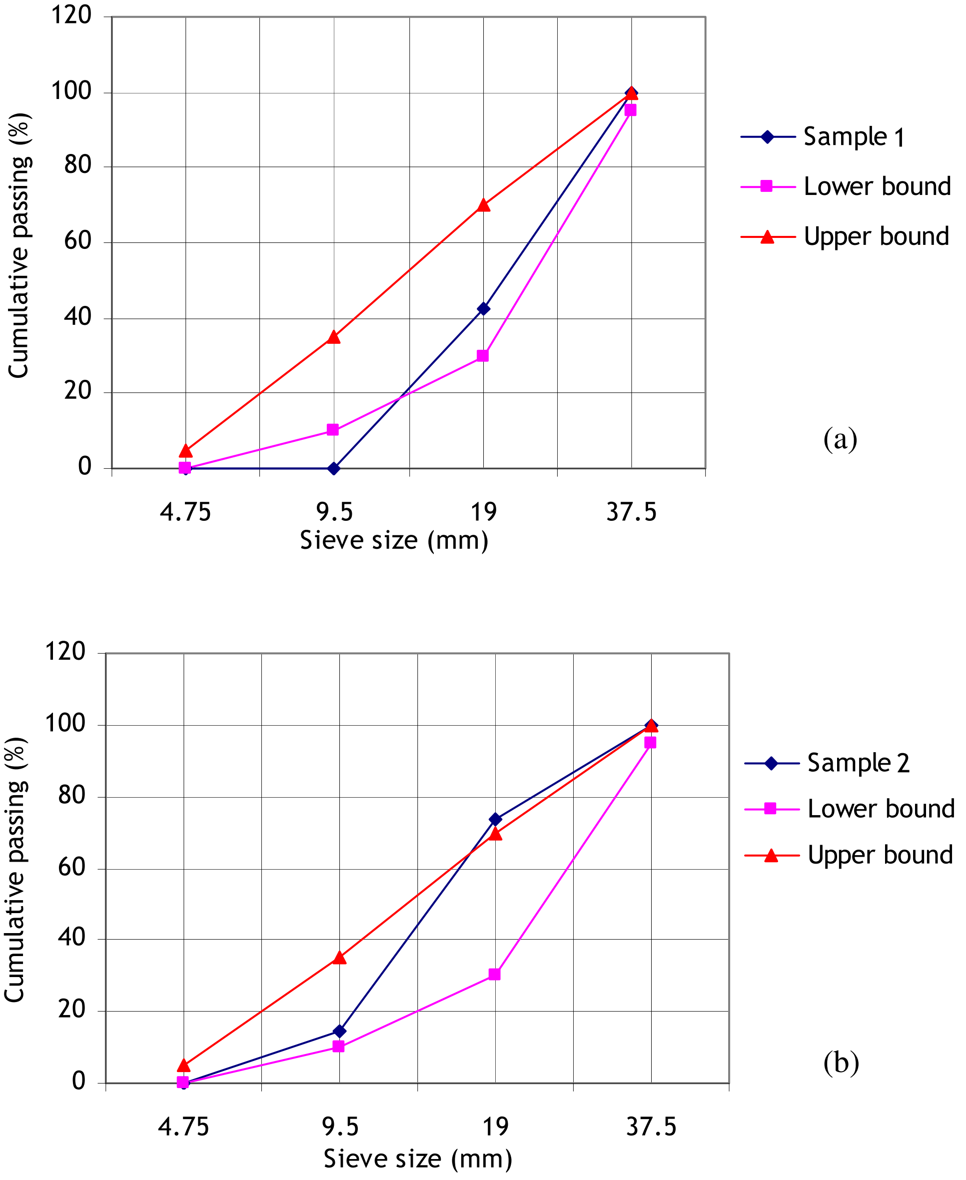


Figure 5.2. Coarse aggregate gradation chart (a) Sample 1 (b) Sample 2

It has to be noted here that both types of coarse aggregates are outside the recommended range and:

- The nominal size of both is 37mm which basically not allows any increase in the cement content when the DOE method is used, and
- Cumulative passing 4.75mm sieve is 0 in both cases while that recommended by the Ethiopian Standard is 0-5%.

Therefore, to rectify the aggregate gradations as per the recommendation and to obtain alternative cement content, the following options were sought.

In the first option, sample 2 was sieved on a 37mm sieve and the material passing was blended with 10% of another aggregate passing 4.75 and retained on 2.36mm sieve. The recommendation of the Ethiopian Standard for cumulative passing 4.75mm sieve in this case (when the nominal size of the aggregate is reduced to 19mm) is 0-10%. The resulting gradation of the blended sample is shown in Figure 5.3. Here, the nominal aggregate size is reduced to 19mm.

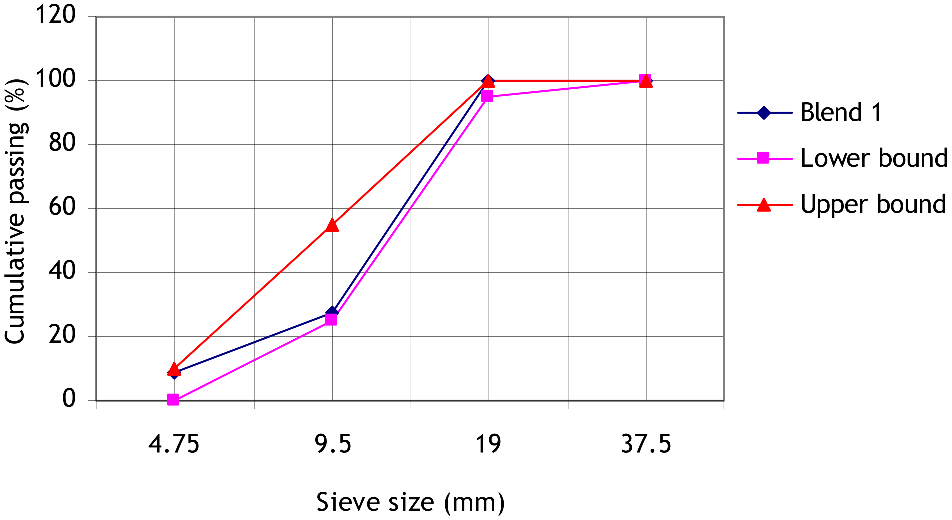


Figure 5.3. Gradation chart of coarse aggregate blend 1

The second alternative was calculating various blending proportions of the two aggregates keeping them as they are, which will keep them within range. It was obtained that 25% of sample 1 blended with 75% of sample 2 and with 5% aggregate passing 4.75 and retained on 2.36mm sieve added yields a good gradation which is shown in Figure 5.4. Here, the nominal aggregate size is kept the same, i.e. 37mm. Hence, both blend 1 and blend 2 are within the range recommended by the Ethiopian Standard and their suitability can therefore be assessed by preparing trial mixes out of each one. It is going to be shown eventually that selecting appropriate aggregate gradation is as good as, if not more so than merely increasing the cement content!

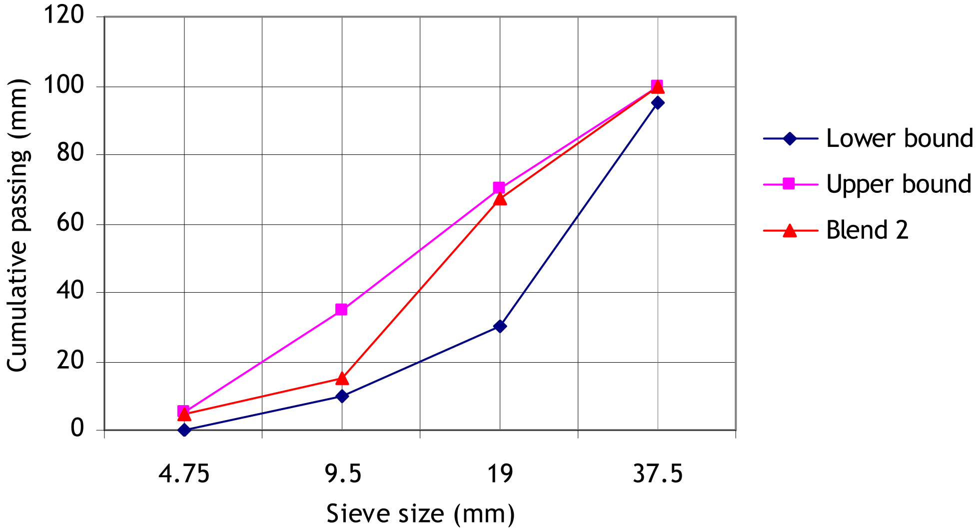


Figure 5.4. Gradation chart of coarse aggregate blend 2

5.3.2. Specific gravity

The specific gravity of the coarse aggregates was determined using displacement method. First, approximately 2kg of coarse aggregate sample was taken and submerged in water for 24 hours. The aggregates were then taken out and their surface was dried using a towel to remove the excess moisture. After determining their masses, the aggregates were carefully immersed into a beaker filled with water, after which volume of the displaced water was measured. The results obtained are shown in Table 5.3.

Table 5.3. Specific gravity of coarse aggregate

Coarse aggregate	SSD mass (gm)	Volume of displaced water (ml)	Specific gravity
Sample 1	1681	650	2.59
Sample 2	1417	545	2.6

5.4. Cement

By the time this test was conducted, there was severe shortage of cement in the country and the manufacturers were not able to satisfy the demand at all. Dire Dawa cement never reaches here in Addis Ababa, and had it not been for the severe shortage, Mugher and Messobo cements were at once available in the market. Especially, Mugher OPC was distributed only to licensed contractors engaged in big projects by that time. Anyway, both the Mugher cement factory, and Messobo cement factory through its marketing department here in Addis Ababa, were contacted formally, however, none of them responded positively. So both Messobo OPC and PPC, and Mugher PPC were purchased from suppliers as soon as they receive their quota from the factories. Dire Dawa PPC was also purchased from local distributors there and transported to Addis. It was possible to obtain Mugher OPC with the kind assistance of Varnero Construction P.L.C. They were very considerate to respond positively once I made request to them. Moreover, in addition to providing the cement from their ongoing project, they didn't charge me any money. Their understanding is highly commendable because the work would have been stalled otherwise.

5.5. Preparation of trial mix and results

It is intended to prepare concrete grades C-25 and C-40, and the DOE method was used to determine the mix proportions. Three trial mixes were prepared, the first two for both the C-25 and C-40 concretes using blend 2 coarse aggregate and of course, the only sand available. The third trial mix was prepared for the C-40 concrete using blend 1 coarse aggregate so that higher cement content is obtained. C-40A and C-40B identifications are used for the two C-40 concretes respectively. The resulting mix proportions are shown in Table 5.4.

Table 5.4. Trial mix proportions

Ingredient	**Quantities to the nearest 5kg for:**		
	C-25	**C-40A**	**C-40B**
Cement (kg)	325	380	420
Water (kg or lt)	170	170	190
Fine aggregate (kg)	700	680	735
Coarse aggregate (kg)	1195	1160	1015
Water-cement ratio	0.52	0.45	0.45

Messobo PPC was used for preparing the trial mixes. During the preparation of the trial mixes, the slump was found to be slightly out of range. An obvious reason for this is that, although extreme precaution is taken to keep the aggregates in SSD state before the mixing is carried out, it can't be said that the condition could be met absolutely. Moreover, some water is also lost during wetting of the surface of the mixer initially. Therefore, adjustments were carried out by adding small amount of additional water and as a result the water-cement ratio has increased to 0.58 for the C-25 mix and 0.50 for the C-40. As stated above however, this can't be taken as total additional water. Once the trial mixes are prepared with the above mix proportions, cube specimens were cast for testing their compressive strength. Third day compressive strength tests were conducted and accordingly, the results obtained are shown in Table 5.5 (refer appendix 1 for detailed results of the test).

Table 5.5. Trial mix results

Cube ID	**σ_3 (3 days Comp. Strength), MPa**
C-25	6.99
C-40A	13.11
C-40B	12.17

It was noted here that the cement used is PPC which is slower in compressive strength development as compared to OPC. Moreover, it was found out that blend 2 coarse aggregate yields better result for the C-40 concrete. It was inferred then that if these trial mix proportions are adopted, the compressive strength targets will be satisfied by at least one cement type, notably, either of the OPC's especially at early age. Or else, it was projected that they will get reasonably close to the intended targets. Besides, because of the limited funding, it was not possible to be more flexible on the choice of aggregates than the already attempted. Therefore, it was decided that these trial proportions be adopted for preparing the main samples, with the adjusted water-cement ratios, and compressive strengths be taken alongside for all the specimens. The slump at those water-cement ratios is also recorded. Consequently, as long as every factor is kept identical for all the samples before, during and after their preparation, it's evident that the resulting effects will be a reflection of nothing but the cement type.

Therefore, based on the above assessment, casting was carried out successively keeping the cement, other ingredients and water-cement ratio in every mix constant. The slump for each batch of concrete mix is also recorded. Particular emphasis was given to the compaction effort during casting and it was carefully controlled using a stop watch. And a mixture of cube and cylindrical specimens were cast as the later are also required for some of the tests. Table 5.6 shows the mix proportions, casting sequence and slumps recorded for each mix. 24 hours after casting, the specimens were demolded and kept in a curing tank for 28 days.

Table 5.6. Main mix proportions and recorded slump

Mix ID	Concrete Grade	Casting date	Cement used	Volume (m^3)	Cement (kg)	Sand (kg)	CA_1 (kg)	CA_2 (kg)	CA_3 (kg)	Water (kg)	W/C ratio	Slump (mm)
A1	C-25	14.10.06	Messobo PPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	25
				0.034	11.05	23.80	9.67	29.02	1.93	6.42	0.58	35
A2	C-40			0.041	15.58	27.88	11.32	33.97	2.26	7.79	0.50	25
				0.034	12.92	23.12	9.39	28.17	1.88	6.46	0.50	25
B1	C-25	15.10.06	Diredawa PPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	30
				0.031	10.08	21.70	8.82	26.46	1.76	5.84	0.58	35
B2	C-40			0.041	15.58	27.88	11.32	33.97	2.26	7.79	0.50	35
				0.034	12.92	23.12	9.39	28.17	1.88	6.46	0.50	30
C1	C-25	16.10.06	Mugher PPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	25
				0.031	10.08	21.70	8.82	26.46	1.76	5.84	0.58	30
C2	C-40			0.041	15.58	27.88	11.32	33.97	2.26	7.79	0.50	20
				0.031	11.78	21.08	8.56	25.69	1.71	5.89	0.50	20
D1	C-25	17.10.06	Mugher OPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	20
				0.031	10.08	21.70	8.82	26.46	1.76	5.84	0.58	30
D2	C-40			0.041	15.58	27.88	11.32	33.97	2.26	7.79	0.50	40
				0.027	10.26	18.36	7.46	22.37	1.49	5.13	0.50	25
E1	C-25	18.10.06	Messobo OPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	20
				0.040	13.00	28.00	11.38	34.14	2.28	7.54	0.58	20
E2	C-40			0.041	15.58	27.88	11.32	33.97	2.26	7.79	0.50	15
				0.035	13.30	23.80	9.67	29.00	1.93	6.65	0.50	10
F1	C-25	19.10.06	Mugher OPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	25
				0.040	13.00	28.00	11.38	34.14	2.28	7.54	0.58	20
F2	C-40			0.041	15.58	27.88	11.32	33.97	2.26	7.79	0.50	40
				0.038	14.44	25.84	10.50	31.49	2.10	7.22	0.50	25
G1	C-25	20.10.06	Mugher PPC	0.042	13.65	29.40	11.95	35.85	2.39	7.92	0.58	10
				0.021	6.83	14.70	17.93	5.97	1.19	3.98	0.58	15
G2	C-40			0.063	23.94	42.84	52.20	17.40	3.48	11.97	0.50	25
H1	C-25	21.10.06	Messobo OPC	0.063	20.48	44.10	53.78	17.92	3.58	11.88	0.58	15
H2	C-40			0.063	23.94	42.84	52.20	17.40	3.48	11.97	0.50	20
I1	C-25	22.10.06	Messobo PPC	0.063	20.48	44.10	53.78	17.92	3.58	11.88	0.58	40
I2	C-40			0.063	23.94	42.84	52.20	17.40	3.48	11.97	0.50	20
J1	C-25	23.10.06	Diredawa PPC	0.063	20.48	44.10	53.78	17.92	3.58	11.88	0.58	40
J2	C-40			0.063	23.94	42.84	52.20	17.40	3.48	11.97	0.50	25

Note: CA_1 = Coarse aggregate sample 1

CA_2 = Coarse aggregate sample 2

CA_3 = Crushed aggregate passing 4.75mm and retained on 2.36mm sieve

After 28 days water curing, the samples were taken out and kept inside the laboratory until the durability tests were conducted. As discussed earlier, compressive strength tests were also carried out on the standard cube specimens at the ages of 28, 56 and 91 days. Table 5.7 shows summary of the results of the compressive strength tests conducted at the specified ages (refer appendix 1 for details of the compressive strength test results).

Table 5.7. Compressive strength test results

Cube ID	**Design grade**	**Cement used**	**σ_{28} (MPa)**	**σ_{56} (MPa)**	**σ_{91} (MPa)**
A1	C-25	Messobo PPC	19.50	27.06	28.54
A2	C-40		25.51	36.37	38.43
B1	C-25	Dire Dawa PPC	11.19	17.07	17.42
B2	C-40		13.73	19.67	21.14
C1	C-25	Mugher PPC	23.39	30.78	32.39
C2	C-40		29.98	37.47	39.13
D1	C-25	Mugher OPC	33.51	41.57	43.64
D2	C-40		40.60	48.78	49.06
E1	C-25	Messobo OPC	24.47	35.41	37.18
E2	C-40		29.29	41.52	43.36

As shown in Table 5.7, the target strengths are satisfied by the OPC's, especially, by Mugher OPC after 28 days and eventually by Messobo OPC too. It must be noted here that compressive strength of even the C-25 concrete prepared by Mugher OPC exceeds 40MPa after 60 days. However, it is observable that compressive strength results of the concrete produced by Dire Dawa PPC in particular are far below normal. This is also an indication of the comparative effect of the different cements with respect to the development of compressive strength.

CHAPTER SIX
DURABILITY TESTS AND RESULTS

6.1. General

The durability of concrete is an intricate behavior and as opposed to compressive strength, it can not be exactly determined by using a simple test. Therefore, it is normally assessed over a period of time by conducting several tests. Even the tests themselves may not yield consistent results because they require relatively higher precision, and some of the factors determining reactions of the concrete to a particular test depend on the microclimate in addition to the actual concrete characteristics. Therefore, coupled with the delicacy of concrete microstructure as discussed earlier, correlation of the test results to the microstructure of concrete is a complex task.

The tests to be conducted in this study are selected depending on the facilities available in the laboratory as well as the duration of each test in relation to the allotted time for the research. The sudden reduction of the funds approved to be disbursed during the proposal was also a major hiccup in determining the scope of the works. However, it was tried not to make a significant compromise as much as possible, and the tests were selected in such a way that they will yield primary information on the three major transport properties in concrete discussed previously, namely permeability, capillary absorption, and diffusion.

6.2. Permeability

Non-steady state permeability was selected to be conducted because of the large sample size in this study and the long duration required to conduct steady state water permeability test on a sample. For instance, in one experimental study, manometer readings were taken everyday successively for 24 days to eventually find out that the water flow has reached steady state after 7 days (20). Moreover, the depth of the samples to be used for steady state water permeability test is 50mm and they also require special treatment using epoxy mortar to prevent escaping out of water through the sides of the disk. In general, the steady state water permeability test has been found out to be suitable for concretes with high permeability.

The test was conducted on normal concrete cubes of 150mm depth. The top surface of the cubes was first scraped and polished to remove the troweled surface and smoothen any irregularities present which may cause leakage laterally. The sides of the cubes were coated with a thick film of varnish to prevent evaporation of water from the inside. The cubes were then saturated in water before the test is started. Then the cubes were transferred to the permeability rig and assembled. To calculate average depths of penetrations, three samples of the same kind were tested simultaneously. Figure 6.1 shows the permeability apparatus with the test cubes assembled onto it. Once the setup was ready, water was filled into the reservoir of the test cells and pressure was applied to the specimens in successions described in section 4.2.2.

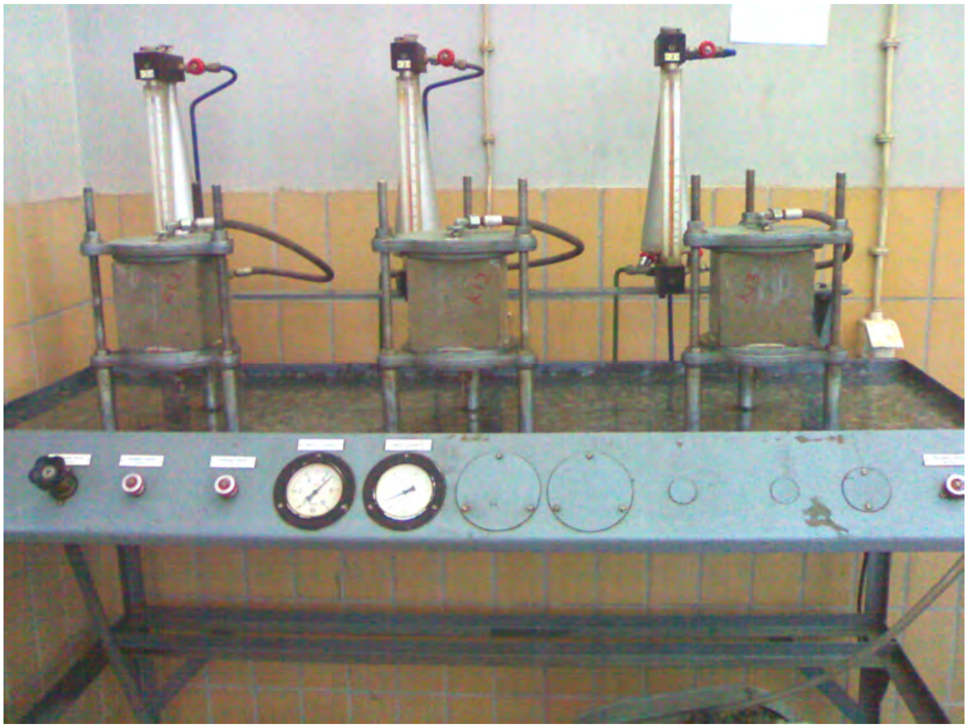


Figure 6.1. Permeability apparatus with samples assembled onto it

At the end of the 72 hours period, all the valves supplying water and compressed air to the specimens were closed and the cubes were removed from the permeability rig and split. Upon visual examination, the portion of the specimen into which water has penetrated appears darker than the rest, and immediately after splitting this zone was marked and measured. Figure 6.2 shows a typical water penetrated sample just after splitting. To determine the average depth of penetration with more accuracy, measurements were taken at 10mm intervals. Table 6.1 lists the average and maximum depth of penetrations obtained for the different samples (refer appendix 2 for detailed results obtained from each sample).

Figure 6.2. Typical concrete sample just after splitting at the end of the water penetration test

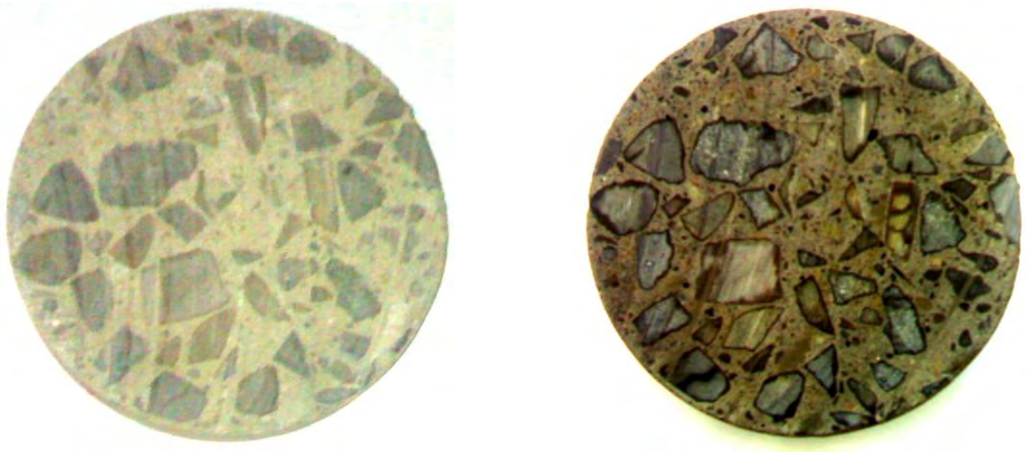
Table 6.1. Results of the water penetration test

Sample ID	**Cement used**	**Concrete Grade**	**Penetration depths (mm)**	
			Average	**Maximum**
F1	Mugher OPC	C-25	21	30
F2	»	C-40	15	22
G1	Mugher PPC	C-25	28	36
G2	»	C-40	22	30
H1	Messobo OPC	C-25	25	37
H2	»	C-40	28	37
I1	Messobo PPC	C-25	36	48
I2	»	C-40	30	40
J1	Dire Dawa PPC	C-25	39	49
J2	»	C-40	29	34

6.3. Capillary absorption

The capillary absorption test was conducted on 25mm thick concrete disks cut from ø150mmx300mm concrete cylinders. Rock cutting equipment was used to cut the specimens from the cylinders and they were sliced from the interior portion of the cylinders after removing the upper and lower portions. After the disks were cut, their thickness was measured and they were washed to remove the paste accumulated on their surface during cutting as a result of the dust and circulating water. The specimens were then kept in an oven at 105°C for 24 hours and after drying, their mass was recorded. Then, they were transferred to a closed container where they were placed on a mesh suspended over free water so as to naturalize the state of moisture distribution inside them. After the preconditioning of the samples was completed, their initial mass was taken and they were placed in a closed container containing water being simply supported on wooden supports in such a way that not more than 3mm of their bottom is submerged in the water. This ensures that the water movement is only through capillary action.

To obtain a number of values for the capillary absorption versus square root of time curve, the mass of the samples was taken every 10 minutes for the first one hour and every hour for next 7 hours. Afterwards, the mass measurements were carried out every day for three consecutive days. Figure 6.3 shows a typical water absorption pattern observed in a sample exposed to capillary absorption test.



(a) (b)

Figure 6.3. Typical water absorption pattern in a sample exposed to capillary absorption test (a) at the start (b) after 24 hours

The specimens were then completely submerged in water for further three days and their final mass recorded. During every mass measurement, the specimens were dried using a wet towel to remove only the excess water from their surface. To obtain a mean and representative value, five specimens were tested simultaneously from each category.

After the test was completed, capillary absorption versus square root of time curve was plotted for each category and best fit lines were determined using regression analysis for each limb of the curve. Then capillary number, k, and resistance number, m, were calculated for each category using the relations explained in section 4.3. Suction porosity was also determined using Equation 4.6. Table 6.2 gives the values of k and m obtained for the different concrete samples at the ages of 60 and 90 days along with the corresponding suction porosities (refer appendix 3 for the complete data and calculations of the different variables).

Table 6.2. Capillary number k, resistance number m, and suction porosity (ε_{suc}) values for the different concrete samples

Sample ID	**Cement used**	**Concrete Grade**	**Testing age (days)**	**Capillary no (k) ($x10^{-2}$ kg/m^{2}s$^{0.5}$)**	**Resistance no (m) ($x10^7$ s/m^2)**	**Suction porosity (%)**
F1	Mugher OPC	C-25	60	2.83	2.49	16.49
F2	»	C-40	»	2.58	2.57	15.01
D1	»	C-25	90	3.17	1.74	15.94
D2	»	C-40	»	3.06	1.88	15.73
G1	Mugher PPC	C-25	60	2.39	3.25	17.20
G2	»	C-40	»	2.25	2.74	16.52
C1	»	C-25	90	2.48	3.26	17.22
C2	»	C-40	»	2.17	4.26	16.97
H1	Messobo OPC	C-25	60	2.68	2.77	15.92
H2	»	C-40	»	2.56	3.02	16.02
E1	»	C-25	90	2.96	2.53	17.48
E2	»	C-40	»	2.93	2.43	16.71
I1	Messobo PPC	C-25	60	3.08	2.65	18.46
I2	»	C-40	»	2.88	2.64	17.44
A1	»	C-25	90	3.53	1.79	18.03
A2	»	C-40	»	3.33	1.77	16.33
J1	Dire Dawa PPC	C-25	60	2.67	2.86	17.90
J2	»	C-40	»	2.38	3.38	17.91
B1	»	C-25	90	3.01	2.70	18.44
B2	»	C-40	»	2.74	3.08	18.63

6.4. Diffusion

Similar to the capillary absorption test, chloride diffusion test was also conducted on concrete specimens cut from ø150mmx300mm concrete cylinders. In this case, the concrete samples were of 6cm height and three similar specimens were tested simultaneously in order to obtain a more representative average value.

The required reagents for this test, namely sodium hydroxide (NaOH), sodium chloride (NaCl), and silver nitrate ($AgNO_3$) were first made ready. The reagents were obtained in solid form and therefore, distilled water was used to prepare fresh solutions just before the start of the test.

The experimental setup was prepared cautiously to accomplish the test with high accuracy. After the specimens were cut from the cylinders, their thickness was measured and they were thoroughly washed and kept in water for 24 hours to equalize the initial water content within each sample. After 24 hours, the samples were taken out of water and a rubber sleeve was tightly secured over them. The inner tube of a vehicle tyre having a slightly smaller diameter was used to make the rubber sleeve. After putting the tube onto the specimens, it was firmly tightened at two points using stainless steel clamps. After assembling, the rubber sleeve was filled with water and kept for a couple of hours to check if there was any leakage. So this constitutes the anolyte chamber.

The entire assembly was then suspended on a firm stand using plastic strings in such a way that the bottom of the specimen would be completely submerged in the catholyte solution contained in an appropriate reservoir. Fresh solutions of NaCl and NaOH were then prepared in accordance with the prescribed concentrations and placed in their respective chambers. Electrodes were immersed in each solution and the positive pole of the electric supply was connected to the anode (the electrode placed in the anolyte solution) and vice versa, as shown earlier in Figure 4.6. The voltage in the electric source was set to 30V. Figure 6.4 shows the actual experimental setup used for the test.

Figure 6.4. Experimental setup used for conducting chloride migration test

Initial current across each specimen was measured using a multimeter, the temperature in the anolyte solution was also measured at the beginning and end of the test. The test was run for a six hour period and at the completion of the test period, the samples were taken out of the assembly and rinsed with water. They were then split and freshly prepared silver nitrate solution was sprayed on the cut surface immediately after splitting. After a while, the portion of the specimens penetrated by the chloride ions turns white as shown in Figure 6.5, and this zone was marked and penetration depths were measured afterwards as discussed in section 4.3.

Figure 6.5. Freshly split concrete sample after spraying $AgNO_3$ at the end of the chloride migration test

Non-steady state migration coefficient (D_{nssm}) and electrical resistivity (ρ) of the samples were then calculated using Equations 4.12 and 4.13 respectively, and the results are summarized in Table 6.3 (refer appendix 4 for detailed results of measurement of the different variables).

Table 6.3. Results of chloride diffusion test

Sample ID	**Cement used**	**Concrete Grade**	**D_{nssm} ($\times10^{-12}$ m^2/s) at**		**Resistivity, ρ (Ω.m) at**	
			60 days	**90 days**	**60 days**	**90 days**
F1	Mugher OPC	C-25	21.35	21.69	62.37	71.80
F2	»	C-40	16.94	16.17	63.43	72.08
G1	Mugher PPC	C-25	17.60	15.72	106.84	124.03
G2	»	C-40	13.28	13.93	114.89	109.81
H1	Messobo OPC	C-25	14.02	17.39	96.60	108.71
H2	»	C-40	13.29	15.87	83.21	91.47
I1	Messobo PPC	C-25	19.85	26.17	65.46	74.32
I2	»	C-40	18.69	17.27	70.09	82.64
J1	Dire Dawa PPC	C-25	14.07	18.51	115.42	136.24
J2	»	C-40	12.84	16.08	125.01	143.94

CHAPTER SEVEN
DISCUSSION AND CONCLUSION

7.1. General

As it has been shown in the previous section, results of the durability tests vary over a wide range in some cases, and as opposed to the compressive test results, results of some of the tests could even be inconsistent. This may result from a combination of several factors pertaining to the internal behavior of the concrete and its reaction to the particular exposure condition, as well as factors which are external to the concrete that are normally determined by the microclimate. However, closer examination of the results could yield comparative assessment of the characteristics of each concrete sample with respect to its long term durability behaviors.

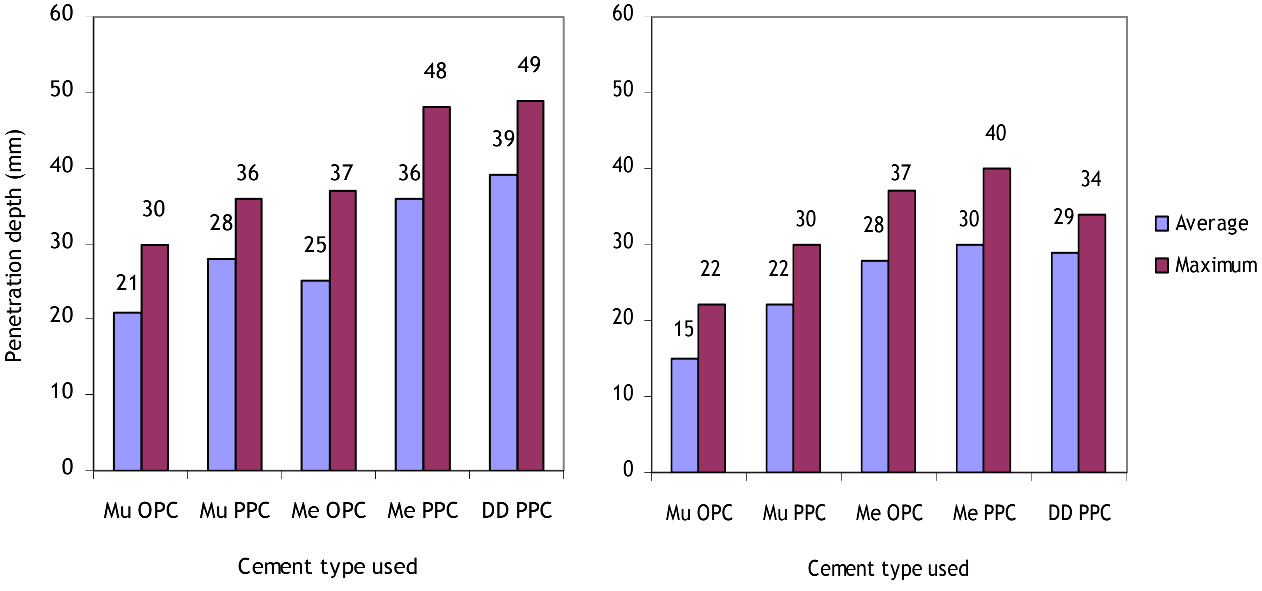
In this context, the results are viewed from the perspective of determining the degree of variation of each parameter from one concrete type to another. It must be noted here that investigating the underlying features that are responsible for such variations is another distinct subject of significant interest. Therefore, the following discussion is presented to examine closely the pattern of variation of the different parameters assessed in the foregoing sections.

7.2. Discussion of the test results

In this section, detailed analysis of the test results is undertaken from the point of view of determining the comparative effect of each cement type on the variable under investigation. The factors contributing to a particular mode of transport in concrete are different, and so is the effect of each cement type in determining those factors. Therefore, it is attempted to scrutinize the results one by one by selecting a convenient reference point from each set of test results, and finally, the findings are summarized as one to convey the collective picture.

7.2.1. Water penetration test results

As given in Table 6.1 earlier, the results of the water penetration test, i.e. the average and maximum depths of water penetration, show a noticeable magnitude of variation over the different types of concrete specimens. On the overall, the average depth of water penetration varied from 21mm to 39mm for the C-25 concretes and from 15mm to 30mm for the C-40 ones. The corresponding variations for the maximum depth of water penetration are 30mm to 49mm and 22mm to 40mm for the C-25 and C-40 concretes respectively. It can thus be said that the degree of variation from the highest to the worst quality concretes is almost 100%. Figure 7.1 shows the general trend in the penetration depths for the C-25 and C-40 concretes as a function of the cement type used.



(a) (b)

Figure 7.1. Graph showing penetration depth as a function of the cement type used to make the concrete (a) C-25 concrete (b) C-40 concrete

It can be easily observed from Figure 7.1 that the trend in the penetration depths slightly changes from the C-25 to the C-40 concretes, notably for the concrete made by Dire Dawa cement. This means the increase in the cement content from the C-25 to C-40 concrete has relatively greater effect for the Dire Dawa cement as compared to the other ones. It can be seen from the values that for the other cements, the effect of the increase in cement content has almost equivalent impact.

In general, using water penetration depth as a qualitative assessment of concrete, a depth of penetration of 50mm classifies the concrete as impermeable, and that of less than 30mm as impermeable under aggressive conditions (2). In this regard, it can thus be noted that all the cements produce an impermeable concrete, where as Mugher OPC and PPC in the case of C-40 concrete, and only Mugher OPC in normal concrete (C-25) lay in the range of producing impermeable concrete under aggressive conditions.

From all the cements, Mugher OPC produces the most impermeable concrete in both cases and therefore taking it as a reference, the percentage increase in the penetration depths for the other cements is calculated and the results are shown in Table 7.1.

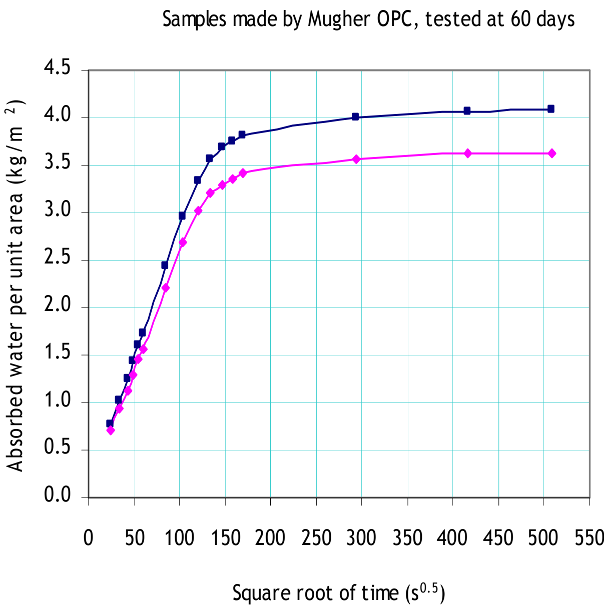
Table 7.1. Comparative analysis of the water penetration depths

Cement type	**Percentage increase in average depth of penetration**		**Percentage increase in maximum depth of penetration**	
Mugher OPC (reference)	**C-25**	**C-40**	**C-25**	**C-40**
Mugher PPC	33.3	46.7	20.0	36.4
Messobo OPC	19.0	86.7	23.3	68.2
Messobo PPC	71.4	100.0	60.0	81.8
Dire Dawa PPC	85.7	93.3	63.3	54.5

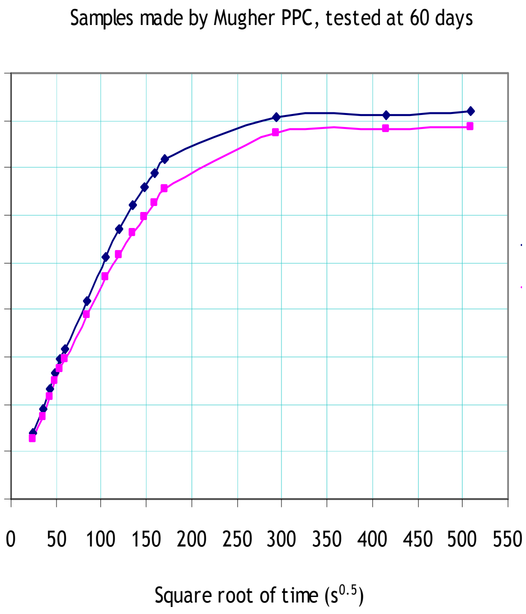
Considering the fact that in many cases, all the cement types belong to the same category while designing concrete mixes, the magnitudes of variations shown in the above table are very significant and therefore care should be taken while using the cements for concretes to be exposed to aggressive environments.

7.2.2. Capillary suction test results

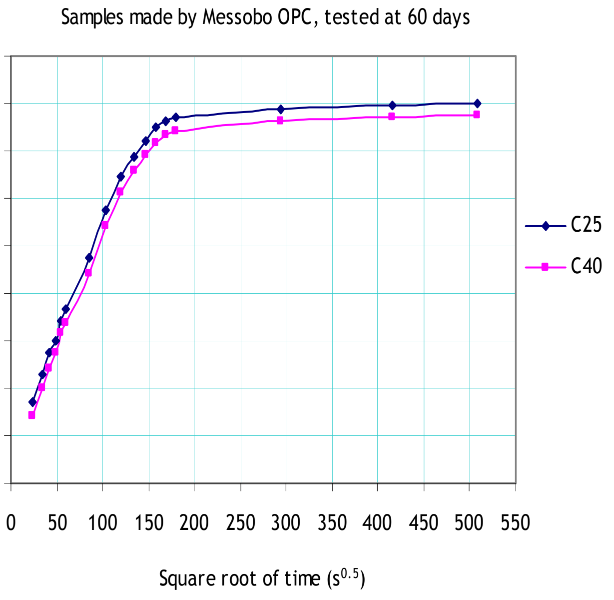
The results of the capillary suction test do not show as big a variation as those of the water penetration test; however, some of the parameters do not show consistent results with age or with increasing cement content. As shown in figure 7.2, a typical capillary absorption versus square root of time relationship is obtained in all the cases. Once, the best fit lines are determined from these curves using regression analysis, the various capillary absorption parameters were obtained, the results of which were given earlier in table 6.2. At the instant the specimens become in contact with water in their lowest 2-3mm layer, there is a small increase in their masses, therefore, the point of origin is avoided in plotting the curves (2).



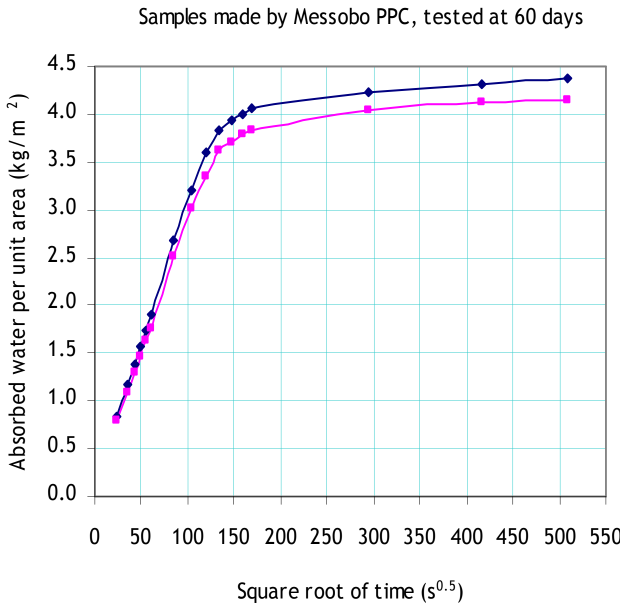
Samples made by Mugher OPC, tested at 60 days



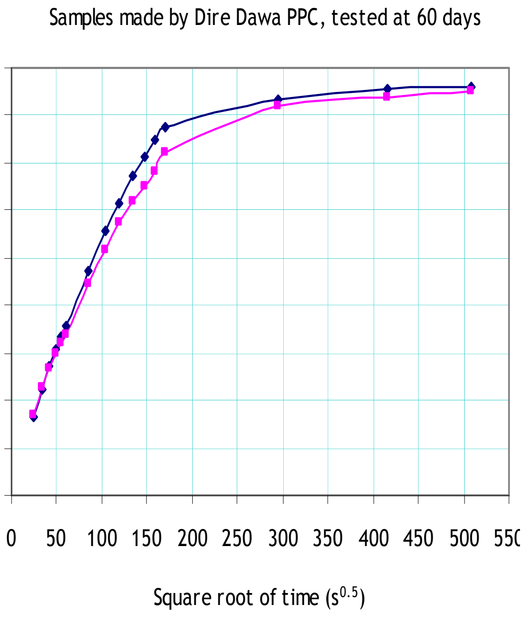
Samples made by Mugher PPC, tested at 60 days



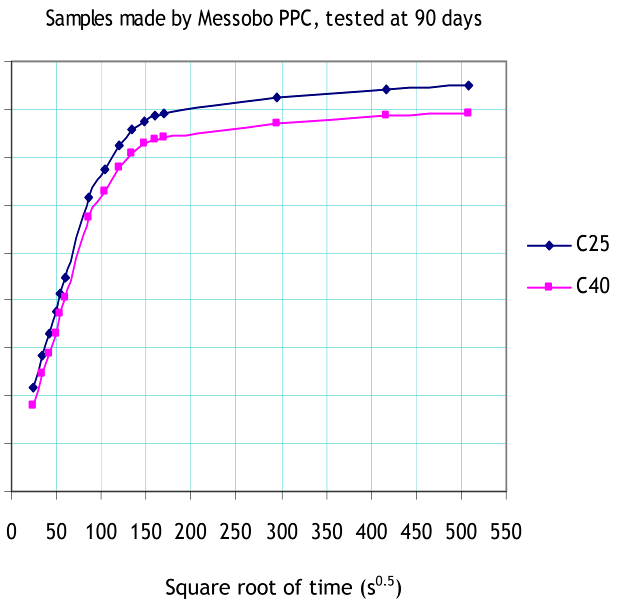
Samples made by Messobo OPC, tested at 60 days



Samples made by Messobo PPC, tested at 60 days



Samples made by Dire Dawa PPC, tested at 60 days



Samples made by Messobo PPC, tested at 90 days

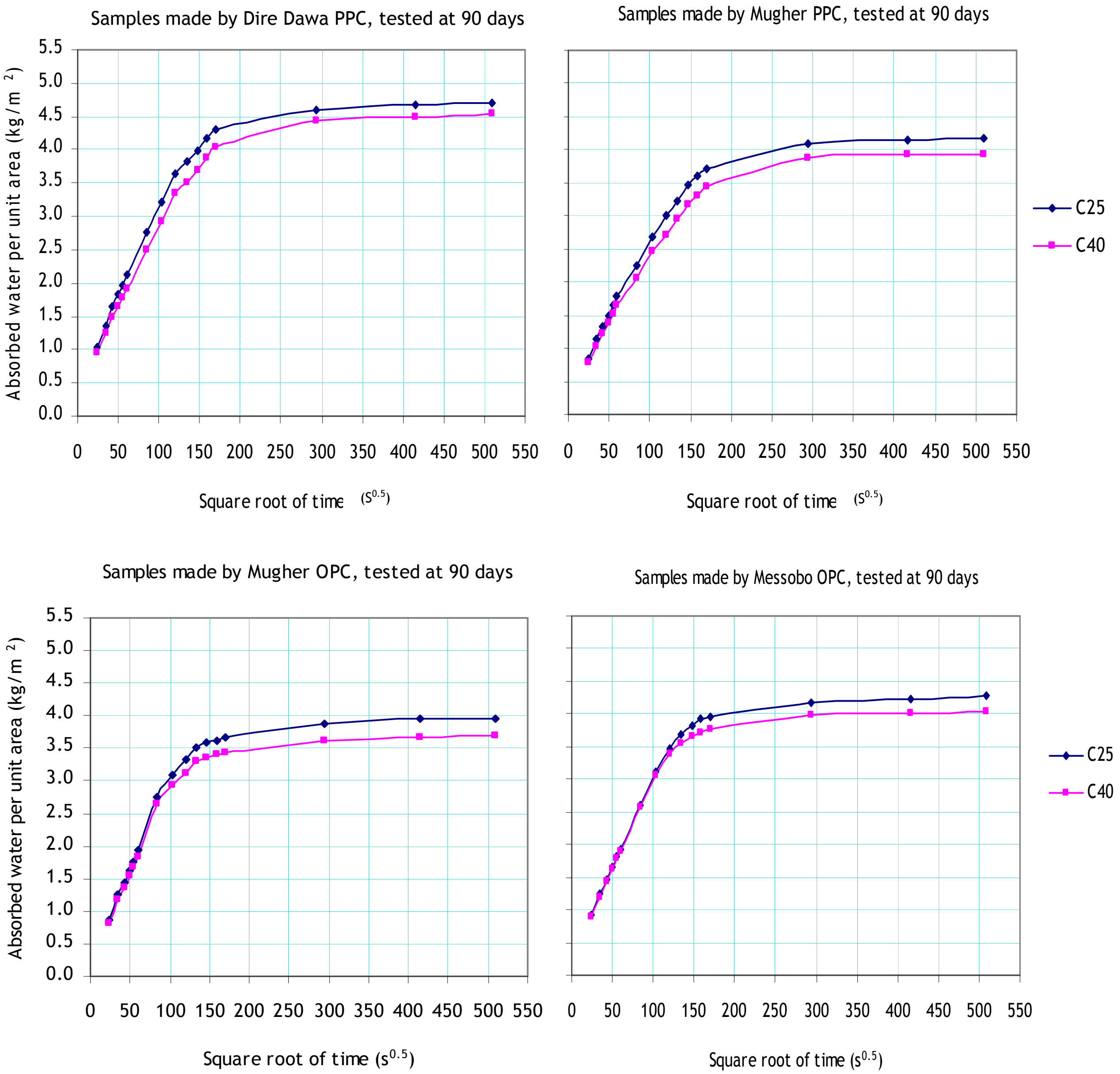


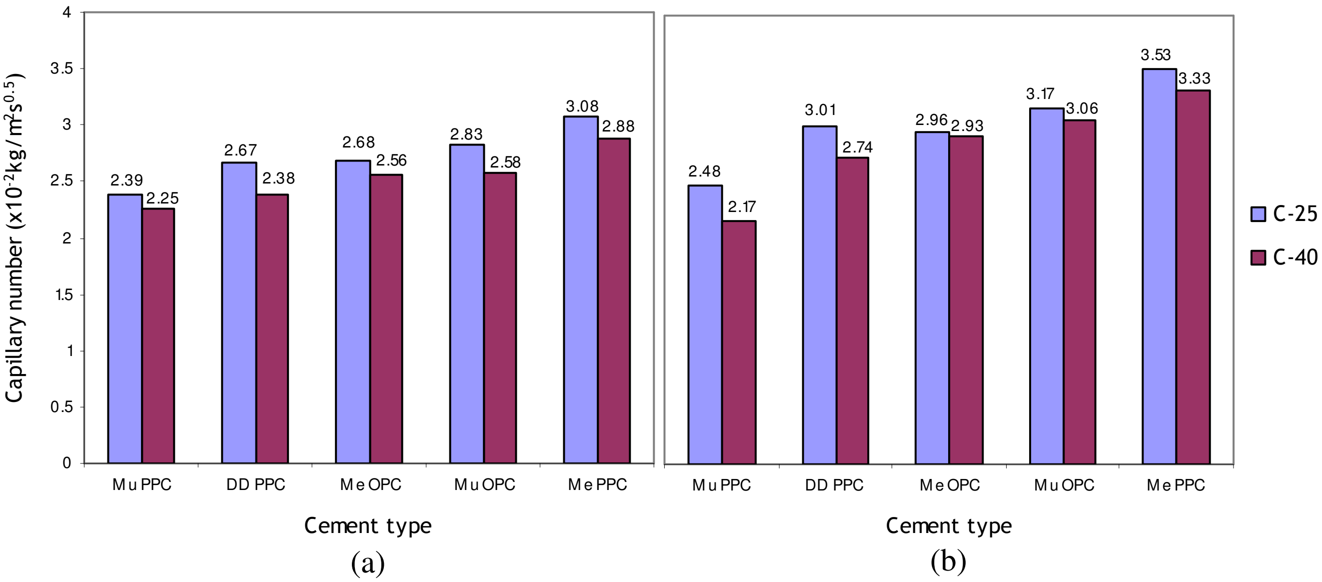
Figure 7.2. Capillary absorption versus square root of time curves

As depicted in the graphs, typical capillary absorption versus square root of time curves are established and equations of the best fit lines obtained after regression analysis using a spreadsheet program are summarized in Table 7.2 from which, the parameters obtained in Table 6.2 earlier are calculated.

Table 7.2. Regression analysis results of capillary suction curves

Curve identifications			**Equation of the best fit line for**					**Q_c (kg/m^2)**	**$t_c^{0.5}$ ($s^{0.5}$)**
Cement used	**Concrete type**	**Age**	**First limb**			**Second limb**			
			Slope	**Intercept**	**Corr. Coeff.**	**Slope**	**Intercept**		
Mugher OPC	C-25	60 days	0.0276	0.0850	0.9999	0.0015	3.4183	3.61	127.81
	C-40		0.0253	0.0569	0.9998	0.0012	3.0905	3.24	125.77
Mugher PPC	C-25		0.0224	0.1995	0.9989	0.0024	3.0329	3.37	141.48
	C-40		0.0213	0.1622	0.9979	0.0032	2.5212	2.95	130.85
Messobo OPC	C-25		0.0245	0.3149	0.9990	0.0012	3.4840	3.64	135.71
	C-40		0.0243	0.1776	0.9985	0.0012	3.3259	3.49	136.30
Messobo PPC	C-25		0.0298	0.1142	0.9998	0.0015	3.6711	3.86	125.63
	C-40		0.0280	0.1048	0.9998	0.0016	3.4395	3.64	126.30
Dire Dawa PPC	C-25		0.0244	0.2950	0.9982	0.0026	3.1666	3.51	131.58
	C-40		0.0208	0.4220	0.9976	0.0029	2.9453	3.35	140.74
Messobo PPC	C-25	90 days	0.0324	0.2952	0.9999	0.0020	3.3906	3.60	101.87
	C-40		0.0324	0.0911	0.9995	0.0015	3.3050	3.46	103.87
Dire Dawa PPC	C-25		0.0265	0.4800	0.9984	0.0020	3.7887	4.07	135.18
	C-40		0.0243	0.4306	0.9991	0.0025	3.4357	3.77	137.70
Mugher PPC	C-25		0.0211	0.3844	0.9981	0.0022	3.2094	3.52	141.49
	C-40		0.0191	0.4160	0.9980	0.0018	3.1413	3.42	157.34
Mugher OPC	C-25		0.0304	0.1356	0.9984	0.0017	3.2298	3.41	107.71
	C-40		0.0297	0.0920	0.9981	0.0015	3.0602	3.21	105.06
Messobo OPC	C-25		0.0273	0.2892	0.9995	0.0016	3.5424	3.75	126.65
	C-40		0.0271	0.2724	0.9996	0.0014	3.4285	3.60	122.78

As shown in Table 6.2 previously, keeping in mind the multipliers, capillary number of the samples vary from 2.39 to 3.08 for the C-25 concretes at the age of 60 days and from 2.25 to 2.88 for the C-40 concretes at the same age. In both cases, the extreme values are exhibited by Mugher PPC and Messobo PPC respectively, with the rest consistently distributed in between. A similar pattern exists at the age of 90 days, the values changing from 2.48 to 3.53 for the C-25 concretes and 2.17 to 3.33 for the C-40 ones. Figure 7.3 shows the variation of capillary number as a function of the cement used at the two ages.

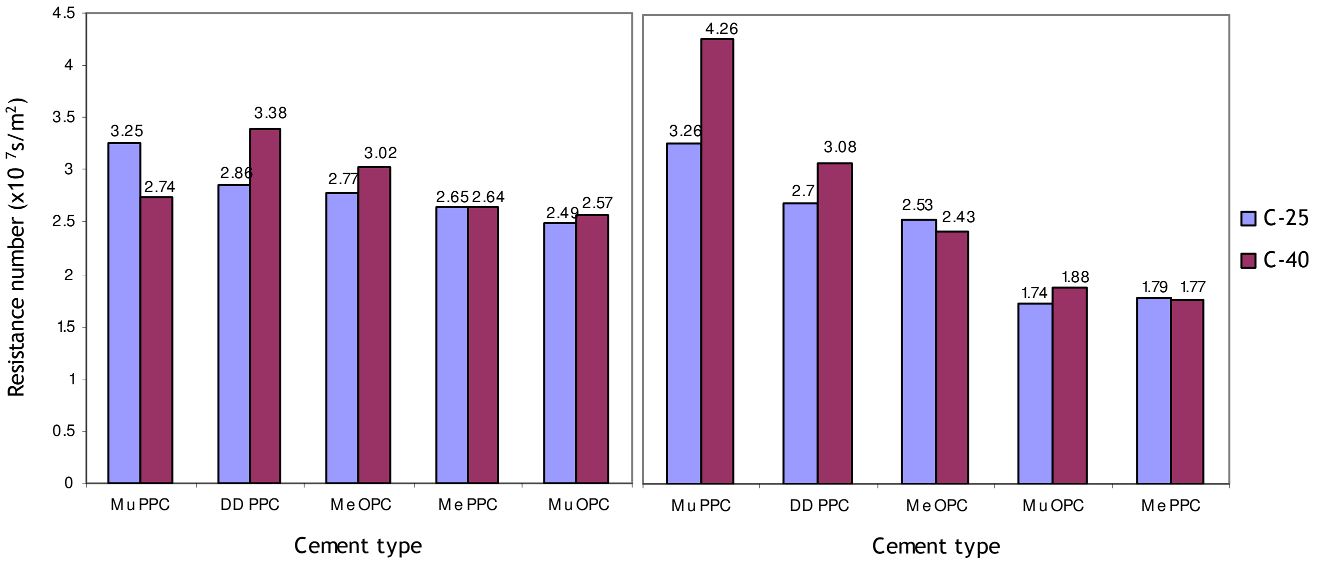


(a) (b)

Figure 7.3. Variation of capillary number for the different cements used
(a) at the age of 60 days (b) at the age of 90 days

It can be observed from the above graphs that in all the cases, the capillary number decreased with increasing cement content which, as expected, illustrates the reduction in the capillary porosity as the concrete becomes denser and denser.

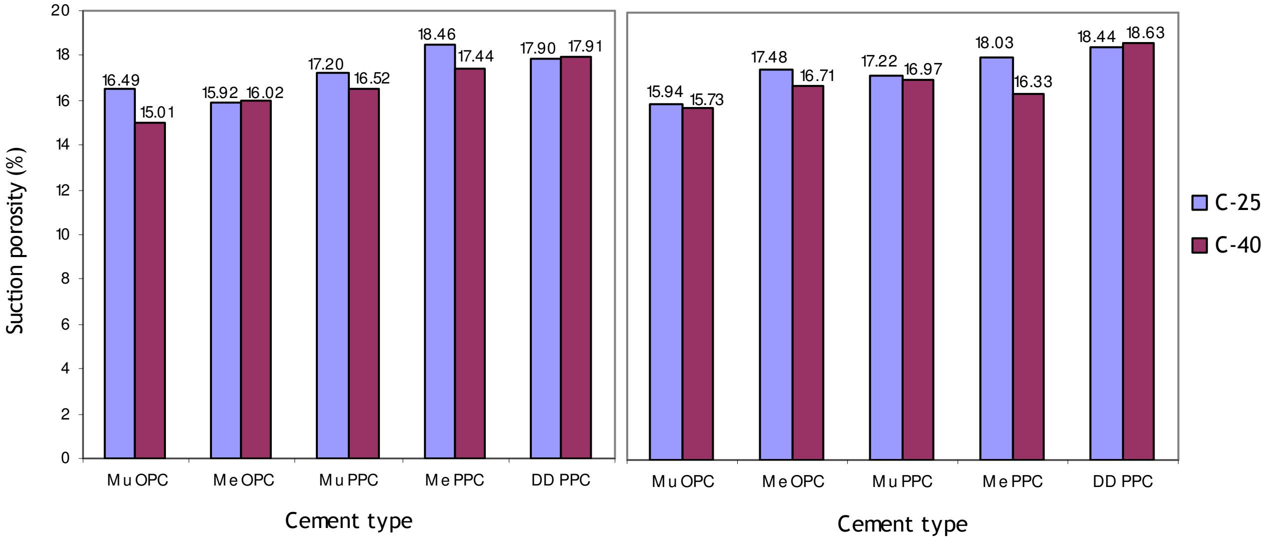
The resistance number also exhibits a more or less similar variation as the resistance number over the different cements used in the concretes. Again keeping in mind the multipliers, the resistance number varies from 2.49 to 3.25 for the C-25 concretes and from 2.57 to 3.38 for the C-40 concretes, both at the age of 60 days. At the age of 90 days, the variation is from 1.74 to 3.26 for C-25 concretes and from 1.77 to 4.26 for the C-40 ones. In this case, the extreme values are not exhibited by specific types of cements consistently and there is also little inconsistency with the shift from C-25 to C-40 concretes. However, a dominant pattern, similar to the one exhibited by the capillary number for the most part, can be obtained as shown in Figure 7.4.



(a) (b)

Figure 7.4. Variation of resistance number for the different cements used (a) at the age of 60 days (b) at the age of 90 days

The values of suction porosity show a different pattern with the cements used. At the age of 60 days, the values show a variation from 15.92% to 18.46% for the C-25 concretes and from 15.01% to 17.91% for the C-40 concretes, while at the age of 90 days, the variation exhibited is from 15.94% to 18.44% and from 15.73% to 18.63% for the C-25 and C-40 concretes respectively. The apparent pattern of variation is shown in Figure 7.5.



(a) (b)

Figure 7.5. Variation of suction porosity for the different cements used (a) at the age of 60 days (b) at the age of 90 days

It is apparent that with respect to capillary absorption, two distinct features are observable - the rate and amount of capillary absorption. Both capillary and resistance numbers are reflections of the rate of capillary absorption in concrete up to the point where the major capillary pores are filled. Therefore, it's likely that these parameters are affected significantly by the diameter of capillary pores as capillary pores of smaller diameter absorb water faster than those of larger diameter. However, suction porosity is indicative of the total amount of pores that can be filled by water transported by capillary suction. In fact both the parameters are significant and hence, they should be evaluated together.

It can thus be concluded that the rate of capillary absorption is the lowest in concretes made by Mugher PPC and the highest in those made by Messobo PPC. However, suction porosity is found to be the lowest in concretes made by Mugher OPC and the highest in those made by Dire Dawa PPC. Critical examination of the results obtained for both the parameters indicates a more or less overlapping outcome for some of the cement types. Mugher PPC tends to have better results as far as both the rate and amount of capillary absorption are concerned while Messobo PPC has lower values in both the cases. Therefore, it can be summed up that in terms of capillary absorption, concretes made by Mugher PPC have the highest performance and those made by Messobo PPC the lowest. Refer appendix 3 for superimposed capillary absorption versus square root of time plots for the various cements.

7.2.3. Chloride diffusion test results

The parameters obtained from the chloride diffusion test also show a significant variation for samples of the same category. The non-steady state migration coefficient shows a variation of 14.02x$10^{-12}$$m^2$/s to 21.35 x$10^{-12}$$m^2$/s for the C-25 concretes tested at the age of 60 days. In the case of the C-40 concretes, the coefficients have in fact reduced ranging in value from 12.84 x$10^{-12}$$m^2$/s to 18.69 x$10^{-12}$$m^2$/s at the age of 60 days. But apparently, there is no distinct pattern in the results and no one concrete made of a particular type of cement exhibits the extreme points consistently.

Likewise, at the age of 90 days, the non-steady state migration coefficient has varied from 15.72 x$10^{-12}$$m^2$/s to 26.17 x$10^{-12}$$m^2$/s for the C-25 concretes and from 13.93 x$10^{-12}$$m^2$/s to 17.27 x$10^{-12}$$m^2$/s for the C-40 ones. Similar to the 60 days result, the D_{nssm} has consistently exhibited reduction with increasing cement content at the age of 90 days too. The variation of D_{nssm} for the different cements used is shown in Figure 7.6.

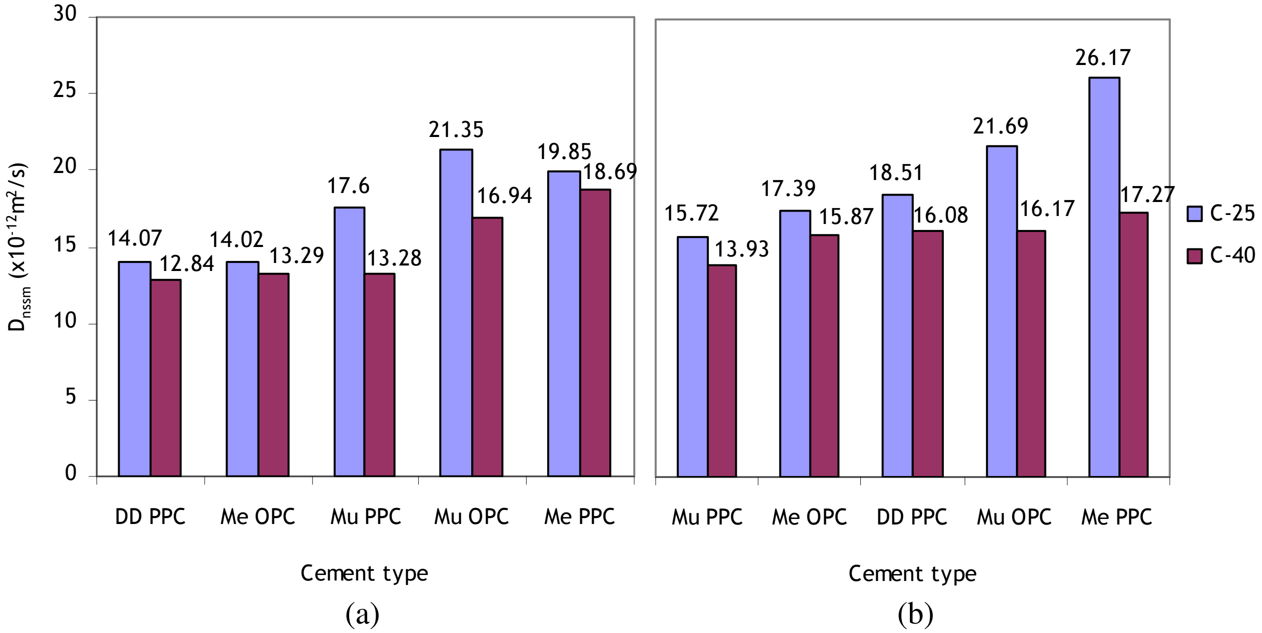
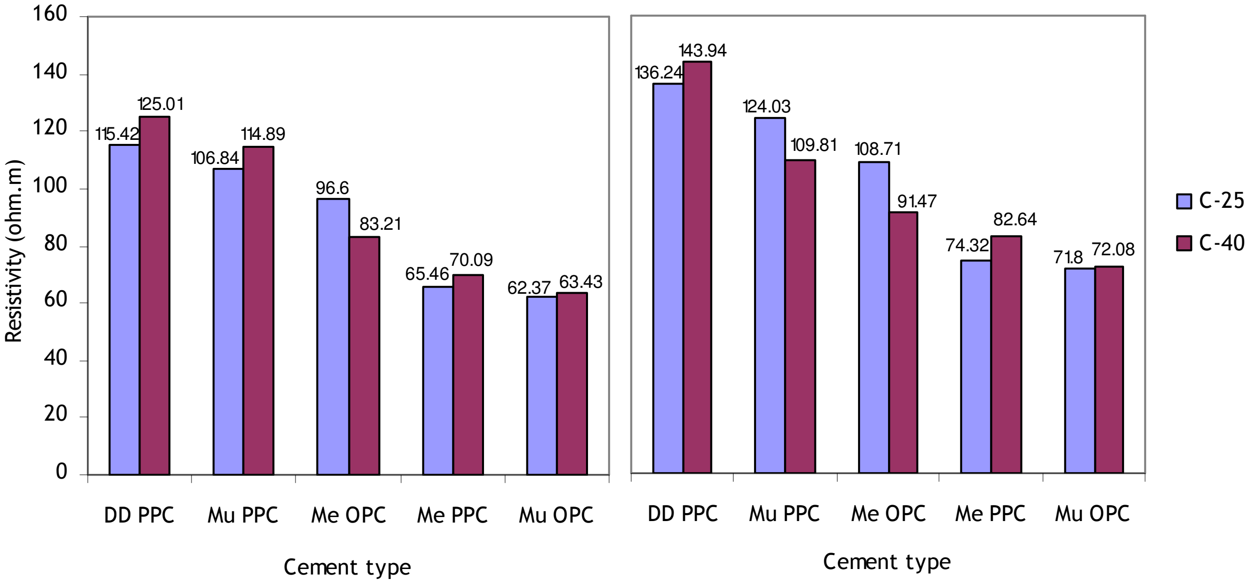


Figure 7.6. Variation of D_{nssm} for the different cements used (a) at the age of 60 days (b) at the age of 90 days

As opposed to the non-steady state migration coefficient, the electrical resistivity of the samples follows a distinct pattern both at the 60 and 90 days ages and for the C-25 as well as C-40 concretes. The reason for this might be the better precision with which the variables for resistivity calculation can be determined, both the thickness and initial resistance of the samples. The only factor affecting initial resistance of the samples is their initial water content which is made uniform as much as possible by saturating the specimens equally prior to the start of the test. However, the variables for determining the non-steady state migration coefficient, particularly the depth of chloride penetration could introduce errors in the calculation. In addition to the approximations while measurement, for instance, the interfacial zone effect is more significant in affecting the depth measurements, because, where a solid aggregate is present, the diffusion will likely take place trough the cement paste and mainly, the interfacial layer. This has been clearly observed while measuring the depths. In many of the split samples where the section passes through the aggregate, the depth of penetration is limited to the periphery of the aggregate and the cement paste only, while actually the movement is taking place at all other points outside the aggregate. This could definitely mislead in the calculation of the average penetration depth and consequently the D_{nssm}.

The resistivity values for the C-25 concretes vary from 62.37Ωm to 115.42Ωm at the age of 60 days and from 71.18Ωm to 136.24Ωm at the age of 90 days. The minimum and maximum values are obtained for the specimens made from Mugher OPC and Dire Dawa PPC respectively in both cases. The other specimens also follow a consistent pattern at both the ages.

In the case of the C-40 concretes, the magnitude of the resistivity has increased in comparison to the C-25 concretes and it ranges from 63.43Ωm to 125.01Ωm at the age of 60 days and from 72.08Ωm to 143.94Ωm at the age of 90 days. The extreme points in this case are also obtained for concretes made of Mugher OPC and Dire Dawa PPC cements and the value of the resistivity for the other cements is also exactly consistent as was obtained in the above case. It's also apparent that the degree of change for the minimum values of resistivity which are obtained for Mugher OPC are very small compared to the change in the maximum values. Figure 7.7 illustrates the variation of resistivity values for concretes made by the different cements at the two ages.



(a) (b)

Figure 7.7. Variation of resistivity for the different cements used (a) at the age of 60 days (b) at the age of 90 days

It can be concluded from the diffusion test results that concretes made by Dire Dawa PPC have the highest resistance to chloride migration while those made by Mugher OPC have the lowest. However, as discussed in section 4.3, diffusion is more likely to act together with capillary absorption as the diffusing species, the chloride ions in this case, are in solution form. Thus, although the samples are saturated prior to the diffusion test, they are not expected to be fully saturated and hence the factors which affect the rate of capillary absorption at the initial periods discussed earlier are likely to affect the diffusion results too, as the test duration is 6 hours. This makes the results obtained from the diffusion test the outcome of a mixed mode of transport which tends to amplify the magnitudes accordingly.

Comparing the diffusion test results with those obtained from the compressive strength tests shows a complete reversal in the case of Mugher OPC and Dire Dawa PPC cements. This shows that the nature of the material from which the cement is made is likely to affect transport properties across the concrete and therefore its durability irrespective of the compressive strength development potential.

7.3. Conclusion

Critical examination of the test results has revealed a variation in the reaction of concrete with respect to the different transport mechanisms. Accordingly, the results reflected that a type of concrete which reacts well to a specific transport phenomenon may not consistently do so for every other. This in turn shows that a single type of concrete may not perform effectively under different exposure conditions. Therefore, the suitability of concrete to a particular application is to be determined in relation to the actual environment under which it is designed to perform.

From theoretical perspectives, a set of complex and interrelated behaviors of concrete are responsible for determining its reaction to a particular transport mechanism. The microstructure of concrete may allow one type of transport process to take place readily, but may be less likely to others. Mixed modes of transport could also augment the combined effect as compared to each one acting separately.

Coming to the results of the tests, the comparative effect of the different cements has been found out to be different for each transport process considered. Accordingly, the effect of the cements is found to have the following general priority from most to least suitable for each case investigated.

- Permeability

1. Mugher OPC
2. Mugher PPC
3. Messobo OPC
4. Messobo PPC
5. Dire Dawa PPC

- Capillary absorption

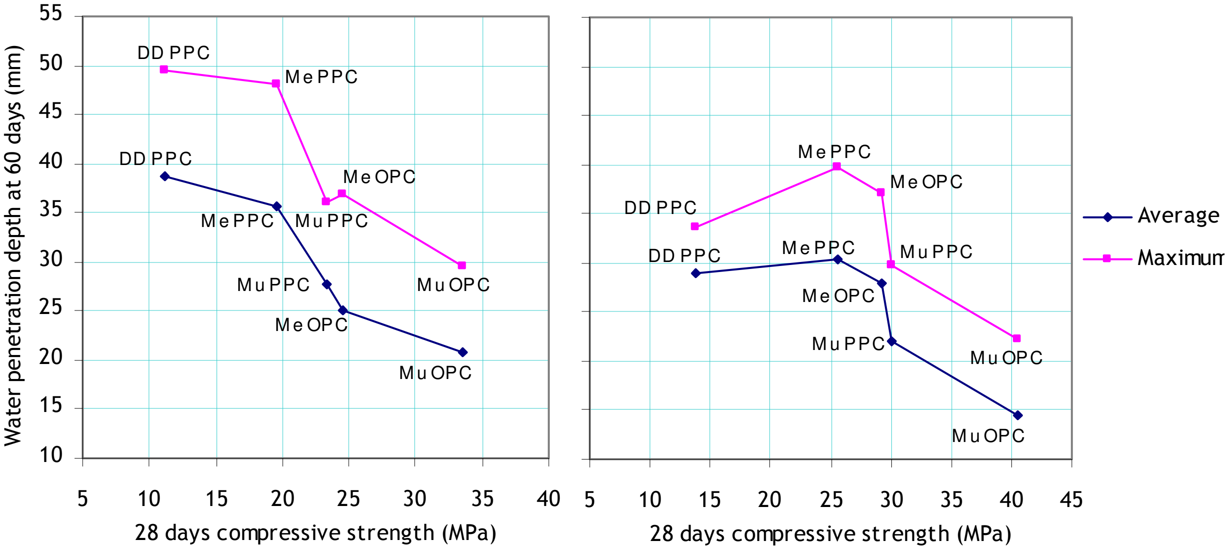
Rate	Suction porosity
1. Mugher PPC	1. Mugher OPC
2. Dire Dawa PPC	2. Messobo OPC
3. Messobo OPC	3. Mugher PPC
4. Mugher OPC	4. Messobo PPC
5. Messobo PPC	5. Dire Dawa PPC

- Chloride diffusion

1. Dire Dawa PPC
2. Mugher PPC
3. Messobo OPC
4. Messobo PPC
5. Mugher OPC

It is preferred not to sum up the results and convey them on absolute scale because, as stated earlier, effect of the environment will have an additional impact. For instance, in most exposure conditions, permeability is less relevant as compared to the other transport mechanisms considered. In addition, in determining overall suitability, the compressive strength factor will also come into picture. Therefore, it is essential to determine if particular cement is appropriate or not depending on the service to which it is intended to be applied. The following valid observations can however be made by thoroughly analyzing the test results.

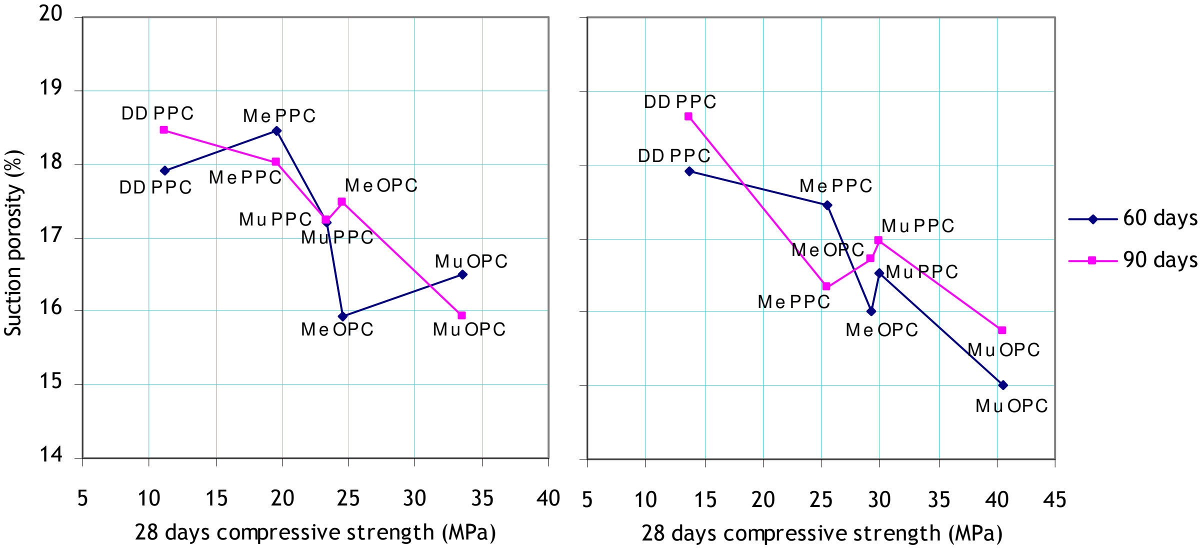
The trends obtained for compressive strength, permeability and suction porosity against the cements used tend to follow a more or less similar pattern. This is justified by the general fact that the denser the concrete, the more will be its compressive strength and the lower its permeability. Thus the total porosity is likely to have a significant effect on compressive strength and permeability as compared to the other types of transport processes. In other words, other configurations of the pore structure in concrete like the shape, size, distribution, tortuosity and continuity have less effect on compressive strength and permeability in comparison to their effect on other transport mechanisms. The following graphs show the interrelation between these parameters for the different cements investigated.



(a) (b)

Figure 7.8. Variation of water penetration depth with 28 days compressive strength for the different cements used (a) C-25 concretes (b) C-40 concretes

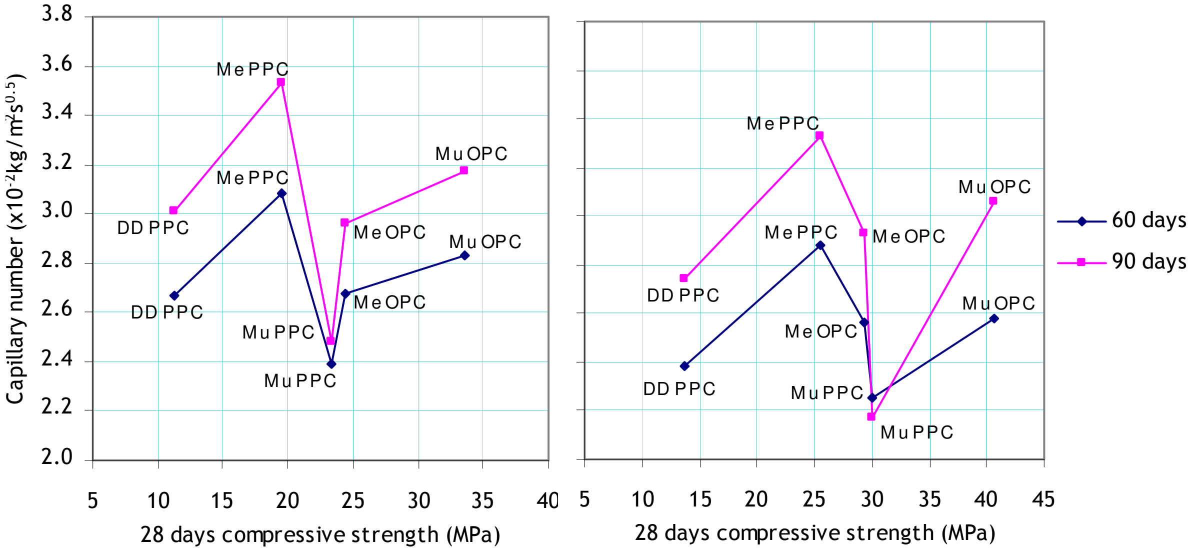
It is apparent from the above curves that in general, as compressive strength increases, both the average and maximum water penetration depths fall. As an exception, concretes made by Dire Dawa PPC showed a considerable decrease in both the average and maximum water penetration depths as the cement content is increased, without proportionate increase in their compressive strength. This shows the effect of Dire Dawa PPC in refining the pore system increases substantially with increase in cement content as compared to the other cements. Suction porosity also generally exhibits reduction with increase in compressive strength as illustrated in Figure 7.9.



(a) (b)

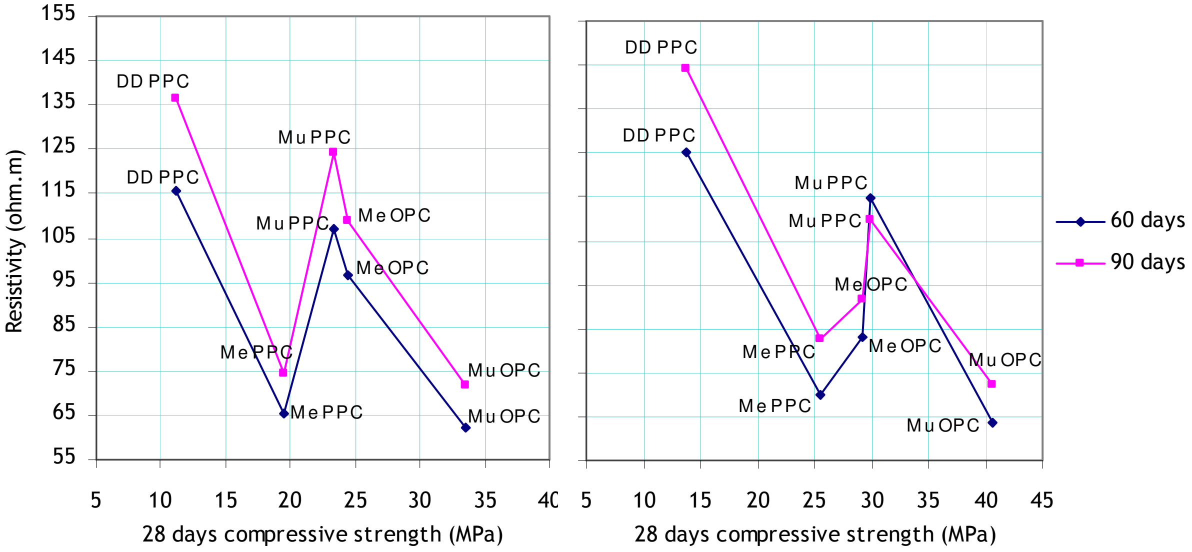
Figure 7.9. Variation of suction porosity with 28 days compressive strength for the different cements used (a) C-25 concretes (b) C-40 concretes

Capillary absorption and diffusion which have a tendency to act together unless the concrete is completely saturated, are however significantly affected by the structure of the pore network in addition to the amount, i.e. the total porosity. It can be observed from the results that the denser concretes with high compressive strength and low permeability have a tendency to show higher values in terms of rate of capillary absorption and diffusion, as shown in Figures 7.10 and 7.11. This shows that they have finer, interconnected pores through which the rate of capillary movement is higher although the total percentage of pores in them could still be lower.



(a) (b)

Figure 7.10. Variation of capillary number with 28 days compressive strength for the different cements used (a) C-25 concretes (b) C-40 concretes



(a) (b)

Figure 7.11. Variation of resistivity with 28 days compressive strength for the different cements used (a) C-25 concretes (b) C-40 concretes

The effect of pozzolanic materials in improving durability of concrete can also be observed from the test results. If we compare the results of concretes made by Mugher OPC and PPC for example, it can be observed that the PPC has a capacity to refine the pore structure making the concrete more resistant to capillary absorption and diffusion movement as compared to the OPC. In both cases, a closer performance is observed from Dire Dawa PPC, but relatively divergent one from Messobo PPC. This can be due to the nature of the pozzolanic materials used in the different cements, the one used in both Mugher and Dire Dawa PPC's is pumice, while that used in Mugher PPC is volcanic basalt. This in turn indicates that unless the suitability of the material in terms of both its pozzolanic and filler behaviors is assessed, the expected improvement in durability characteristics may not be attained. Moreover, natural pozzolans tend to have impurities like organic and other friable particles, and these could hamper their performance in spite of being suitable in their pure form. Thus, chemical analysis of all materials should be made frequently during manufacture to ensure a product of adequate and uniform quality.

A number of studies have also shown that blending of cements with suitable pozzolanic materials, natural or artificial, improves durability of concrete significantly depending on the type of material used. In this respect, there are a number of geological materials in Ethiopia with significant potential to be used as cement additions and therefore, it may be prudent to find alternatives with better performance. From the existing cement products however, it can be concluded that Mugher PPC has the highest performance in terms of the durability parameters assessed and Messobo PPC has comparatively the least. With regard to compressive strength, hydration of pozzolans is a delayed reaction as compared to that of pure Portland cement, and therefore, OPC's tend to gain compressive strength more quickly than PPC's. This could be the reason for the lower values of 28 days compressive strength test results obtained and it can be observed that for Mugher PPC, both the values are satisfied at the age of 91 days. However, it must be noted that there is a scope for improving the mix proportions so as to satisfy the requirements at the specified age as well.

7.4. Suggestions for further study

It is recommended that actual behaviors of the different cements in the country be studied in relation to their effects on durability by conducting tests on the raw materials used to produce the cements and on the cements themselves. It is also suggested to investigate blending options for the different cements, along with the corresponding economic feasibilities of course, from the point of view of improving their overall performance.

REFERENCES

1. Nigus G/Egziabher, “*Comparison of Concrete Properties Produced Using Mugher, Messobo and Dire Dawa Cements*”, MSc. Thesis, School of Graduate Studies, Addis Ababa University, November 2005.
2. Neville A. M., and Brooks J. J., "*Concrete Technology*", Third Indian Reprint, Replika Press Pvt. Ltd., India, 2003.
3. Bensted J., and Barnes P., "*Structure and Performance of Cements*", Second Edition, Edmundsbury Press, Suffolk, Great Britain, 2002.
4. Kosmatka S., Kerkhoff B., and Panarese W., "*Design and Control of Concrete Mixtures*", 14th Edition, Portland Cement Association, USA, 2002.
5. Mengistu T., and Fentaw H., "*Industrial Minerals and Rocks Resource Potential of Ethiopia*", Norway, 2003.
6. Heldal T., and Walle H., "*Building-stones of Ethiopia*", Grytting A/S, Norway, 2002.
7. Kropp J., and Hilsdorf H. K., "*Performance Criteria for Concrete Durability*", RILEM Technical Committee, TC 116-PCD, RILEM Report 12, 1995.
8. Mindess S., Young F. J., and Darwin D., "*Concrete*", Second Edition, Prentice Hall, Upper Saddle River, NJ07458, USA, 2003.
9. Bertolini L., Elsener B., Pedeferri P., and Polder R. P., “*Corrosion of Steel in Concrete*”, WILEY VCH Verlag & Co. KGaA, Weinheim, 2004.
10. Moskvin V., "*Concrete and Reinforced Concrete Deterioration and Protection*", Mir Publishers, Moscow, 1983.
11. Desta S. K., “*Some Laboratory Tests on the Durability of Concrete*”, Prosjektrapport, NTNU Trondheim, Norway, March 2000.
12. Desta S. K., “*Utilization of Ethiopian Natural Pozzolans*”, Dr. Ing. Thesis, Norwegian University of Science and Technology, Trondheim, Norway, March 2003.
13. Bentz D. P., Clifton J. R., Ferraris C. F., and Garboczi E. J., “*Transport Properties and Durability of Concrete: Literature Review and Research Plan*”, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, September 1999.
<http://www.fire.nist.gov/bfrlpubs/build99/PDF/b99038.pdf>

14. Roy D. M., and Idorn G. M., "*Concrete Microstructure*", Strategic Highway Research Program, National Research Council, Washington DC, August 1993. <http://www.trb.org/publications/shrp/SHRP-C-340.pdf>
15. Stanish K.D., Hooton R.D., and Thomas M.D.A., "*Testing the Chloride Penetration Resistance of Concrete: A Literature Review*", Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada. < http://www.tfhrc.gov/hnr20/pubs/chlconcrete.pdf>
16. Martys N. S., "*Survey of Concrete Transport Properties and Their Measurement*", U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology, Gaithersburg, MD 20899, February 1995. < http://www.fire.nist.gov/bfrlpubs/build95/PDF/b95095.pdf>
17. Shane J. D., Hwang J. H., Sohn D., Mason T.O., Jennings H. M., and Garboczi E. J., "*Recent Developments in the Measurement of Transport Properties in Cement-based Materials*", National Institute of Standards and Technology, Gaithersburg, MD, USA. < http://www.fire.nist.gov/bfrlpubs/build97/PDF/b97060.pdf>
18. The American Association of State Highway and Transportation Officials, "*Standard Specifications for Transportation Materials and Methods of Sampling and Testing: Part II – Methods of Sampling and Testing*", Thirteenth Edition, AASHTO, 444 North Capitol St., N.W., Suite 225 Washington, D.C. 20001, July 1982.
19. Dinku A., "*Constructions Materials Laboratory Manual*", Addis Ababa University Printing Press, Addis Ababa, June 2002.
20. Iliff L., and Dhanasekar R., "*Investigating the Water Permeability of Concrete by Means of the Constant Flow Method*", James Goldston Faculty of Engineering and Physical Systems, Central Queensland University, Rockhampton, Australia. <www.engineering.cqu.edu.au/fyep/Papers_pdf/Iliff.pdf>

APPENDIX ONE
COMPRESSIVE STRENGTH TEST RESULTS

Table A-1.1. 3 days compressive strength test results of trial samples

Cube ID	Dimension (cm)	Mass (gm)	Rate of loading (kN/s)	Max. load (kN)	σ (MPa)	σ_{avg} (MPa)
C25-1	15x15x15	7545	6.8	155.8	6.924	6.99
C25-2	15.2x15.2x15	8100	»	161.6	7.184	
C25-3	15x15x15	7657	»	154.1	6.848	
C40A-1	15x15x15	7784	»	300.1	13.34	13.11
C40A-2	»	7683	»	282.4	12.55	
C40A-3	15.2x15.2x15	8156	»	302.5	13.44	
C40B-1	15x15x15	7523	»	269.5	11.98	12.17
C40B-2	15.2x15.2x15	7914	»	286.2	12.72	
C40B-3	15x15x15	7552	»	265.9	11.82	

Table A-1.2. 28 days compressive strength test results

Cube ID	Dimension (cm)	Mass (gm)	Rate of loading (kN/s)	Max. load (kN)	σ (MPa)	σ_{avg} (MPa)
A11	15x15x15	7550	6.8	448.8	19.95	19.50
A12	15.2x15.2x15.2	8023	»	433.8	19.28	
A13	15x15x15	7597	»	433.8	19.28	
A21	15x15x15	7600	»	567.1	25.20	25.51
A22	»	7630	»	595.1	26.45	
A23	»	7657	»	559.7	24.88	
B11	14.9x14.9x15.2	7482	»	264.3	11.75	11.19
B12	14.8x14.8x15.3	7449	»	256.6	11.40	
B13	15x15x15	7489	»	234.5	10.42	
B21	14.7x14.8x15	7305	»	314.0	13.96	13.73
B22	15x15x15	7489	»	310.3	13.79	
B23	»	7508	»	302.5	13.44	
C11	15x15x15	7497	»	508.2	22.59	23.39
C12	15.2x15.2x15.2	7859	»	552.9	24.57	
C13	15x15x15	7539	»	517.6	23.00	
C21	14.7x15x15	7330	»	661.8	29.41	29.98
C22	15.1x14.9x15	7448	»	667.0	29.64	
C23	14.8x15x15	7306	»	694.8	30.88	
D11	15x15x15	7617	»	794.0	35.29	33.51
D12	»	7572	»	712.2	31.65	
D13	»	7506	»	755.4	33.58	
D21	15.2x15.2x15.2	8064	»	955.9	42.48	40.60
D22	15x14.8x15	7584	»	910.8	40.48	
D23	15x15x15	7589	»	874.0	38.85	
E11	14.9x15x15	7532	»	554.1	24.63	24.47
E12	15.3x15.3x15.2	7941	»	577.0	25.64	
E13	15x15x15	7531	»	520.6	23.14	
E21	15x15x15	7498	»	661.4	29.40	29.29
E22	14.8x15x15	7620	»	670.0	29.78	
E23	15x15x15	7600	»	645.7	28.70	

Table A-1.3. 56 days compressive strength test results

Cube ID	Dimension (cm)	Mass (gm)	Rate of loading (kN/s)	Max. load (kN)	σ (MPa)	σ_{avg} (MPa)
F11	15x15x15	7490	6.8	894.1	39.74	41.57
F12	»	7510	»	936.8	41.63	
F13	»	7478	»	974.9	43.33	
F21	»	7501	»	1072.0	47.64	48.78
F22	»	7492	»	1145.0	50.90	
F23	»	7499	»	1076.0	47.80	
G11	»	7340	»	693.9	30.85	30.78
G12	15.2x15x15.2	7790	»	699.5	31.09	
G13	15x14.9x15	7385	»	684.0	30.40	
G21	15.2x15.2x15.2	7851	»	844.5	37.53	37.47
G22	15x14.9x15	7414	»	839.9	37.33	
G23	15x15x15	7455	»	844.9	37.55	
H11	15x15x15.3	8078	»	871.1	35.83	35.41
H12	15x15x15	7579	»	835.4	35.59	
H13		7486	»	802.8	34.80	
H21		7516	»	953.7	41.03	41.52
H22		7504	»	994.7	41.83	
H23		7448	»	978.4	41.70	
I11	15x15.2x15.2	7818	»	623.5	27.71	27.06
I12	15x15x15	7470	»	594.0	26.40	
I13	»	7362	»	609.2	27.08	
I21	15x15x15	7567	»	821.7	36.52	36.37
I22		7381	»	787.2	34.99	
I23	15.3x15.3x15.3	7987	»	845.9	37.60	
J11	15x15x15	7343	»	366.6	16.29	17.07
J12	15.2x15.2x15	7780	»	398.5	17.71	
J13	15x14.9x15	7276	»	387.4	17.22	
J21	15x15x15	7299	»	440.1	19.56	19.67
J22	15x15x14.9	7281	»	429.2	19.08	
J23	15x14.9x15	7339	»	458.2	20.37	

Table A-1.3. 91 days compressive strength test results

Cube ID	Dimension (cm)	Mass (gm)	Rate of loading (kN/s)	Max. load (kN)	σ (MPa)	σ_{avg} (MPa)
A11	15x15x15	7234	6.8	638.5	28.38	28.54
A12	14.8x15.2x15	7306	»	626.4	27.84	
A13	15x15x15	7311	»	661.2	29.39	
A21	15x15x15	7416	»	868.2	38.59	38.43
A22	»	7443	»	865.8	38.48	
A23	»	7330	»	859.8	38.21	
B11	15.2x15.2x15.2	7577	»	365.4	16.24	17.42
B12	15x15x15	7179	»	386.6	17.18	
B13	»	7219	»	424.1	18.85	
B21	15x15x15	7186	»	486.4	21.62	21.14
B22	»	7275	»	477.2	21.21	
B23	15.2x15.2x15.3	7662	»	463.2	20.59	
C11	15x15x15.1	7255	»	722.9	32.13	32.39
C12	14.9x14.9x15	7376	»	742.1	32.98	
C13	14.9x15x15	7270	»	721.5	32.07	
C21	15x15x15	7291	»	885.9	39.37	39.13
C22	»	7281	»	865.4	38.46	
C23	»	7284	»	890.4	39.57	
D11	14.7x15x15	7337	»	973.0	43.25	43.64
D12	15x15x15	7378	»	988.8	43.95	
D13	»	7440	»	983.9	43.73	
D21	15x14.9x15.1	7474	»	1128.0	50.14	49.06
D22	15x15x15	7471	»	1053.0	46.79	
D23	15.2x15.2x15.4	7961	»	1131.0	50.26	
E11	15.1x15.2x15.2	7840	»	871.1	38.72	37.18
E12	15x15x15	7408	»	835.4	37.13	
E13	15x15x14.8	7396	»	802.8	35.68	
E21	14.7x15.2x15	7441	»	953.7	42.39	43.36
E22	14.7x15x15	7219	»	994.7	44.21	
E23	15x15x15	7462	»	978.4	43.48	

APPENDIX TWO
WATER PENETRATION TEST MEASUREMENTS

Table A-2.1. Water penetration depth measurements

Sample ID	Penetration depths measured at 10mm intervals (mm)															Avg (mm)	D_{max} (mm)	Avg (mm)
	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{12}	D_{13}	D_{14}	D_{15}	D_{avg}			
F11	18.23	21.22	25.34	27.48	25.91	26.23	29.45	30.51	28.72	32.14	26.35	25.64	23.81	24.03	26.40	20.71	33.51	29.62
F12	2.34	7.96	13.52	18.23	19.12	20.03	22.75	26.54	30.21	23.48	21.11	14.83	10.69	7.02	17.40		30.29	
F13	7.11	8.95	15.94	21.23	17.66	18.38	19.56	21.27	21.50	25.12	23.40	21.82	19.11	10.74	18.33		25.07	
G11	27.91	24.00	27.33	30.08	28.69	32.64	34.05	34.15	31.55	29.48	25.94	26.32	25.63	23.07	28.53	27.82	38.13	36.14
G12	19.89	21.77	31.97	35.02	37.55	41.59	33.67	38.48	34.59	31.78	28.11	27.46	24.95	23.67	30.65		41.59	
G13	18.39	25.85	27.54	25.52	25.15	27.74	26.59	22.73	25.78	28.09	23.65	27.75	21.55	15.99	24.27		28.70	
H11	14.33	20.61	26.70	28.92	30.92	30.59	27.91	25.66	24.06	24.61	24.58	20.09	14.66	11.91	23.36	25.09	33.11	36.79
H12	12.66	15.55	20.31	27.05	26.55	27.44	29.26	33.94	31.86	31.23	26.64	22.72	20.66	18.28	24.93		33.94	
H13	9.07	22.76	30.42	32.50	36.47	42.48	39.21	28.86	27.70	27.76	19.39	21.72	24.12	19.39	26.99		43.31	
I11	22.12	34.25	49.42	50.65	53.65	55.68	54.16	54.45	53.91	52.98	44.87	40.03	32.22	24.18	45.02	35.72	56.52	48.01
I12	13.73	18.34	23.34	30.69	39.85	41.69	45.26	42.95	42.30	41.81	32.68	30.76	26.01	19.35	32.44		45.75	
I13	15.36	19.60	23.54	28.95	32.76	36.25	37.49	41.76	38.89	37.40	30.46	27.59	23.02	19.58	29.71		41.76	
J11	17.19	21.15	25.88	31.93	38.51	44.17	47.59	47.16	45.10	45.56	39.84	35.99	28.73	21.76	35.53	38.67	47.59	49.45
J12	24.51	33.17	41.17	44.69	44.09	46.82	50.16	52.97	49.99	49.21	45.16	41.39	32.40	25.57	42.04		52.97	
J13	19.25	30.22	39.92	46.34	46.49	43.33	43.81	44.00	45.51	44.96	37.77	33.32	30.95	28.76	38.44		47.79	

Table A-2.2. Water Penetration depth measurements

Sample	**Penetration depths measured at 10mm intervals (mm)**															**Avg**	**D_{max}**	**Avg**
ID	**D_1**	**D_2**	**D_3**	**D_4**	**D_5**	**D_6**	**D_7**	**D_8**	**D_9**	**D_{10}**	**D_{12}**	**D_{13}**	**D_{14}**	**D_{15}**	**D_{avg}**	**(mm)**	**(mm)**	**(mm)**
F21	4.62	5.21	9.27	11.13	15.13	18.52	20.75	20.59	17.77	16.10	15.96	12.24	9.13	7.14	13.37	14.55	21.19	22.31
F22	9.04	10.49	14.50	17.55	17.36	15.12	16.25	15.63	13.43	15.68	24.65	22.20	17.86	14.05	16.17		25.95	
F23	8.74	10.97	12.41	15.14	18.03	17.89	18.26	17.93	15.15	12.54	13.57	14.08	11.53	11.18	14.11		19.78	
G21	13.93	19.56	21.25	23.29	23.78	25.76	27.32	28.97	27.56	27.76	22.50	21.40	15.03	11.50	22.28	22.07	29.63	29.73
G22	20.54	25.21	28.91	28.99	29.18	28.27	27.51	25.36	23.02	21.01	18.87	17.79	16.49	12.49	22.90		30.58	
G23	11.92	16.59	22.35	24.39	26.79	26.22	26.88	28.27	23.77	19.70	19.88	17.51	16.79	14.03	21.03		28.99	
H21	16.76	17.50	20.50	23.34	26.80	32.70	33.22	31.31	33.17	29.69	30.41	27.13	23.90	18.50	26.35	27.84	33.83	37.00
H22	16.85	25.14	32.85	34.67	34.87	34.42	35.12	38.68	35.71	31.71	28.08	25.39	20.18	18.79	29.43		39.48	
H23	8.61	15.25	20.94	24.13	28.15	30.93	35.22	36.24	34.92	33.78	36.67	29.15	25.37	21.49	27.74		37.68	
I21	17.48	19.25	27.31	31.64	33.19	33.74	35.25	36.17	36.35	37.41	29.43	25.25	24.05	17.69	29.14	30.39	37.41	39.68
I22	20.92	28.55	35.40	41.29	39.23	38.05	36.50	36.14	34.03	33.83	30.15	27.91	23.59	17.03	31.72		41.29	
I23	15.70	16.02	19.77	25.79	30.81	37.26	38.13	36.08	39.87	38.28	35.91	35.45	29.19	19.11	30.31		40.35	
J21	26.51	30.14	37.14	31.11	27.49	26.04	30.49	33.67	29.70	28.60	31.15	31.71	36.18	37.55	31.13	29.01	37.33	33.60
J22	24.94	30.80	31.05	28.22	26.70	29.39	28.62	27.78	27.94	27.16	26.49	27.30	27.53	25.30	27.69		31.21	
J23	19.95	21.25	26.94	26.86	25.71	31.20	31.41	32.09	32.27	30.25	29.24	29.46	28.25	26.97	28.20		32.27	

APPENDIX THREE
CAPILLARY SUCTION TEST MEASUREMENTS AND CALCULATION

Table A-3.1. Measured capillary suction data for C-25 and C-40 concrete samples made by Mugher OPC (tested at 60 days)

Sample ID	Thickness (cm)	Oven dry mass (gm)	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
F11	2.5	885	889	902	906	910	914	917	919	933	942	949	952	953	954	955	958	960	960
F12	2.4	847	852	864	868	871	875	877	880	892	901	906	909	910	911	911	914	915	916
F13	2.6	965	970	984	989	993	996	999	1002	1015	1025	1033	1038	1040	1041	1042	1046	1047	1048
F14	2.6	941	945	960	964	968	971	974	976	988	997	1003	1007	1009	1011	1012	1015	1016	1016
F15	2.7	1022	1027	1042	1047	1051	1054	1057	1059	1070	1079	1086	1092	1096	1098	1100	1103	1104	1104
Average	2.56	932	937	950	955	959	962	965	967.2	979.6	988.8	995.4	999.6	1001.6	1003	1004	1007.2	1008.4	1009
F21	2.6	962	966	978	982	985	988	990	992	1003	1010	1017	1022	1024	1026	1027	1030	1031	1031
F22	2.5	910	914	926	930	934	937	940	942	954	962	968	970	971	972	973	976	977	977
F23	2.5	908	912	924	928	932	935	938	940	952	961	968	972	974	975	976	979	980	980
F24	2.5	856	860	873	877	880	883	886	888	900	909	914	917	919	920	921	923	924	924
F25	2.3	796	800	813	817	820	823	826	828	839	848	852	854	855	856	857	859	860	860
Average	2.48	886	890	903	907	910	913	916	918	929.6	938	943.8	947	948.6	949.8	950.8	953.4	954.4	954.4

Table A-3.2. Calculation of Q_i's for C-25 and C-40 concrete samples made by Mugher OPC (tested at 60 days)

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.849	1.132	1.358	1.528	1.698	1.811	2.490	2.999	3.339	3.622	3.735	3.848	3.848	4.075	4.131	4.131
0	0.905	1.245	1.471	1.641	1.811	1.924	2.603	3.113	3.452	3.622	3.735	3.792	3.848	4.018	4.075	4.131
0	0.849	1.132	1.358	1.528	1.698	1.868	2.490	2.999	3.339	3.565	3.679	3.735	3.792	4.018	4.075	4.131
0	1.019	1.358	1.585	1.754	1.924	2.037	2.716	3.226	3.565	3.792	3.962	4.075	4.131	4.358	4.414	4.471
0	0.962	1.302	1.585	1.754	1.924	2.037	2.716	3.226	3.622	3.848	4.018	4.131	4.188	4.414	4.471	4.527
0	0.917	1.234	1.471	1.641	1.811	1.935	2.603	3.113	3.463	3.69	3.826	3.916	3.962	4.177	4.233	4.278
0	0.849	1.132	1.358	1.585	1.754	1.868	2.547	3.113	3.509	3.735	3.848	3.905	3.962	4.188	4.244	4.244
0	0.905	1.188	1.415	1.641	1.811	1.924	2.547	3.056	3.452	3.679	3.848	3.905	3.905	4.188	4.188	4.244
0	0.905	1.188	1.415	1.585	1.754	1.868	2.603	3.056	3.339	3.396	3.509	3.509	3.565	3.735	3.735	3.792
0	0.962	1.245	1.471	1.641	1.811	1.924	2.603	3.169	3.509	3.792	3.905	4.018	4.075	4.301	4.358	4.414
0	0.905	1.245	1.471	1.641	1.811	1.924	2.547	2.943	3.113	3.17	3.226	3.282	3.282	3.452	3.509	3.509
0	0.905	1.2	1.426	1.619	1.788	1.902	2.569	3.067	3.384	3.55	3.667	3.724	3.758	3.973	4.007	4.041

Table A-3.3. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Mugher PPC (tested at 60 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
G11	2.4	883	887	898	903	906	909	911	914	923	932	938	943	947	950	952	959	959	960
G12	2.6	1006	1010	1022	1026	1030	1033	1035	1037	1045	1053	1058	1063	1066	1069	1072	1084	1085	1086
G13	2.3	835	838	850	855	858	861	864	865	875	884	889	894	897	900	902	906	906	907
G14	2.6	1028	1031	1043	1047	1051	1054	1057	1059	1067	1074	1079	1083	1086	1089	1092	1104	1105	1106
G15	2.5	879	883	898	902	906	909	912	914	923	932	937	941	944	946	948	952	953	953
Average	2.48	926	930	942	947	950	953	956	957.8	966.6	975	980.2	984.8	988	990.8	993.2	1001	1002	1002
G21	2.4	843	847	860	865	869	873	876	878	888	898	902	907	910	912	914	917	918	919
G22	2.5	954	958	970	974	978	981	983	985	994	1003	1007	1012	1016	1019	1022	1035	1036	1036
G23	2.6	1010	1014	1026	1030	1034	1037	1039	1041	1049	1055	1059	1064	1066	1069	1072	1086	1087	1087
G24	2.5	1008	1011	1020	1024	1027	1029	1031	1033	1039	1045	1048	1051	1053	1055	1057	1068	1068	1069
G25	2.5	968	972	982	986	989	992	994	995	1003	1009	1014	1017	1020	1023	1026	1038	1038	1039
Average	2.50	957	960	972	976	979	982	985	986.4	994.6	1002	1006	1010.2	1013	1016	1018.2	1028.8	1014	1015

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.623	0.905	1.075	1.245	1.358	1.528	2.037	2.547	2.886	3.169	3.396	3.565	3.679	4.075	4.075	4.131
0	0.679	0.905	1.132	1.302	1.415	1.528	1.981	2.434	2.716	2.999	3.169	3.339	3.509	4.188	4.244	4.301
0	0.679	0.962	1.132	1.302	1.471	1.528	2.094	2.603	2.886	3.169	3.339	3.509	3.622	3.848	3.848	3.905
0	0.679	0.905	1.132	1.302	1.471	1.585	2.037	2.434	2.716	2.943	3.113	3.282	3.452	4.131	4.188	4.244
0	0.849	1.075	1.302	1.471	1.641	1.754	2.264	2.773	3.056	3.282	3.452	3.565	3.679	3.905	3.962	3.962
0	0.702	0.951	1.154	1.324	1.471	1.585	2.083	2.558	2.852	3.113	3.294	3.452	3.59	4.029	4.063	4.109
0	0.736	1.019	1.245	1.471	1.641	1.754	2.320	2.886	3.113	3.396	3.565	3.679	3.792	3.962	4.018	4.075
0	0.679	0.905	1.132	1.302	1.415	1.528	2.037	2.547	2.773	3.056	3.282	3.452	3.622	4.358	4.414	4.414
0	0.679	0.905	1.132	1.302	1.415	1.528	1.981	2.320	2.547	2.830	2.943	3.113	3.282	4.075	4.131	4.131
0	0.509	0.736	0.905	1.019	1.132	1.245	1.585	1.924	2.094	2.264	2.377	2.490	2.603	3.226	3.226	3.282
0	0.566	0.792	0.962	1.132	1.245	1.302	1.754	2.094	2.377	2.547	2.716	2.886	3.056	3.735	3.735	3.792
0	0.634	0.872	1.075	1.245	1.37	1.471	1.935	2.354	2.581	2.818	2.977	3.124	3.27	3.871	3.905	3.939

Table A-3.4. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Messobo OPC (tested at 60 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
H11	2.5	949	949	963	968	972	974	978	980	990	1000	1007	1011	1014	1016	1017	1020	1021	1021
H12	2.7	1024	1024	1039	1044	1047	1050	1053	1055	1064	1072	1079	1084	1088	1091	1093	1095	1096	1097
H13	2.4	879	879	895	901	905	908	912	915	926	935	940	943	946	948	948	950	951	951
H14	2.5	889	889	904	909	913	915	919	921	930	939	945	947	949	951	952	953	954	955
H15	2.8	1052	1052	1068	1073	1077	1079	1082	1084	1093	1101	1107	1111	1115	1118	1120	1122	1123	1123
Average	2.58	959	959	974	979	983	985	988.8	991	1001	1009.4	1016	1019	1022	1025	1026	1028	1029	1029
H21	2.7	993	997	1009	1014	1018	1022	1026	1028	1037	1046	1053	1058	1062	1064	1067	1070	1071	1071
H22	2.6	981	984	995	1000	1004	1007	1010	1012	1021	1030	1037	1043	1047	1051	1053	1057	1057	1058
H23	2.3	836	838	849	854	858	860	864	866	876	885	891	893	895	897	898	900	900	901
H24	2.4	854	854	869	874	878	880	884	886	896	904	910	913	916	918	918	920	921	921
H25	2.4	897	897	911	916	919	922	926	928	936	944	950	953	955	957	958	960	961	961
Average	2.48	912	914	927	932	935	938	942	944	953.2	961.8	968.2	972	975	977.4	978.8	981.4	982	982.4

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.792	1.075	1.302	1.415	1.641	1.754	2.320	2.886	3.282	3.509	3.679	3.792	3.848	4.018	4.075	4.075
0	0.849	1.132	1.302	1.471	1.641	1.754	2.264	2.716	3.113	3.396	3.622	3.792	3.905	4.018	4.075	4.131
0	0.905	1.245	1.471	1.641	1.868	2.037	2.660	3.169	3.452	3.622	3.792	3.905	3.905	4.018	4.075	4.075
0	0.849	1.132	1.358	1.471	1.698	1.811	2.320	2.830	3.169	3.282	3.396	3.509	3.565	3.622	3.679	3.735
0	0.905	1.188	1.415	1.528	1.698	1.811	2.320	2.773	3.113	3.339	3.565	3.735	3.848	3.962	4.018	4.018
0	0.86	1.154	1.37	1.505	1.709	1.834	2.377	2.875	3.23	3.43	3.611	3.746	3.814	3.928	3.984	4.01
0	0.679	0.962	1.188	1.415	1.641	1.754	2.264	2.773	3.169	3.452	3.679	3.792	3.962	4.131	4.188	4.188
0	0.623	0.905	1.132	1.302	1.471	1.585	2.094	2.603	2.999	3.339	3.565	3.792	3.905	4.131	4.131	4.188
0	0.623	0.905	1.132	1.245	1.471	1.585	2.151	2.660	2.999	3.113	3.226	3.339	3.396	3.509	3.509	3.565
0	0.849	1.132	1.358	1.471	1.698	1.811	2.377	2.830	3.169	3.339	3.509	3.622	3.622	3.735	3.792	3.792
0	0.792	1.075	1.245	1.415	1.641	1.754	2.207	2.660	2.999	3.169	3.282	3.396	3.452	3.565	3.622	3.622
0	0.713	0.996	1.211	1.37	1.585	1.698	2.218	2.705	3.07	3.282	3.452	3.588	3.667	3.814	3.848	3.87

Table A-3.5. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Messobo PPC (tested at 60 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
I11	2.5	932	939	954	959	963	966	969	972	984	992	999	1003	1005	1006	1007	1010	1011	1012
I12	2.5	912	918	931	936	939	943	945	948	961	971	978	983	985	987	988	991	993	994
I13	2.5	920	926	940	946	950	953	956	958	972	981	989	992	994	995	995	999	1000	1001
I14	2.6	984	991	1007	1014	1018	1022	1025	1029	1044	1055	1064	1070	1072	1074	1075	1079	1080	1081
I15	2.1	828	834	850	856	860	863	866	869	883	892	896	899	900	900	901	903	905	906
Average	2.44	915	922	936	942	946	949	952.2	955.2	968.8	978.2	985.2	989.4	991.2	992.4	993.2	996.4	997.8	999
I21	2.3	861	867	882	887	891	894	897	899	912	921	926	928	929	929	930	933	934	935
I22	2.3	842	849	864	870	874	877	880	883	897	906	909	911	912	913	913	916	918	918
I23	2.6	987	993	1006	1011	1014	1017	1020	1023	1035	1044	1052	1059	1062	1065	1066	1070	1071	1072
I24	2.6	979	986	999	1005	1008	1011	1014	1016	1029	1038	1045	1051	1053	1055	1056	1060	1062	1062
I25	2.5	893	899	913	918	921	924	927	929	942	951	958	964	966	967	968	972	973	973
Average	2.46	912	919	933	938	942	945	947.6	950	963	972	978	982.6	984.4	985.8	986.6	990.2	991.6	992

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.849	1.132	1.358	1.528	1.698	1.868	2.547	2.999	3.396	3.622	3.735	3.792	3.848	4.018	4.075	4.131
0	0.736	1.019	1.188	1.415	1.528	1.698	2.434	2.999	3.396	3.679	3.792	3.905	3.962	4.131	4.244	4.301
0	0.792	1.132	1.358	1.528	1.698	1.811	2.603	3.113	3.565	3.735	3.848	3.905	3.905	4.131	4.188	4.244
0	0.905	1.302	1.528	1.754	1.924	2.151	2.999	3.622	4.131	4.471	4.584	4.697	4.754	4.980	5.037	5.093
0	0.905	1.245	1.471	1.641	1.811	1.981	2.773	3.282	3.509	3.679	3.735	3.735	3.792	3.905	4.018	4.075
0	0.838	1.166	1.381	1.573	1.732	1.902	2.671	3.203	3.599	3.84	3.939	4.007	4.052	4.233	4.312	4.369
0	0.849	1.132	1.358	1.528	1.698	1.811	2.547	3.056	3.339	3.452	3.509	3.509	3.565	3.735	3.792	3.848
0	0.849	1.188	1.415	1.585	1.754	1.924	2.716	3.226	3.396	3.509	3.565	3.622	3.622	3.792	3.905	3.905
0	0.736	1.019	1.188	1.358	1.528	1.698	2.377	2.886	3.339	3.735	3.905	4.075	4.131	4.358	4.414	4.471
0	0.736	1.075	1.245	1.415	1.585	1.698	2.434	2.943	3.339	3.679	3.792	3.905	3.962	4.188	4.301	4.301
0	0.792	1.075	1.245	1.415	1.585	1.698	2.434	2.943	3.339	3.679	3.792	3.848	3.905	4.131	4.188	4.188
0	0.792	1.098	1.29	1.46	1.63	1.766	2.501	3.011	3.35	3.61	3.713	3.792	3.837	4.041	4.12	4.143

Table A-3.6. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Dire Dawa PPC (tested at 60 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
J11	2.5	883	887	903	908	913	916	918	920	931	938	943	948	951	954	956	960	962	963
J12	2.4	763	768	783	788	792	795	797	799	809	816	821	826	829	832	835	840	842	842
J13	2.4	774	779	792	797	801	804	806	808	817	825	829	834	837	840	842	847	848	849
J14	2.5	927	932	946	952	956	959	962	964	975	984	989	995	998	1002	1005	1012	1014	1014
J15	2.5	846	851	866	871	876	878	881	883	894	901	907	912	916	919	922	927	929	929
Average	2.46	839	843	858	863	868	870	872.8	874.8	885.2	892.8	897.8	903	906.2	909.4	912	917.2	919	919
J21	2.4	801	806	820	825	828	830	832	834	842	848	853	856	859	862	864	871	873	874
J22	2.5	912	917	932	937	941	944	945	947	957	964	969	973	976	979	983	996	998	999
J23	2.3	766	771	786	792	795	798	800	802	811	817	821	825	828	830	833	838	839	840
J24	2.4	800	806	821	826	830	832	835	836	845	852	857	861	864	866	870	877	879	880
J25	2.5	956	961	976	981	985	988	990	992	1002	1009	1014	1019	1022	1026	1030	1041	1043	1043
Average	2.42	847	852	867	872	876	878	880.4	882.2	891.4	898	902.8	906.8	909.8	912.6	916	924.6	926.4	927

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.905	1.188	1.471	1.641	1.754	1.868	2.490	2.886	3.169	3.452	3.622	3.792	3.905	4.131	4.244	4.301
0	0.849	1.132	1.358	1.528	1.641	1.754	2.320	2.716	2.999	3.282	3.452	3.622	3.792	4.075	4.188	4.188
0	0.736	1.019	1.245	1.415	1.528	1.641	2.151	2.603	2.830	3.113	3.282	3.452	3.565	3.848	3.905	3.962
0	0.792	1.132	1.358	1.528	1.698	1.811	2.434	2.943	3.226	3.565	3.735	3.962	4.131	4.527	4.641	4.641
0	0.849	1.132	1.415	1.528	1.698	1.811	2.434	2.830	3.169	3.452	3.679	3.848	4.018	4.301	4.414	4.414
0	0.826	1.121	1.37	1.528	1.664	1.777	2.366	2.796	3.079	3.37	3.554	3.735	3.882	4.177	4.278	4.301
0	0.792	1.075	1.245	1.358	1.471	1.585	2.037	2.377	2.660	2.830	2.999	3.169	3.282	3.679	3.792	3.848
0	0.849	1.132	1.358	1.528	1.585	1.698	2.264	2.660	2.943	3.169	3.339	3.509	3.735	4.471	4.584	4.641
0	0.849	1.188	1.358	1.528	1.641	1.754	2.264	2.603	2.830	3.056	3.226	3.339	3.509	3.792	3.848	3.905
0	0.849	1.132	1.358	1.471	1.641	1.698	2.207	2.603	2.886	3.113	3.282	3.396	3.622	4.018	4.131	4.188
0	0.849	1.132	1.358	1.528	1.641	1.754	2.320	2.716	2.999	3.282	3.452	3.679	3.905	4.527	4.641	4.641
0	0.838	1.132	1.336	1.483	1.596	1.698	2.218	2.592	2.864	3.09	3.26	3.418	3.611	4.097	4.199	4.244

Table A-3.7. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Messobo PPC (tested at 90 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
A11	2.60	966	974	993	1000	1004	1009	1012	1015	1031	1037	1042	1046	1048	1049	1050	1053	1055	1056
A12	2.46	877	885	904	910	915	918	922	925	940	945	950	953	954	955	955	959	960	961
A13	2.29	808	815	834	840	844	848	851	854	868	872	875	877	878	879	879	881	883	883
A14	2.54	911	918	937	943	947	950	954	957	971	976	981	984	987	988	988	991	992	993
A15	2.48	882	889	909	914	918	922	925	928	943	948	953	956	957	958	959	961	963	963
Average	2.41	889	896	915	921	926	929	932.8	935.8	950.6	955.6	960.2	963.2	964.8	965.8	966.2	969	970.6	971
A21	2.44	858	866	881	888	891	895	898	901	916	921	926	930	931	932	933	936	937	938
A22	2.31	799	807	822	828	832	836	840	843	857	862	865	867	868	869	869	871	873	873
A23	2.44	825	832	849	855	859	862	866	869	884	888	893	896	898	898	899	901	903	903
A24	2.40	882	889	905	911	914	918	921	924	938	943	947	949	950	951	951	954	956	956
A25	2.46	854	862	878	884	888	892	895	898	914	919	924	927	930	931	931	934	935	936
Average	2.47	844	851	867	873	877	881	884	887	901.8	906.6	911	913.8	915.4	916.2	916.6	919.2	920.8	921

Q_0	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	1.075	1.471	1.698	1.981	2.151	2.320	3.226	3.565	3.848	4.075	4.188	4.244	4.301	4.471	4.584	4.641
0	1.075	1.415	1.698	1.868	2.094	2.264	3.113	3.396	3.679	3.848	3.905	3.962	3.962	4.188	4.244	4.301
0	1.075	1.415	1.641	1.868	2.037	2.207	2.999	3.226	3.396	3.509	3.565	3.622	3.622	3.735	3.848	3.848
0	1.075	1.415	1.641	1.811	2.037	2.207	2.999	3.282	3.565	3.735	3.905	3.962	3.962	4.131	4.188	4.244
0	1.132	1.415	1.641	1.868	2.037	2.207	3.056	3.339	3.622	3.792	3.848	3.905	3.962	4.075	4.188	4.188
0	1.087	1.426	1.664	1.879	2.071	2.241	3.079	3.362	3.622	3.79	3.882	3.939	3.962	4.12	4.211	4.244
0	0.849	1.245	1.415	1.641	1.811	1.981	2.830	3.113	3.396	3.622	3.679	3.735	3.792	3.962	4.018	4.075
0	0.849	1.188	1.415	1.641	1.868	2.037	2.830	3.113	3.282	3.396	3.452	3.509	3.509	3.622	3.735	3.735
0	0.962	1.302	1.528	1.698	1.924	2.094	2.943	3.169	3.452	3.622	3.735	3.735	3.792	3.905	4.018	4.018
0	0.905	1.245	1.415	1.641	1.811	1.981	2.773	3.056	3.282	3.396	3.452	3.509	3.509	3.679	3.792	3.792
0	0.905	1.245	1.471	1.698	1.868	2.037	2.943	3.226	3.509	3.679	3.848	3.905	3.905	4.075	4.131	4.188
0	0.894	1.245	1.449	1.664	1.856	2.026	2.864	3.135	3.384	3.54	3.633	3.679	3.701	3.85	3.939	3.962

Table A-3.8. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Dire Dawa PPC (tested at 90 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
B11	2.66	883	890	908	914	919	924	926	929	941	949	958	962	965	969	971	977	978	978
B12	2.58	895	900	918	923	928	931	934	937	947	956	965	968	972	975	978	983	985	985
B13	2.53	848	854	872	878	883	886	889	892	903	910	917	920	923	926	928	933	934	935
B14	2.44	825	830	848	853	858	861	863	865	876	883	889	892	894	897	899	904	905	905
B15	2.80	978	984	1004	1010	1015	1018	1020	1022	1034	1043	1050	1053	1057	1060	1062	1068	1069	1070
Average	2.60	886	892	910	916	921	924	926.4	929	940.2	948.2	955.8	959	962.2	965.4	967.6	973	974.2	975
B21	2.61	923	928	945	949	954	957	959	961	972	979	986	989	993	997	1000	1009	1010	1011
B22	2.29	804	809	826	832	836	838	841	843	853	859	866	869	872	875	878	883	884	885
B23	2.35	805	811	828	833	837	840	843	845	855	863	871	874	877	880	882	887	888	889
B24	2.49	853	858	875	880	884	887	889	891	902	910	917	920	923	927	929	936	937	938
B25	2.68	945	950	967	973	977	980	982	984	995	1003	1011	1013	1017	1020	1023	1032	1033	1034
Average	2.48	866	871	888	893	898	900	902.8	904.8	915.4	922.8	930.2	933	936.4	939.8	942.4	949.4	950.4	951

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	1.019	1.358	1.641	1.924	2.037	2.207	2.886	3.339	3.848	4.075	4.244	4.471	4.584	4.924	4.980	4.980
0	1.019	1.302	1.585	1.754	1.924	2.094	2.660	3.169	3.679	3.848	4.075	4.244	4.414	4.697	4.810	4.810
0	1.019	1.358	1.641	1.811	1.981	2.151	2.773	3.169	3.565	3.735	3.905	4.075	4.188	4.471	4.527	4.584
0	1.019	1.302	1.585	1.754	1.868	1.981	2.603	2.999	3.339	3.509	3.622	3.792	3.905	4.188	4.244	4.244
0	1.132	1.471	1.754	1.924	2.037	2.151	2.830	3.339	3.735	3.905	4.131	4.301	4.414	4.754	4.810	4.867
0	1.041	1.358	1.641	1.834	1.969	2.117	2.75	3.203	3.633	3.81	3.995	4.177	4.301	4.61	4.675	4.697
0	0.962	1.188	1.471	1.641	1.754	1.868	2.490	2.886	3.282	3.452	3.679	3.905	4.075	4.584	4.641	4.697
0	0.962	1.302	1.528	1.641	1.811	1.924	2.490	2.830	3.226	3.396	3.565	3.735	3.905	4.188	4.244	4.301
0	0.962	1.245	1.471	1.641	1.811	1.924	2.490	2.943	3.396	3.565	3.735	3.905	4.018	4.301	4.358	4.414
0	0.962	1.245	1.471	1.641	1.754	1.868	2.490	2.943	3.339	3.509	3.679	3.905	4.018	4.414	4.471	4.527
0	0.962	1.302	1.528	1.698	1.811	1.924	2.547	2.999	3.452	3.565	3.792	3.962	4.131	4.641	4.697	4.754
0	0.962	1.256	1.494	1.653	1.788	1.902	2.501	2.92	3.339	3.497	3.69	3.882	4.029	4.43	4.482	4.539

Table A-3.9. Measured data and calculation of Q_i’s for C-25 and C-40 concrete samples made by Mugher PPC (tested at 90 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
C11	2.43	827	833	848	854	858	861	864	866	876	884	890	894	897	899	900	905	906	906
C12	2.63	921	927	942	947	950	953	956	958	966	974	980	984	989	993	996	1006	1007	1007
C13	2.53	904	911	925	929	933	935	937	940	947	955	960	964	969	972	974	982	983	984
C14	2.46	852	859	875	880	884	887	890	893	902	910	916	920	924	926	928	933	934	934
C15	2.37	817	823	838	843	846	849	851	853	860	868	872	876	880	882	884	888	889	890
Average	2.48	864	871	886	891	894	897	899.6	902	910.2	918.2	923.6	927.6	931.8	934.4	936.4	942.8	943.8	944
C21	2.60	930	937	950	955	958	961	964	966	973	981	986	990	994	997	999	1008	1009	1009
C22	2.54	934	940	954	959	962	965	967	969	977	983	988	992	996	998	1001	1012	1013	1013
C23	2.39	863	869	883	887	890	893	895	898	904	911	915	919	923	925	927	936	937	937
C24	2.35	841	847	862	866	869	872	874	877	884	892	896	900	904	906	909	915	916	916
C25	2.16	773	779	793	797	800	803	805	807	815	822	827	831	835	837	839	843	844	844
Average	2.41	868	874	888	893	896	899	901	903.4	910.6	917.8	922.4	926.4	930.4	932.6	935	942.8	943.8	944

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.849	1.188	1.415	1.585	1.754	1.868	2.434	2.886	3.226	3.452	3.622	3.735	3.792	4.075	4.131	4.131
0	0.849	1.132	1.302	1.471	1.641	1.754	2.207	2.660	2.999	3.226	3.509	3.735	3.905	4.471	4.527	4.527
0	0.792	1.019	1.245	1.358	1.471	1.641	2.037	2.490	2.773	2.999	3.282	3.452	3.565	4.018	4.075	4.131
0	0.905	1.188	1.415	1.585	1.754	1.924	2.434	2.886	3.226	3.452	3.679	3.792	3.905	4.188	4.244	4.244
0	0.849	1.132	1.302	1.471	1.585	1.698	2.094	2.547	2.773	2.999	3.226	3.339	3.452	3.679	3.735	3.792
0	0.849	1.132	1.336	1.494	1.641	1.777	2.241	2.694	2.999	3.23	3.463	3.611	3.724	4.086	4.143	4.165
0	0.736	1.019	1.188	1.358	1.528	1.641	2.037	2.490	2.773	2.999	3.226	3.396	3.509	4.018	4.075	4.075
0	0.792	1.075	1.245	1.415	1.528	1.641	2.094	2.434	2.716	2.943	3.169	3.282	3.452	4.075	4.131	4.131
0	0.792	1.019	1.188	1.358	1.471	1.641	1.981	2.377	2.603	2.830	3.056	3.169	3.282	3.792	3.848	3.848
0	0.849	1.075	1.245	1.415	1.528	1.698	2.094	2.547	2.773	2.999	3.226	3.339	3.509	3.848	3.905	3.905
0	0.792	1.019	1.188	1.358	1.471	1.585	2.037	2.434	2.716	2.943	3.169	3.282	3.396	3.622	3.679	3.679
0	0.792	1.041	1.211	1.381	1.505	1.641	2.049	2.456	2.716	2.94	3.169	3.294	3.43	3.871	3.928	3.928

Table A-3.10. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Mugher OPC (tested at 90 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
D11	2.61	927	933	947	953	957	960	962	966	980	987	992	996	997	998	999	1003	1004	1005
D12	2.58	872	879	894	901	904	908	910	913	928	933	937	940	942	942	943	946	948	948
D13	2.72	968	975	991	999	1003	1006	1009	1012	1027	1034	1039	1043	1044	1045	1046	1050	1051	1051
D14	2.28	852	858	873	879	882	885	887	891	904	909	912	915	915	916	917	920	921	921
D15	2.70	1007	1013	1029	1036	1039	1042	1045	1048	1061	1067	1071	1074	1076	1076	1077	1081	1083	1083
Average	2.58	925	932	947	954	957	960	962.6	966	980	986	990.2	993.6	994.8	995.4	996.4	1000	1001.4	1002
D21	2.38	839	845	859	865	869	872	874	877	891	896	899	901	902	903	904	907	907	908
D22	2.41	873	879	894	900	903	906	909	912	927	932	935	938	939	940	941	944	945	945
D23	2.53	896	903	917	923	927	930	932	935	950	956	960	963	964	965	965	969	970	970
D24	2.56	906	913	928	935	939	942	944	948	963	969	972	976	978	978	979	982	984	984
D25	2.21	802	807	821	827	830	833	835	838	850	854	857	860	860	861	862	864	866	866
Average	2.42	863	869	884	890	894	897	898.8	902	916.2	921.4	924.6	927.6	928.6	929.4	930.2	933.2	934.4	935

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.792	1.132	1.358	1.528	1.641	1.868	2.660	3.056	3.339	3.565	3.622	3.679	3.735	3.962	4.018	4.075
0	0.849	1.245	1.415	1.641	1.754	1.924	2.773	3.056	3.282	3.452	3.565	3.565	3.622	3.792	3.905	3.905
0	0.905	1.358	1.585	1.754	1.924	2.094	2.943	3.339	3.622	3.848	3.905	3.962	4.018	4.244	4.301	4.301
0	0.849	1.188	1.358	1.528	1.641	1.868	2.603	2.886	3.056	3.226	3.226	3.282	3.339	3.509	3.565	3.565
0	0.905	1.302	1.471	1.641	1.811	1.981	2.716	3.056	3.282	3.452	3.565	3.565	3.622	3.848	3.962	3.962
0	0.86	1.245	1.437	1.619	1.754	1.947	2.739	3.079	3.316	3.51	3.577	3.611	3.667	3.871	3.95	3.962
0	0.792	1.132	1.358	1.528	1.641	1.811	2.603	2.886	3.056	3.169	3.226	3.282	3.339	3.509	3.509	3.565
0	0.849	1.188	1.358	1.528	1.698	1.868	2.716	2.999	3.169	3.339	3.396	3.452	3.509	3.679	3.735	3.735
0	0.792	1.132	1.358	1.528	1.641	1.811	2.660	2.999	3.226	3.396	3.452	3.509	3.509	3.735	3.792	3.792
0	0.849	1.245	1.471	1.641	1.754	1.981	2.830	3.169	3.339	3.565	3.679	3.679	3.735	3.905	4.018	4.018
0	0.792	1.132	1.302	1.471	1.585	1.754	2.434	2.660	2.830	2.999	2.999	3.056	3.113	3.226	3.339	3.339
0	0.815	1.166	1.37	1.539	1.664	1.845	2.649	2.943	3.124	3.29	3.35	3.396	3.441	3.611	3.679	3.69

Table A-3.11. Measured data and calculation of Q_i's for C-25 and C-40 concrete samples made by Messobo OPC (tested at 90 days)

Sample ID	Thickness (cm)	OD mass	m_0 (Initial)	m_1 (10')	m_2 (20')	m_3 (30')	m_4 (40')	m_5 (50')	m_6 (1h)	m_7 (2h)	m_8 (3h)	m_9 (4h)	m_{10} (5h)	m_{11} (6h)	m_{12} (7h)	m_{13} (8h)	m_{14} (24h)	m_{15} (48h)	m_{16} (72h)
E11	2.49	830	835	850	855	859	862	865	867	879	888	894	899	901	903	903	907	908	908
E12	2.46	873	877	893	899	903	906	909	911	923	932	938	941	943	944	945	948	949	950
E13	2.44	863	868	883	888	892	895	898	901	912	921	927	931	933	934	935	939	940	941
E14	2.60	911	916	934	940	944	947	950	952	964	973	979	983	986	988	989	993	994	995
E15	2.60	933	938	955	961	966	969	972	974	986	995	1002	1006	1009	1011	1012	1016	1017	1018
Average	2.52	882	887	903	909	913	916	918.8	921	932.8	941.8	948	952	954.4	956	956.8	960.6	961.6	962
E21	2.53	935	941	956	961	965	969	972	974	986	996	1003	1007	1009	1010	1011	1015	1016	1016
E22	2.65	971	976	992	997	1001	1005	1008	1010	1021	1030	1037	1041	1044	1045	1045	1050	1050	1051
E23	2.39	778	784	800	805	809	812	815	817	830	838	843	844	846	846	847	850	850	851
E24	2.55	946	951	968	973	977	980	983	985	997	1007	1013	1018	1020	1022	1023	1027	1028	1029
E25	2.34	819	824	840	846	850	853	856	858	869	876	879	880	881	882	882	885	886	886
Average	2.49	890	895	911	916	920	924	926.8	928.8	940.6	949.4	955	958	960	961	961.6	965.4	966	967

Q_o	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}	Q_{14}	Q_{15}	Q_{16}
0	0.849	1.132	1.358	1.528	1.698	1.811	2.490	2.999	3.339	3.622	3.735	3.848	3.848	4.075	4.131	4.131
0	0.905	1.245	1.471	1.641	1.811	1.924	2.603	3.113	3.452	3.622	3.735	3.792	3.848	4.018	4.075	4.131
0	0.849	1.132	1.358	1.528	1.698	1.868	2.490	2.999	3.339	3.565	3.679	3.735	3.792	4.018	4.075	4.131
0	1.019	1.358	1.585	1.754	1.924	2.037	2.716	3.226	3.565	3.792	3.962	4.075	4.131	4.358	4.414	4.471
0	0.962	1.302	1.585	1.754	1.924	2.037	2.716	3.226	3.622	3.848	4.018	4.131	4.188	4.414	4.471	4.527
0	0.917	1.234	1.471	1.641	1.811	1.935	2.603	3.113	3.463	3.69	3.826	3.916	3.962	4.177	4.233	4.278
0	0.849	1.132	1.358	1.585	1.754	1.868	2.547	3.113	3.509	3.735	3.848	3.905	3.962	4.188	4.244	4.244
0	0.905	1.188	1.415	1.641	1.811	1.924	2.547	3.056	3.452	3.679	3.848	3.905	3.905	4.188	4.188	4.244
0	0.905	1.188	1.415	1.585	1.754	1.868	2.603	3.056	3.339	3.396	3.509	3.509	3.565	3.735	3.735	3.792
0	0.962	1.245	1.471	1.641	1.811	1.924	2.603	3.169	3.509	3.792	3.905	4.018	4.075	4.301	4.358	4.414
0	0.905	1.245	1.471	1.641	1.811	1.924	2.547	2.943	3.113	3.17	3.226	3.282	3.282	3.452	3.509	3.509
0	0.905	1.2	1.426	1.619	1.788	1.902	2.569	3.067	3.384	3.55	3.667	3.724	3.758	3.973	4.007	4.041

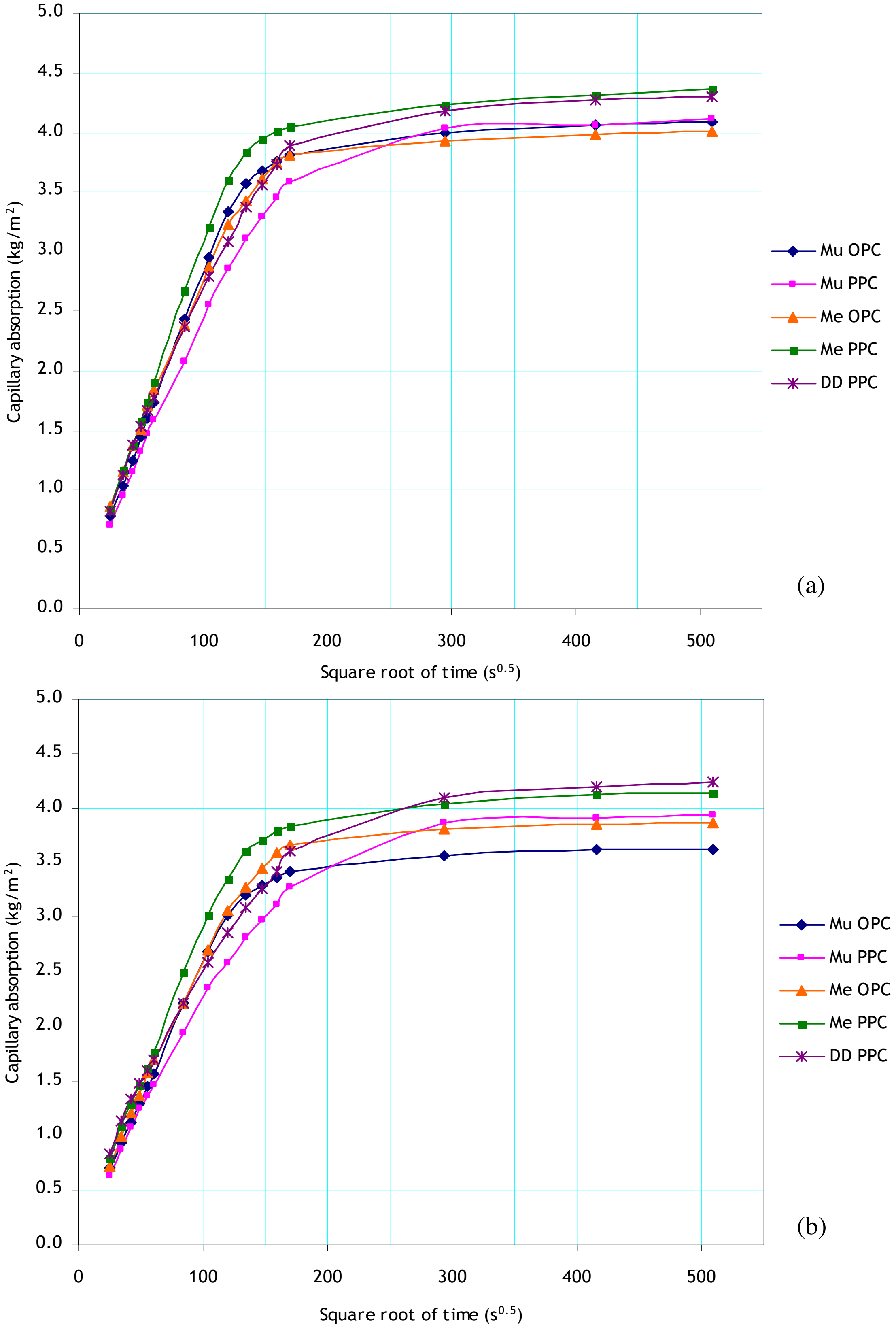


Figure A-3.1. Superimposed capillary absorption curves for samples tested at the age of 60 days (a) C-25 concretes (b) C-40 concretes

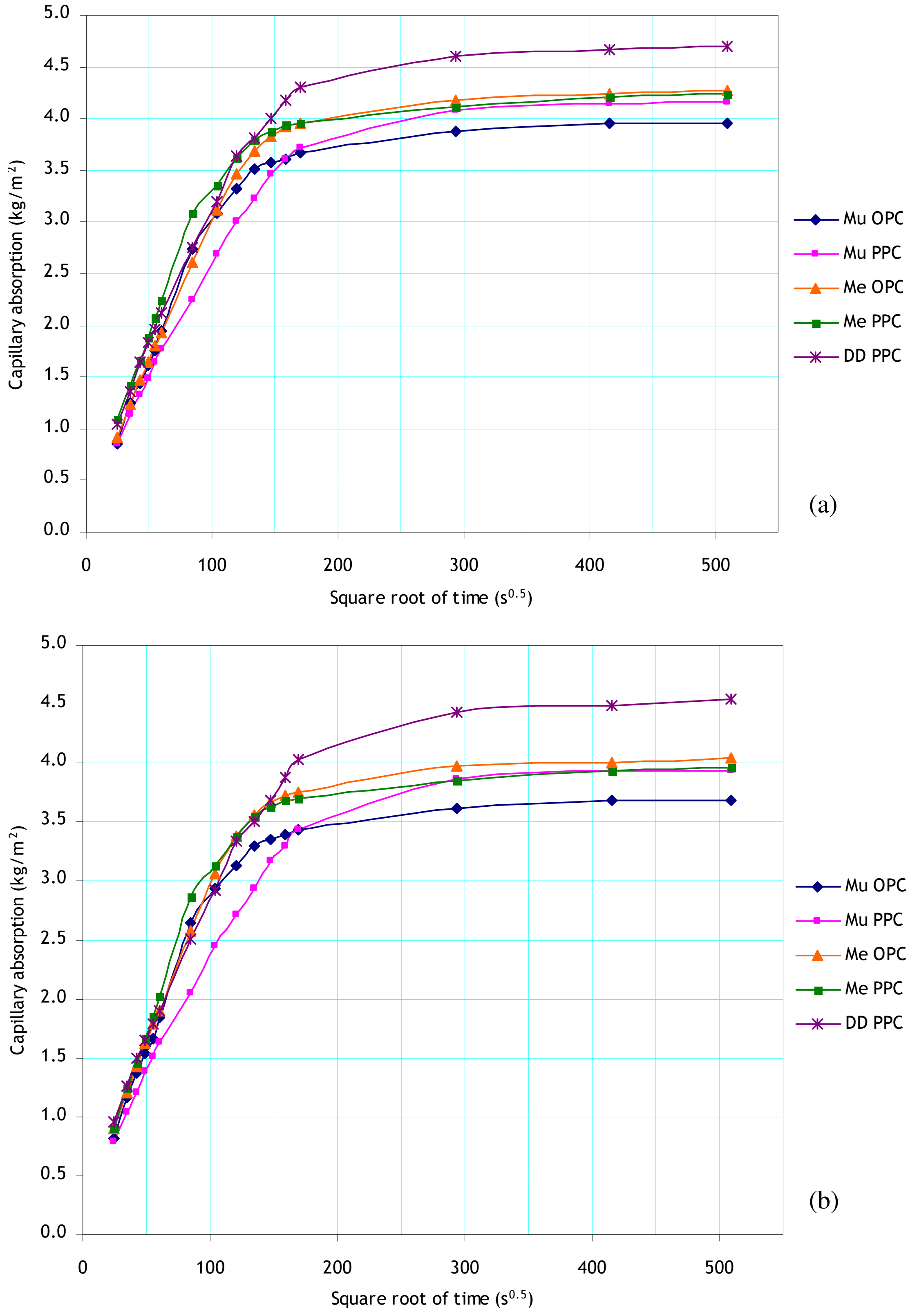


Figure A-3.2. Superimposed capillary absorption curves for samples tested at the age of 90 days (a) C-25 concretes (b) C-40 concretes

APPENDIX FOUR
CHLORIDE PENETRATION DEPTH MEASUREMENTS

Table A-4.1. Measurements of chloride penetration depth and other required data

Sample ID	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}	D_{13}	D_{14}	Average Depth (mm)	Sample Thickness (mm)	Temperature (°c)	Initial Current (mA)	Test at Age
F11	9.14	9.11	13.24	14.05	12.57	12.76	12.41	11.78	13.98	11.61	9.74	14.06	9.20	8.88	11.61	62.33	19.8 (Initial)	147	60 days
F12	7.06	9.00	3.28	6.82	6.99	8.50	11.77	11.80	12.52	12.30	14.33	12.33	11.38	14.85	10.21	59.85		144	
F13	6.95	9.89	7.63	8.52	9.30	9.74	10.90	11.81	10.74	6.05	7.92	7.83	7.84	12.28	9.10	60.67	21.2 (Final)	129	
F21	8.79	8.36	4.85	7.81	9.01	11.36	10.27	9.04	9.53	8.97	6.73	6.99	5.67	4.44	7.99	63.90		132	
F22	6.20	7.66	6.93	6.80	10.11	11.93	8.65	7.80	11.08	10.69	10.49	10.13	7.59		8.93	61.41	20.5 (Average)	135	
F23	6.09	6.15	7.50	8.49	7.77	8.14	10.68	6.64	6.91	7.80	7.46	8.42	9.17	8.65	7.85	61.85		135	
G11	5.56	6.19	7.72	7.73	8.59	7.57	5.44	6.41	8.25	9.62	6.03	8.44	6.44	4.78	7.06	58.70	20.4 (Initial)	81	
G12	11.39	9.52	8.78	9.35	8.88	10.88	13.11	6.63	10.81	10.59	6.80	9.14	12.75		9.89	60.76		88.5	
G13	8.91	9.57	7.81	8.33	9.00	7.75	8.98	8.73	9.28	10.02	9.07	9.79	10.58	11.26	9.22	61.55	21.5 (Final)	78	
G21	6.90	7.25	6.86	8.01	7.02	7.15	7.78	5.69	5.87	5.89	6.38	6.01	4.86	6.54	6.59	62.46		75	
G22	6.34	7.12	8.52	7.67	7.91	6.95	5.90	6.91	6.54	6.87	9.02	8.88	9.43		7.54	58.86	20.95 (Average)	81	
G23	4.37	4.20	5.21	6.43	6.64	6.21	6.94	5.12	7.58	7.51	6.76	6.63	6.32	7.76	6.26	61.20		72	
H11	7.45	6.12	4.23	4.71	6.78	8.56	8.05	6.69	6.07	6.45	5.70	5.50	6.03	5.75	6.29	57.96	19.6 (Initial)	87	
H12	6.51	6.58	6.22	7.02	6.48	8.89	7.18	6.02	8.99	7.87	6.40	9.09	10.30	11.24	7.77	60.06		99	
H13	8.57	6.87	6.53	6.97	7.54	7.81	8.23	7.78	7.40	8.25	5.78	7.29	10.47	8.57	7.72	59.69	20.7 (Final)	93	
H21	6.68	8.63	7.85	7.19	10.05	10.41	7.65	6.35	6.66	4.70	5.31	6.68	7.36	6.25	7.27	61.43		111	
H22	5.11	5.43	5.79	5.66	7.82	7.45	8.19	5.54	5.57	6.63	6.19	4.27	6.50	8.08	6.30	59.84	20.15 (Average)	102	
H23	8.41	6.77	5.44	6.91	6.42	7.09	9.00	9.64	6.75	6.13	7.33	5.98	7.58	6.37	7.13	57.74		108	

Table A-4.2. Measurements of chloride penetration depth and other required data

Sample ID	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}	D_{13}	D_{14}	Average Depth (mm)	Sample Thickness (mm)	Tempe-rature (°c)	Initial Current (mA)	Test at Age
I11	9.13	10.09	9.31	12.08	10.88	5.96	6.03	9.43	10.46	10.44	10.40	10.32	10.66	9.19	9.60	61.96	19.8 (Initial)	129	60 days
I12	10.13	9.49	8.08	5.49	9.46	10.76	9.29	8.71	11.22	12.93	12.17	12.77	11.55	11.23	10.23	61.45		114	
I13	7.80	12.58	10.00	7.06	7.57	3.68	7.40	5.10	8.56	10.45	12.16	9.86	11.86	12.96	9.07	60.20	21.2 (Final)	162	
I21	8.60	10.29	9.49	9.90	10.90	12.10	9.32	7.57	8.52	8.61	9.90	8.16	10.73	11.02	9.65	61.36		132	
I22	9.79	8.64	10.13	9.80	10.07	9.74	8.64	8.25	8.60	10.44	11.63	10.05	12.24	12.21	10.02	59.75	20.5 (Average)	121.5	
I23	8.39	10.05	9.99	9.09	8.44	5.77	8.02	8.14	8.47	5.11	5.69	8.27	9.06	7.88	8.03	60.03		123	
J11	10.99	6.93	3.18	3.95	7.13	6.66	5.52	6.34	6.79	4.53	6.00	7.05	12.11	9.25	6.89	58.87	20.4 (Initial)	78	
J12	7.70	3.16	6.36	6.74	6.36	6.54	7.83	6.08	5.69	5.57	9.65	8.34	13.68	13.11	7.63	61.13		75	
J13	12.17	6.74	6.16	6.21	6.40	6.53	6.78	6.62	5.91	3.91	7.78	8.87	5.98		6.93	62.62	21.5 (Final)	73.5	
J21	8.29	5.92	6.75	6.37	7.08	6.89	7.83	8.22	6.32	8.99	7.93	5.84	6.40	8.36	7.23	59.58		72	
J22	8.12	8.06	6.37	6.54	6.68	8.43	7.47	6.46	6.13	4.58	6.68	3.58	6.99		6.62	62.17	20.95 (Average)	70.5	
J23	10.27	6.83	6.89	5.19	3.84	4.76	4.49	5.52	4.82	6.65	5.63	5.41	4.68	5.23	5.73	64.48		63	
J11	11.15	9.85	6.15	6.99	5.56	7.68	6.61	5.93	7.18	7.78	6.96	8.60	6.90	8.02	7.53	63.76	19.6 (Initial)	63	90 days
J12	14.27	12.15	9.60	7.48	8.47	6.60	8.87	10.14	8.78	7.76	10.16	9.23	14.06		9.81	62.85		61.5	
J13	12.33	11.72	9.46	8.69	7.89	7.86	6.68	7.84	6.92	7.16	7.22	12.22	14.42		9.26	61.76	20.7 (Final)	61.5	
J21	9.27	10.61	10.65	9.33	8.92	8.01	6.24	7.96	7.03	7.00	8.74	9.80	12.91	13.96	9.32	61.13		63	
J22	10.12	8.62	4.75	8.02	7.46	6.86	6.97	8.18	5.18	8.12	6.56	6.61	8.79	8.53	7.48	58.96	20.15 (Average)	60	
J23	11.43	10.90	7.93	5.68	6.73	5.80	6.86	5.23	4.71	5.94	7.17	6.95	8.24	9.44	7.36	61.23		60	
I11	8.84	12.27	7.94	9.25	11.72	8.67	8.51	6.99	11.60	15.11	11.83	10.40	11.98	13.14	10.59	64.04	19.7 (Initial)	111	
I12	10.04	11.90	9.50	5.80	12.87	12.96	12.39	12.40	17.75	15.88	15.39	14.62	12.23	11.11	12.49	64.28		114	
I13	17.82	15.33	12.56	12.54	12.67	15.19	12.99	10.16	9.84	10.17	8.81	12.32	19.26	19.20	13.49	58.10	21.1 (Final)	120	
I21	11.82	10.47	11.70	9.17	7.39	9.39	8.77	7.98	8.50	7.57	10.90	7.98	7.60	7.21	9.03	58.50		120	
I22	6.85	9.17	9.64	9.24	10.28	6.99	7.26	8.18	10.90	10.45	9.81	9.44	9.98	9.17	9.10	53.43	20.4 (Average)	117	
I23	5.85	8.52	9.51	6.74	7.80	10.26	8.27	8.43	8.88	8.78	6.45	10.88	11.91	9.99	8.73	59.33		102	

Table A-4.3. Measurements of chloride penetration depth and other required data

Sample ID	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}	D_{13}	D_{14}	Average Depth (mm)	Sample Thickness (mm)	Tempe-rature (^{o}c)	Initial Current (mA)	Test at Age
G11	7.73	7.77	10.25	10.42	6.78	8.22	8.68	9.79	9.49	8.97	8.72	9.47	7.29	8.84	8.74	60.08	19.4 (Initial)	66	90 days
G12	4.53	6.61	7.15	10.29	8.13	9.29	8.00	5.43	9.16	11.16	7.95	11.42	8.32		8.26	61.17		87	
G13	7.55	7.72	5.91	6.15	5.68	6.51	6.85	7.20	6.32	5.26	7.51	6.18	8.86	7.49	6.80	57.88	20.9 (Final)	66	
G21	11.67	8.77	6.82	6.11	6.46	8.63	6.44	5.81	5.53	5.67	5.70	6.33	6.49	6.42	6.92	58.55		84	
G22	7.88	5.20	6.69	5.90	7.41	6.81	7.82	8.67	6.46	7.47	5.67	6.69	7.36		6.93	59.78	20.15 (Average)	79.5	
G23	9.74	10.00	7.14	7.12	7.64	11.82	7.06	6.47	7.75	7.51	6.47	7.08	6.44	6.02	7.73	59.45		81	
D11	9.00	12.92	8.00	8.14	6.86	8.20	13.69	9.89	10.34	7.90	7.66	10.49	13.03	9.00	9.65	60.11	20.6 (Initial)	102	
D12	16.96	11.45	8.57	8.54	7.28	12.31	12.98	13.29	9.71	12.08	13.41	12.44	11.24		11.56	60.90		144	
D13	8.68	9.90	9.03	11.63	11.50	9.72	11.20	11.70	9.71	11.22	10.72	9.98	12.16	11.03	10.58	59.32	21.8 (Final)	130.5	
D21	6.98	8.68	8.66	8.33	8.67	8.54	8.37	7.92	6.46	7.96	6.39	6.69	6.73	6.53	7.64	58.82		127.5	
D22	8.06	8.63	7.46	7.24	6.67	7.29	9.21	9.50	9.81	9.64	9.37	5.64	8.82		8.26	61.88	21.2 (Average)	126	
D23	7.03	6.44	8.25	10.79	9.91	7.63	10.51	9.41	7.28	9.49	6.80	7.22	10.00	10.07	8.63	59.18		115.5	
E11	12.46	8.45	6.35	9.27	6.08	6.49	9.85	9.43	8.15	7.70	7.70	8.23	8.11	6.47	8.20	58.91	21.9 (Initial)	81	
E12	6.24	10.06	7.59	8.48	10.46	9.93	9.57	14.27	10.92	11.36	11.64	4.96	5.24	9.36	9.29	59.84		85.5	
E13	11.07	7.92	10.15	8.31	7.06	8.36	9.07	7.10	9.13	8.86	11.89	11.62	8.03	6.60	8.94	58.74	22.6 (Final)	81	
E21	8.53	7.83	16.63	6.47	9.29	11.32	7.36	7.80	8.70	12.48	10.53	8.06	8.11	8.02	9.37	62.08		96	
E22	7.53	4.33	7.71	7.52	5.22	6.82	8.01	9.14	11.04	10.92	8.51	6.52	7.86		7.78	59.71	22.25 (Average)	99	
E23	4.28	5.74	6.61	7.44	7.86	8.93	6.24	6.56	7.96	7.04	6.73	6.68	6.77	5.84	6.76	59.53		93	

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any other university and that all sources of material used for the thesis have been duly acknowledged.

Name: Birhanu Bogale

Signature:

Place: Faculty of Technology, Addis Ababa University

Date of Submission: February 2007