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RHEOLOGY - COVERCRETE: A CONCEPT FOR CONTROLLING QUALITY AND DURABILITY OF CONCRETE

by

Omran Maadani

B.Eng. (Civil Engineering)

A thesis submitted
to the faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
MASTER OF ENGINEERING*

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The undersigned hereby recommend to the
Faculty of Graduate Studies and Research
acceptance of the thesis entitled

**" Rheology - Covercrete: A Concept for Controlling Quality and
Durability of Concrete "**

submitted by
Omran Maadani

in partial fulfillment of the requirements for the degree of
Master of Engineering

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ABSTRACT

Premature deterioration of concrete structures has created awareness and concern about the durability of concrete. It has been suggested that concrete is inherently durable, provided good mixing and construction practices are followed. Traditionally, the slump has been used to measure concrete consistency; however, it has been pointed out by many researchers that the slump alone is not a sufficient measure of consistency and that other quantifiable rheological properties such as slump rate, slump-flow and time of slump are important and should be considered. In this thesis, a Slump Rate Machine (SLRM) was adapted and calibrated, with a view to facilitate the measurement of the preceding properties in a consistent manner. The SLRM was used to measure the foregoing concrete properties for a number of concrete mixes.

To correlate the slump, slump rate, slump flow and time of slump with the fresh concrete shear yield stress and plastic viscosity, a theoretical model was modified and applied. An attempt was made to correlate the plastic viscosity and/or the shear yield stress of fresh concrete to some of the measured mechanical and physical characteristics of hardened concrete. The latter characteristics included core strength, shrinkage, pull-off strength, and pulse velocity. The air tightness and absorption of the cover concrete, also referred to as the mass transport properties, were measured to evaluate the effect of mix proportions, vibration, and formwork finish on the finished concrete cover.

The results showed that it is indeed possible to relate the rheological properties of a fresh concrete (its plastic viscosity and yield value) to its mechanical, physical and permeation properties. Based on the findings of the present study, using the newly derived

design curves, the rheological properties of fresh mix can be determined in the field. Thus, in the event of a poor mix, remedial steps can then be taken before concrete hardens.

The results of the study also showed that for the type of mixes used in the current study, vibration has little effect on the permeation properties of the hardened concrete while the type of form finish has some influence on such properties. Specifically, very high W/C concrete, cast in unlined forms, was found to have generally less absorptivity than the same concrete cast in lined forms.

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List of Symbols

Symbol	Definition
W/C	Water to cement ratio
S/A	Sand to the total aggregate ratio
R	Radius of action
t_v	Time of vibration, s
k	Proportionality factor as defined in (2.1)
g	Gravitational acceleration (9.8067 m/s^2)
V	Volume of slump cone, m^3
SL	Slump of concrete, m
i	Volume of water absorbed per unit area of inflow surface, mm
t	Time of penetration or slump, second
S	Sorptivity, $\text{mm/h}^{1/2}$
m	Dimensionless decay parameter as defined in (2.2)
d	Depth of penetration, mm
d_o	A variable defined in (2.3), mm
f_c	Compressive strength of concrete at time of testing, MPa
S_o and a	Constants as defined in (2.4) and their units are $\text{mm/h}^{1/2}$ and $\text{mm}^3/\text{N.h}^{1/2}$, respectively
ISA_{10}	Initial surface absorption at 10 minute, $\text{ml/m}^2.\text{s}$
τ	Shear stress, Pa
τ_y	Yield stress, Pa

$\dot{\epsilon}$	Strain rate, s^{-1}
A, B, and C	Constants as defined in (2.7), (2.8), and (2.9)
r_t	Top radius of slump cone, m
r_b	Bottom radius of slump cone, m
H	Height of slump cone, 0.30 m
α	Dimensionless shape factor as defined in (2.10)
SF	Slump-flow value, m
$sL_{(t)}$	Slumping value (m) at time t (s)
$sF_{(t)}$	Slump-flowing value (m) at time t (s)
τ_b	Normal stress at base of slump cone, Pa
ρ	Density of the material, kg/m^3
$\sqrt{\sigma_I^2}$	Quadratic invariant of stress deviation as defined in (2.14)
Z_y	Variable (m) as defined in (2.15)
η_{re}	Relative viscosity
η & η_o	Plastic viscosities (Pa.s) as defined in (2.18) and (2.20)
C	Percentage of absolute volume as defined in (2.18) and (2.20)
V_c	Volumetric concentration as defined in (2.18) and (2.20)
K_1 & K_2	Experimental constants as defined in 2.18
$\Delta\eta_1$	Increase in plastic viscosity due to temperature change, Pa.s/ $^{\circ}C$
p_1 & q_1	Experimental constants are defined in (2.19)
μ	Fineness modulus of fine aggregate in case of mortar or coarse aggregate in case of concrete
a & b	Experimental constants as defined in (2.20)

τ_z Stress-deviation as defined in (2.22)

SLRM Slump Rate Machine

1. INTRODUCTION

1.1 General

In recent years there has been an increasing demand for and production of high performance concrete with better workability, higher strength and greater durability for “important” concrete structures such as off-shore oil platforms, bridges, high-rise buildings, etc. However, the technology has not trickled down to the housing industry due to economic reasons and lack of quality control.

The concrete mix for a single house basement is designed for a 15 to 20 MPa compressive strength and a minimum target slump of 175 mm. The mix consists of 0.8 to 0.9 water to cement ratio and a cement content of 275 kg/m^3 . The concrete is poured into forms at near fluid consistency in order to obtain adequate compaction in the forms without the additional cost of vibration. The resultant concrete is adequate for supporting the design structural loads; however, it manifests a host of surface defects and has a highly porous surface layer. These qualities impact the durability of concrete because they reduce the effectiveness of the concrete cover, or “covercrete”, to act as a protective barrier against the penetration of external substances. (Chidiac et al. 1997a, Dhir et al. 1987, 1994, Kreijger, 1987).

Microstructure investigation by Kreijger (1987) have shown that the condition, structure, and mechanical and physical properties of the outside 50 mm of the concrete differ from those of the bulk, with the lowest quality attributed to the outermost layer. On the macroscopic level, it has been recognized that the W/C, curing and the workability of concrete affect its transport properties (Dhir, 1989a).

The experimental work of Ho and Lewis (1987) showed a linear relationship between sorptivity and compressive strength, and it revealed that sorptivity decreases with a decreasing slump value. The interplay of curing, W/C, and initial surface absorption have been reported by Dhir et al. (1987).

Rheology, the science of flow and deformation of materials, is concerned with the interactions between shear stress, shear strain rate, mixing time, compaction and finishing operation. Banfill (1994) and Tattersall (1991) studied the effect of rheology on the flow characteristics of fresh concrete. They suggested that rheological properties; namely, plastic viscosity and yield value, be used to control the quality of fresh concrete. However, no studies have been reported to relate the rheological properties of fresh concrete to the properties of hardened mix and particularly to its transport properties.

1.2 Problem definition

Concrete is designed to meet its desirable structural and aesthetical characteristics, but many concrete works have been plagued with non-uniform and aesthetically poor surface appearance. Defects and blemishes of concrete surface have been attributed to a number of different factors. Good concrete, i.e. concrete which can be used for any kind of finish, has to be of good quality, homogenous, dense, free from discoloration, voids, honeycombing, and from any other defects associated with poor supervision during the execution of the work. While some of the preceding properties can be easily measured and quantified, others are more difficult to assess quantitatively.

In order to develop some quantitative criteria for the quality of the finished product, one must first deal with those properties of fresh concrete which are known to impact the quality of the hardened concrete surface. Certain rheological properties of the fresh mix, such as its plastic viscosity, yield stress, flow rate, etc. affect the compaction density of the hardened concrete. Other factors, such as the amount and the type of vibration, the type, the shape, the surface finish and the aspect ratio of forms also affect the ability of fresh concrete to yield a homogeneous finished product. While the plethora of factors which influence the final quality of finished concrete need to be studied one by one in order to determine the precise contribution of each factor to the quality (or lack thereof) of the final product, this study is aimed at determining the effect of a limited number of factors which are generally known to affect the quality of the finished concrete surface.

1.3 Objective and scope

The covercrete concept addresses the improvement of quality and reliability of concrete cover of high W/C by:

- I. Introducing a quantitative method to control the quality of concrete that can be used both in the field and in the ready mixed plant.
- II. Optimizing materials and techniques in current practice through the use of different formwork, adjustment to mix proportions, and use of compaction.

The objective of the current study is to investigate preliminarily the effect of some of the preceding methods and materials on the quality of the finished concrete. Specifically, the study intends to:

1. Quantify the rheological properties of fresh concrete from its basic flow properties in a slump type test.
2. Briefly study the effects of vibration, mix proportion, and form type on the quality and surface condition of the concrete cover.
3. Establish tentative relationships between the rheological properties of the fresh concrete and the mechanical and physical properties of the hardened concrete, with emphasis on the transport properties of the concrete cover.

The scope of the present study is limited to unreinforced basement concrete mixes with relatively very high water-cement ratio ($W/C \geq 0.65$).

The investigation is focused on the following variables:

- Concrete mixes of W/C ratio 0.83 and 0.65 and fine to total aggregate ratio 0.49 to 0.60.
- A cement content of 275 kg/m^3 .
- A target minimum slump of 175 mm.
- Two types of form work: conventional plywood and 100% solid urethane lined wood.
- Two levels of vibration: vibrated and unvibrated mix.

- Two admixtures: air entraining agent and water reducer.

It is recognized here that the limited range of each variable considered in this investigation is not sufficient to arrive at definitive conclusions or exact recommendations for practical applications, nevertheless, the study is intended to establish whether a certain parameter has any perceptible effect on the quality of the “covercrete”.

2. LITERATURE REVIEW

2.1 Introduction

A structure is considered durable provided it functions as intended in the actual environment during its design life. The concept of durability, or the service life design of the structure or material, can therefore be established on the basis of functional requirements (Rostam, 1996; Chidiac et al. 1997a). In general, these functional requirements are safety, serviceability and durability. The governing properties for safety and serviceability are the stiffness and the strength of the material, shrinkage, creep, thermal movement and settlement. The requirements for achieving these properties are addressed in current codes and standards. The governing properties for durability are the mass transport properties; namely, permeability, absorption and diffusivity, and the size and location of cracks. These properties are a function of mix design, aggregate type, cement type, curing method, form condition and degree of hydration. The majority of the properties are time dependent. This leads to the notion that durability, particularly during the service life of a concrete structure, is both time and space (geographical location and topography of structural environment) dependent.

Concrete structures deteriorate due to a number electrochemical, chemical and physical processes and due to mechanical damage (Basheer et al., 1996). The effect of these processes manifest themselves as either shrinkage or expansion of the concrete, resulting in cracking and/or spalling. Nearly all types of deterioration develop in two-phases, an initiation phase and a propagation phase (Tuutti, 1982). During the initiation

phase, there are usually no noticeable changes or weakening of the material and/or structure, but some protective barrier is broken down or rendered ineffective. Water and/or chloride penetration are example of process that occurs in the initiation phase. The duration of the first phase depends on the quality of concrete and on the in service exposure conditions. The propagation phase begins once active deterioration begins and loss of function is observed. Corrosion of the steel reinforcement due to either chloride penetration or carbonation is an example of the propagation phase (Basheer et al. 1996). In brief, the concrete deterioration process depend on the penetration of some substance from the outside into the bulk of the concrete through the surface. Thus, much effort is needed to ensure an adequate quality of the concrete in the exposed outer layers of the structures. A well compacted strong concrete cover, with low mass transport properties and without cracking, is desirable to ensure durability.

The adaptation of such procedures to the Canadian housing industry, in particular the concrete basement for single dwellings, is not economically feasible. The 28 day design strength of concrete used in basements of single dwellings ranges from 15 to 20 MPa. The concrete is poured in the forms at consistencies ranging from 175 mm slump to a near fluid condition, with a typical water to cement ratio (W/C) of 0.8 to 0.9 and a cement content of 275 kg/m³. Thus, efforts need to be directed towards the improvement, reliability and better quality of concrete cover (covercrete), of high W/C concrete. To this end, a literature review was first performed to gain knowledge about (1) factors that affect the quality of concrete, (2) the composition of the concrete cover, (3) transport properties

of concrete, and (4) rheology of concrete. The latter is examined in the context of quality assurance for fresh concrete.

2.2 Concrete cover

Surface properties of bulk concrete are determined by the composition and the properties of the surface layer, known as the cover or skin. This surface layer is found to be affected by sedimentation and segregation, compaction method, formwork surface finish and permeation and migration of water in and out of the concrete (Kreijger, 1987).

In reinforced concrete members one of the important parameters for the protection of steel from corrosion is the presence of a dense concrete cover, which acts as a barrier against the penetration of substances from the environment. As noted earlier, deterioration will not occur unless the concrete cover allows the penetration of water, chlorides and other deleterious substances to the bulk concrete where the reinforcing steel is present. Therefore, the main function of covercrete, as a measure of concrete durability, is its ability to resist the penetration of water or moisture containing dissolved aggressive substances. The permeation properties, such as the absorptivity, permeability, and diffusivity, are influenced by many factors, such as concrete mix, compaction and curing (Rostam, 1996). Kreijger (1987) divided concrete cover into three parts:

- Cement paste skin (about 0.1 mm thick).
- Mortar skin (about 5.0 mm thick).

- Concrete skin (about 30.0 mm thick).

Kreijger also investigated microscopically the properties of concrete cover. He found that the properties of the concrete cover vary from outer layer to the bulk of concrete, leading to a significant lowering of the quality of concrete at the outer layer. McCarter et al.(1996) also investigated the covercrete properties. They concluded that the absorption characteristics are dependent on the pore size, distribution and connectivity.

2.3 Factors affecting the quality of concrete

The quality of concrete cover depends primarily on the following factors: mix design, compaction, formwork facing and curing.

2.3.1 Concrete mix design

Concrete workability is greatly affected by the grading, particle shape and proportion of aggregates, and the conditions during mixing. Experiments have shown (ACI 211.1991) that if the aggregate is fairly dry when mixed, air within the aggregate particles can be displaced by water shortly after casting, causing more blow holes than would occur in concrete of the same workability made with fully saturated aggregate. Further, poor sand gradation is a major contributing factor to bleeding.

Excessive amount of coarse aggregate causes insufficient mortar to fill the voids, contributing to loss of cohesion and mobility. This improper mixture, called harsh mixture, will require special care during placement and compaction. On the other hand, excessive amount of fine aggregate will increase the cohesion and cause the mixture to be

sticky. However, an increase in the amount of fine aggregate will increase the total surface area, thus increasing the required amount of water to coat the surface. This significantly increases the tendency of drying shrinkage and cracking, unless the cement content is increased to maintain a constant water to cement ratio. The concrete aggregates must be classified as well-graded aggregates in order to enhance the workability and to reduce bleeding and segregation.

Strength is an important characteristic of concrete which is affected by the water to cement ratio. Using a low water-cement ratio increases strength, which fortunately also improves the permeation properties of concrete cover as reported by (Neville 1981; Dhir et al. 1987, 1989a; Figg 1989; Long et al. 1995). Dhir et al. (1989b) concluded that the W/C ratio is the main factor which has a great influence on the rate of carbonation. ACI standards 201.1992 suggests that to reduce the absorption of de-icing salt, the W/C ratio should be less than 0.4. A W/C ratio of 0.53 will provide an intermediate degree of protection while a W/C ratio of 0.62 will not provide any protection.

Excessive bleeding occurs when there is a deficiency in sand sizes passing the number 30, 50 and 100 sieves. The fineness of the sand is also one of the important factors in determining the air-entraining admixture requirements. By increasing the amount of material passing the 30 and 50 sieves, the air entraining admixture requirement can be lowered. Obtaining an optimum air void system in the concrete and using proper mix design are important in order to avoid scaling problems, and to minimize bleeding (ACI 211.1991). The amount of entrained air recommended by ACI 211.1991 for light weight aggregate concrete is 4 to 6 percent air when maximum aggregate size is 20 mm.

Bleed water will bring to the surface too much fine material, creating water reservoirs below aggregate particles, making vertical channels and depositing weak laitance at the surface. After curing, the dried water reservoirs become air pockets and vertical channels make the concrete porous as illustrated in Figure 2.1 (Madderom, 1986).

Fig. 2.1: Effect of excessive water in concrete mix on its final microstructure

Neville (1981) states that each concrete composition has different pore sizes and distribution. In addition, when the concrete has voids caused by improper compaction or by bleeding, its permeability is increased. Also the permeability of hardened cement paste is higher than that of aggregates; therefore, in fully compacted concrete the

permeability of paste has a great influence on the permeability of concrete. The durability of concrete is affected by the properties of cement, especially its fineness. The finer the cement, the less porosity it will produce. In general the permeability of concrete is greatly affected by both the W/C ratio and curing, but the size, distribution and continuity of its pores will ultimately determine its permeability as reported by Neville (1981). Reduction of W/C ratio from 0.7 to 0.3 will lower the coefficient of permeability by a factor of a thousand.

Concrete discoloration in successive batches can be attributed to variation in water content of the mix. Mailvaganam (1996) indicated that for an increase in W/C ratio, the colour of the hardened concrete was lighter. However as increase in cement content will lead to a darker colour owing to the increased amount of unhydrated cement. Therefore, the cement content is the most important factor in determining the final concrete colour. High W/C ratio usually produces greater amounts of calcium hydroxide during hydration, which lightens the colour. Further change may occur when the calcium hydroxide reacts with CO_2 in air to form CaCO_3 , giving the concrete an even lighter colour.

2.3.2 *Compaction effect*

Vibration removes the entrapped air from the fresh concrete by liquefying the mortar so the concrete can settle. The result is a dense and durable concrete that is less likely to crack. As a general guideline, the selected concrete compaction method must be suitable for the specific purpose to be accomplished. Shilstone (1986) has stated that to minimize surface blemishes, a vibrator must have the proper frequency, amplitude, power source and size, and it must be applied for a sufficient period of time.

Popovics (1982) noted that neither the frequency nor the amplitude alone is sufficient to determine the efficiency of vibration. The maximum acceleration per cycle is often given as a measure of the intensity of vibration. He also drew attention to the mechanism of liquefaction as vibration generates compressive waves in the paste or concrete. As the velocity of these waves increases gradually from the beginning to the end of the vibration period, they move the water molecules in waves of constant velocity but variable amplitude. These waves are effective for a short distance; the area in which the wave is effective is referred to as the radius of action. The radius is influenced by many factors such as entrained air, consistency and composition of the concrete and the presence of reinforcement. Increasingly, damped waves decrease the radius of action, but the radius of action increases as the weight of the vibrating head becomes greater. The relationship between the characteristics of the vibrator and its action on fresh concrete is still not general enough, but the R-t relationship can be approximated by

$$R = k t_v^{1/3} \quad (2.1)$$

where

R = radius of action, t_v = time of vibration and k = proportionality factor (increases with increasing eccentric moment and increasing frequency).

Orchard (1973) noticed that at a constant acceleration of $4g$ and for a period of 2 minutes, the frequency had little effect on the strength of wetter mixes, but for dry mixes the strength decreased as the frequency was increased. A high frequency, however, gives a better surface finish to concrete made of very dry mixes.

Stamenkovic (1986), remarked that for the vibration to be effective, a sufficient amount of mortar must be present in the concrete because when concrete is being vibrated, the coarse aggregate particles move individually in all directions through the mortar, turning about their shorter axis. During this movement any water or air that is trapped beneath them is released and starts to move upward. As illustrated in Figure 2.2, ACI 301.96 suggests 320 kg/m^3 as a minimum cement content for maximum aggregate size of 20 mm.

In practice there are a number of different types of vibrators available and these have been classified (Popovics 1982) as internal or external. Table 2.1 gives some of the characteristics of the internal vibrators while Table 2.2 provides details of both internal and external vibrators.

Fig. 2.2: Schematic illustration of particle movements during vibration

Table 2.1: Range of characteristics, performance, and applications of internal vibrators
by Sandor Popovics (1982), and ACI 301.96.

Diameter of head (mm)	Recommended frequency (Hz)	average amplitude (mm)	Radius of action (mm)	Rate of concrete placement (m^3/h)	application
20~40	170~250	0.4~0.8	80~150	0.8~4	Plastic and flowing concrete in very thin members and confined places
30~60	150~225	0.5~1.0	130~250	2.3~8	Plastic concrete in thin walls, columns, beams, precast piles, thin slabs, and along construction joints.
50~90	130~200	0.6~1.3	180~360	4.6~15	Concrete of less than 80 mm slump.
80~150	120~180	0.8~1.5	300~510	11~31	Mass and structural concrete of less than 50 mm slump deposited in quantities up to 3 m^3 , in relatively open forms of heavy construction
130~180	90~140	0.1~0.2	40~61	19~38	Mass concrete in gravity dams, large piers, massive walls, etc. Two or more vibrators will be required to simultaneously melt down and consolidate quantities of concrete of 4 m^3 or more deposited at one time in the form

Table 2.2: The operating frequency and acceleration range for different types of vibrators
(Khan 1974)

Type of vibrator	Frequency, (Hz)	Acceleration (Unloaded)
Internal vibrator	100~280	30g~80g (much less when immersed)
Clamp on or shelter vibrators	50~100	10g~25g
Vibrating tables	50~100	3g~7g
Surface vibrators	25~70	4g~10g

Note: g = gravitational acceleration (9.8067 m/sec^2)

2.3.3 Characteristics of the formwork facing

Formwork should be designed on the basis of limiting deflection to avoid high amplitudes due to vibration, and it should be sufficiently and uniformly rigid to limit variation of amplitude over the area of a slab or wall panel. Formwork in the past has been usually constructed with boarding, but recently the use of plywood, compressed wood-fiber wall boards, and sheet metal has increased considerably.

Forms can cause blemishes in concrete. Absorptive forms tend to reduce the occurrence of blow holes on the concrete surface. On other hand, the colour of a concrete surface varies according to the absorbency of the form face (Kinnear 1964) which is influenced by the pressure of the concrete during placing, i.e. higher pressure causes greater loss of moisture into the form face. Impermeable lined faces produce better uniformity of colour because they are not vulnerable to forced absorbency.

Generally, for most exposed concrete surfaces it is recommended that impermeable lining be used, with the aim to produce uniform colour. Although the occurrence of blow holes may be considerably reduced by attention to some factors (CIB report no. 5, 1966), some blow holes may have to be accepted.

Tsukinaga et al.(1995) evaluated a new permeable sheet with perforated polyethylene film attached to the form on the concrete side, and a polypropylene non-woven fabric on the outside. They concluded that the perforated polyethylene film was effective in the lowering of water to cement ratio, proportional to the decrease of pore volume, and increased pull off tensile strength, rebound number, pulse velocity and pin penetration resistance in the surface layer, with remarkably reduced bug holes on the concrete surface.

Long et al (1995) developed a new technique which gives comparable benefits to the Japanese permeable formwork, but at a significantly reduced cost. During the vibration of the concrete, the entrapped air and the surplus mixing water escape through the controlled permeability formwork (CPF) and are allowed to drain freely at the bottom of the formwork. As a result of that a significant reduction occurs in W/C ratio near the surface, especially for concrete with high W/C ratio. This greatly reduces incidence of blow holes, increases resistance to carbonation and chloride ingress and greatly improves performance under freezing and thawing conditions.

2.3.4 Curing

The prevention of too rapid loss of moisture from concrete has an important effect on the subsequent appearance, strength and durability of the concrete surface. Curing involves maintaining proper concrete temperature as well as satisfactory moisture content so that desired concrete properties can develop. Neville (1981) mentioned the different factors which have great effect on the evaporation of water from concrete soon after placing. They are temperature and relative humidity of the surrounding air and the velocity of wind, which affects the air over the surface of the concrete.

There are many kinds of curing, selecting one depends on the size, shape, and site conditions. Orchard (1973) divided them into three broad categories:

(A) Those which interpose a source of water to prevent water evaporation

- Forming a pond over the concrete after it has set.
- Covering the concrete with wet burlap soon after it is placed and keeping this continuously wet for as long as possible
- Covering the concrete with earth or straw kept wet.
- Covering the concrete with cotton mats.

(B) Those which minimize loss of water by interposing an impermeable medium or by other means.

- Covering with water proof paper.

- Leaving the shuttering on.
- Mixing calcium chloride with the concrete.
- Spreading calcium chloride over the concrete.
- Spraying with sodium silicate.
- Covering with an impervious polymer-based membrane applied by spraying.

(C) Those which involve the application of artificial heat whilst the concrete is maintained in a moist condition.

- Low pressure steam curing
- High pressure steam curing
- Curing by infrared radiation
- Electrical curing

Dhir et al. (1987 and 1989a) and Long et al. (1995) concluded that the duration of moist curing affects the compressive strength and surface absorption of concrete, but it has more significant effect on the latter property. Dhir et al. (1989b) also observed that by reducing the initial water curing period from 4 days to 1 day, the carbonation depth increased by 80 % after 20 weeks of exposure.

Austin and Robins (1997) studied the influence of curing methods and climate on the permeability and strength of condensed silica fume (CSF) concrete, and they found that the early age strength development of a CSF concrete, moist cured at 20° C, to be

slower than an Ordinary Portland Cement (OPC) control concrete of equal 28 day strength, but at later ages the CSF was found to have higher strength.

Inadequate curing tends to produce concrete with a porous surface, permeable concrete and concrete with tendency towards early age cracking, which increases the physical and chemical processes of degradation (see Figure 2.1). Therefore, it is essential to provide moist curing for an adequate period of time and to ensure that each member or part of a structure is given the same curing conditions.

2.4 Transport properties

All the concrete deterioration mechanisms, physical, chemical, and electrochemical, depend on the mass transport properties of concrete, i.e. on its absorptivity and diffusivity in non-submerged structures, and on its permeability in submerged structures. The transport of water and other aggressive substances may follow different mechanisms, depending on the properties of concrete cover and the exposure conditions. Limited research has been conducted to quantify the absorptivity and permeability of concrete.

The Concrete Society (1985) defined the absorptivity as the process whereby the concrete takes in a fluid to fill spaces within the material by its capillary action. Diffusion is defined as the rate at which a liquid, gas or ion can pass through concrete due to a concentration gradient. Finally the permeability is defined as the ease with which a fluid (liquid or gas) will pass through a porous medium, under action of a pressure differential.

2.4.1 Absorptivity

The quality of concrete cover is quantified by measurement of rate of water penetration by capillary action. The British Standard Initial Surface Absorption Test (ISAT), BS 1881: part 5 (1970), Figg hypodermic methods (air and water) (Figg, 1973) and a new test, the Covercrete Absorption Test (CAT) (Dhir et al., 1987) have been used to measure the rate of absorbed volume of water per unit area. This rate gives a good indication of the pore structure of concrete, and varies linearly with the square root of time. The gradient of the straight part of the absorbed volume of water per unit area versus square root of time curve is defined as sorptivity (Lewis and Ho 1987).

Figg and CAT tests measure mainly the quality of the inner covercrete, so the weak surface layer has less influence on the results. The ISAT and CAT have been used with a water head of 200 mm while the Figg test has been applied with a water head of 100 mm to mimic the effect of wind speed and driven rain. In the present study, the Initial Surface Absorption, denoted by ISA, will be measured due to capillary action, thus ignoring the water head (Hall, 1989).

The so-called Covercrete Absorption Test (CAT) was developed by Dhir et al (1987) to measure the absorption of cover concrete and has been found to give reliable results. The CAT results were found to exhibit trends similar to the Initial Surface Absorption Test (ISAT) measurements (BS 1881: Part 5: 1970). However, both methods have been applied with a water head of 200 ± 20 mm, whereas in the present study the ISA will be measured ignoring the effect of wind speed and rain pressure, hence the measured values are expected to be lower than the BS 1881 ISAT for the same concrete.

Parrott (1992) concluded that water absorption rate drops in the carbonated surface zone of concrete made with ordinary Portland cement due to reduction of capillary pore volume and its continuity, but the opposite occurs with the carbonated surface zone made of concrete with fly ash or ground granulated blast furnace slag. More study is required to verify those claims.

Levitt (1970), Hall (1977) and Lewis (1983), theoretically derived the expression for the absorbed volume of water per unit area, i.e.

$$i = S t^m \quad (2.2)$$

where i = volume of water absorbed per unit area of inflow surface, mm

t = time of penetration, second

S = sorptivity, $\text{mm/hr}^{1/2}$

m = dimensionless decay parameter varying from 0.3 to 0.75

Levitt (1970) found the decay parameter to depend on the quality of covercrete and the moisture content of the concrete specimen. Therefore, m decreases with decreased moisture content.

Dhir et al. (1987) concluded that ISAT increases with workability at a significantly greater rate if the increase in workability is associated with an increase in the water content than when it is attributed to the use of plasticizer admixture. Therefore, the superplasticizer can be employed effectively to reduce the absorptivity of concrete.

The ISAT values of 10 minute period for air curing as reported by Dhir et al. (1987) are in the range of 0.73 to 0.52 ml/m².s for concrete having 20 to 30 MPa compressive strength, respectively. They also remarked on the effect of moist curing and they found ISAT values less than 68 percent and 82 percent, for 3 and 6 days of moist curing, respectively, compared to air curing. Gopalan (1995) compared plain concrete of the same strength with fly ash concrete and he concluded that the sorptivity of fly ash concrete was much higher than the plain concrete.

The water sorptivity of concrete was represented mathematically by Ho and Lewis (1984) and by Emerson (1996) as follows:

$$d = d_0 + S\sqrt{t} \quad (2.3)$$

where d = the mean depth of penetration of water from the suction surface, mm.

t = the elapsed time, h

S = the sorptivity based on the depth of penetration of the water front, mm/h^{1/2}.

d_0 = the intercept value on the $t = 0$ axis, mm

Ho and Lewis (1987) investigated the influence of initial curing, strength, and concrete mix proportion on the rate of water penetration. They observed that the water sorptivity is lowered by the increases in the initial moist curing and that concrete with low W/C ratio and limited moist curing can have the same sorptivity as one with higher W/C ratio but longer initial moist curing period. Furthermore, using both water reducing and air entraining admixtures will lower sorptivity. Also they found that the water sorptivity

varies linearly with the square root of strength at the time of testing, which could be represented by the following:

$$S = S_0 - a \sqrt{f_c} \quad (2.4)$$

where f_c = compressive strength of concrete at time of testing, MPa

S_0 and a = constants for each mix with units of $\text{mm/h}^{1/2}$ and $\text{mm}^3/\text{N.h}^{1/2}$, respectively.

They reported sorptivity values ranging from 10 to 3 $\text{mm/h}^{1/2}$ for 16 to 35 MPa compressive strength, regardless of concrete constituents.

The Concrete Society Working Party (1985) reviewed and recommended the measurement of water sorptivity as a test method for characterizing finished concrete. They classified this property as low, average or high rate according to the depth of water penetration, i.e. less than 30 mm being low, 30 to 60 mm being average and higher than 60 mm being high, This range corresponds to sorptivity values less than 3, 3 to 6 and higher than 6 $\text{mm/hr}^{1/2}$ over a 4 day test period.

Hall (1989) presented some results to demonstrate the influence of the normal tamping and prolonged tamping of concrete on its sorptivity. He found that for normal tamping and W/C ratio 0.60 or 0.80, respectively, the sorptivity was 2.25 or 2.71 $\text{mm/h}^{1/2}$, and the capillary porosity was 13.9% or 14.1%, while for prolonged tamping, the sorptivity was 1.16 or 1.4 $\text{mm/h}^{1/2}$, and the capillary porosity was 12.1% or 13.3%. These results were for concrete with composition of 1:2:4 of cement: sand : aggregate, respectively. He also reported that the sorptivity of concrete with composition 1 : 3 : 4 of

cement : sand : aggregate, and W/C = 0.6 or 0.8 was 2.25 or 2.4, respectively. However, a W/C ratio ≥ 0.6 is considered to be high and therefore it leads to high sorptivity values. Thus, Hall's results are not unexpected. Note that his reported values are within the range of the low sorptivity according to the Working Party classification.

He also established a relationship between sorptivity and ISA at 10 minute (ISA_{10}) due to capillary action as follows:

$$S = 3524 \times ISA_{10} \quad (2.5)$$

where S and ISA_{10} are in $\text{mm/h}^{0.5}$ and $\text{ml/m}^2.\text{s}$, respectively

Dhir et al (1987) found the factors affecting the initial absorption rate to be the same as those mentioned by Ho and Lewis (1987). They concluded that the initial moist curing has a significant impact on the sorptivity of concrete rather than its strength.

The Concrete Society (1985) has categorized the concrete for several ISAT test results as in Table 2.3

Table 2.3: Typical results of Initial Surface Absorption Tests (Concrete Society, 1985)

Absorption level	ISAT results $\text{ml/m}^2/\text{sec}$ Time after starting test			
	10 minute	30 minute	1 hr	2 hr
High	>0.50	>0.35	>0.20	>0.15
Average	0.25~0.50	0.17~0.35	0.10~0.20	0.07~0.15
Low	<0.25	<0.17	<0.10	<0.07

A number of researchers have reported the results of measurements of water sorptivity by concrete. Unfortunately, there is considerable difference in the way they have presented their results. Sorptivity is associated with the unsteady flow of water in un-saturated concrete. It is a variable quantity which depends on the time from the start of the test. Consequently, by not specifying the time at which the value is measured, one obtains substantially different values for different time periods. To overcome this problem, in this study an attempt will be made to redefine the sorptivity for a unique time length within the unsteady flow period.

2.5 Concrete rheology

Rheology is defined as the science of the deformation and flow of matter with time, which is concerned with the interaction between shear stress, shear strain, rate of strain and time (Tattersall and Banfill, 1983). Ritchie (1968), subdivided rheology of fresh concrete into three main properties: stability, compatibility and mobility.

2.5.1 The importance of rheological properties of concrete:

The slump test is one of the simplest and approximate methods that could be used to evaluate qualitatively the workability of concrete. On the other hand, workability itself is composed of two main components, consistency (ease of flow) and cohesiveness (resistance to segregation). Consistency is a measure of the wetness of the concrete mixture, which is commonly evaluated in terms of slump. Further, the slump test does not

apply to extreme cases such as concrete with very low workability (zero slump) or very high workability (collapse slump). In addition, the slump test results are influenced by minor variations in the technique of carrying out the test. The other component of workability is the cohesiveness as a measure of compactability and finishability, which is generally evaluated by ease of trowelling and visual judgment of resistance to segregation (Mehta et al. 1993).

Popovics (1982) reported that different concretes having the same measured consistency, or rheological features, can exhibit different workability, therefore, it is extremely importance to establish a prediction equation for flow and deformation of fresh concrete.

In the past the flow properties of fresh concrete were characterized by a single point test, with the assumption that the rate of shear is the same at all points. The liquid which obeys the latter is called a Newtonian liquid, where the ratio of shear stress to the rate of shear is a constant, and thus concrete would be characterized by a single constant (plastic viscosity). It is obvious that observation of the behavior of concrete shows this assumption not to be true because for all materials, other than the simple Newtonian liquids, such as water, the shear is not constant. The actual behavior exhibited by concrete follows a nonlinear trend as a Bingham material. For the latter model, the $\tau - \dot{\epsilon}$ (shear stress- shear strain rate) relation is not a straight line passing through the origin but it has a clear intercept on the shear stress axis. This means that there is a minimum stress at which no flow occurs. Therefore, the flow properties are characterized by two constants, plastic viscosity and yield stress. To establish a straight line, at least

two points are needed. Accordingly, the workability of concrete can not be defined by a test that produces only a single point. Therefore, a two point test was introduced and developed by Tattersall and Bloomer (1970) and Tattersall and Banfill (1983) as a method of characterizing the flow properties of fresh mortar and concrete.

Presently, the flow properties of fresh paste, mortar and concrete are measured by rotation viscometer (Tattersall and Banfill, 1983); sphere lifting test (Mori and Tanigawa, 1987); LAFARGE rheometer (Tattersall, 1990); ViscoCorder rheometer (Banfill, 1990); CEMAGREF-IMG rheometer (Coussot, 1993); rotation viscometer with inserted sphere (Teranishi et al. 1994) and BTRHEOM, the new rheometer for soft to fluid concrete (Hu et al. 1996).

The relevant testing procedure is generally complicated, requires skill and is not simple to carry out in the field. In fact the slump velocity is not evaluated and only the value at the end of flow is measured (Tanigawa et al. 1986).

Tanigawa et al. (1986) designed and constructed a Slump Rate Machine (SLRM) to measure the slumping velocity. The lifting velocity of slump cone was kept to a constant value of 124 mm/sec. The major criticism of their method is lack of explanation for their selected velocity of 124 mm/s, given that the lifting speed of the slump cone according to the ASTM should vary from 43 to 100 mm/s.

2.5.2 Rheological models

Various other models have also been proposed to represent flow of fresh cement pastes, such as the Hershel-Bulkley model, the Robertson Stiff, and Vom Berg model. For completeness the mathematical form of these models are (Tattersall and Banfill, 1983):

$$1. \text{ Bingham} \quad \tau = \tau_y + \eta \dot{\epsilon} \quad (2.6)$$

$$2. \text{ Herschel-Bulkley} \quad \tau = \tau_y + A \dot{\epsilon}^n \quad (2.7)$$

$$3. \text{ Robertson-Stiff} \quad \tau = A \left(\dot{\epsilon} + C \right)^B \quad (2.8)$$

$$4. \text{ Vom Berg} \quad \dot{\epsilon} = B \sinh \frac{\tau - \tau_y}{A} \quad (2.9)$$

where τ , τ_y , $\dot{\epsilon}$ and η are the , shear stress, shear yield stress, shear strain rate and plastic viscosity, respectively, while A, B and C are constants. The flow of fresh concrete appears to be represented the best by the Bingham model (Tattersal and Banfill, 1983).

2.5.2.1 Yield stress

Tanigawa et al (1992) established a relationship between slump and the shear yield stress using principles of applied mechanics and assuming that the shape of slump to remain a simple cone as shown in Figure 2.3.

The initial volume of the cone can be expressed in terms of its height H, its bottom radius r_b and its top radius r_t as follows:

$$\begin{aligned}
 V &= \frac{\pi}{3} (r_t^2 + r_t r_b + r_b^2) H \\
 &= \frac{\pi}{3} (a^2 + a + 1) r_b^2 H \\
 &= \pi \alpha r_b^2 H
 \end{aligned} \tag{2.10}$$

where α is referred to as a shape factor $= \left(\frac{1 + a + a^2}{3} \right)$

The value of α ranges between 1/3 and 7/12, and by letting $\alpha = 7/12$, the final slumping value is not influenced by the slump shape factor.

Assuming that the volume of the concrete material to be constant, the values of α can be calculated using the experimental values for the slump, SL, and the slump-flow, SF,

$$\alpha = \frac{4V}{\pi SF^2 (H - SL)} \tag{2.11}$$

where V = volume of slump cone, m^3

H = height of slump cone (0.30 m)

SL = slump value, m

SF = slump-flow value, m

Tanigawa et al (1993) reconsidered the effect of the shape of fresh concrete at slumping curvature, and they found that the shape factor α to vary with time, Accordingly, they suggested the following equation:

$$\alpha_{(t)} = \frac{V 4}{\pi (H - sL_{(t)}) sF_{(t)}^2} \quad (2.12)$$

where $sL_{(t)}$ = slumping value (m) at time t (s)

$sF_{(t)}$ = slump flowing value (m) at time t (s)

Fig. 2.3: Shape of slumping material

The vertical stress is assumed to be mainly due to the weight of fresh concrete, thus the maximum compressive stress becomes the normal stress at the base of the cone, i.e.

$$\tau_b = -\frac{\rho g V}{\pi r_b^2} = -\alpha \rho g H \quad (2.13)$$

where ρ = density of the material, kg/m^3

g = acceleration of gravity (9.8067 m/s^2)

Adopting the Hohensemser-Prager's constitutive law (Fung 1977), the flow of material will occur when the quadratic invariant of stress deviation, $\sqrt{\sigma J_2}$, exceeds the yield stress, τ_y . This condition occurs at the base of the cone and is represented by the following relation

$$\tau_y = \sqrt{\sigma J_2} = -\frac{\tau_b}{\sqrt{3}} = \frac{\alpha \rho g (H - SL)}{\sqrt{3}} \quad (2.14)$$

Applying Eq. 2.14, together with the measured slump values of the fresh concrete, the yield stress can be approximated as

$$\tau_y = \frac{\alpha \rho g (Z_y)}{\sqrt{3}} \quad (2.15)$$

where Z_y = represents the height (m) at which the material begins to yield.

The yield value which governs the deformation of fresh concrete can be empirically determined from the relationship (Murata and Kikukawa 1992)

$$\tau_y = 715 - 474 \text{Log}(100SL) \quad (2.16)$$

Eq. 2.16 was derived empirically in the basis of slump data of wet consistency mixes with coarse aggregates of maximum size 20 mm and a slump ranging from 12.5 to 26 cm. The yield stress was measured using a coaxial viscometer.

Hu et al. (1996) also empirically arrived at a relationship between shear yield stress and the product of slump and density of fresh concrete using BTRHEOM

$$\tau_y = (30 - 100SL) \frac{\rho}{27} \quad (2.17)$$

Banfill (1993) reported that the yield stress for flowing concrete and normal concrete were 400 and 1000 Pa. respectively. Inadequate details were provided for the latter quantities.

Tanigawa et al (1986) showed some results of concrete yield stress based on sL-t curve. For example, with W/C = 0.55, the slump and yield stress were measured to be 95 mm and 981 Pa., respectively, and when W/C = 0.70, the slump and yield stress were 197 mm and 588 Pa, respectively.

2.5.2.2 Plastic viscosity

The evaluation of plastic viscosity of fresh concrete is critical to the prediction of consistency in high fluidity and high strength concretes. Murata and Kikukawa (1992) developed an equation to quantify the plastic viscosity, thus avoiding the complicated methods of measuring it. According to them, in order to calculate the viscosity of concrete we must first calculate the viscosity of cement paste and mortar.

Viscosity of cement paste

$$\eta_{re} = \frac{\eta}{\eta_o} = \left(1 - \frac{1}{C} V_c\right)^{-(K_1 V_c + K_2)} \quad (2.18)$$

where η_{re} = relative viscosity of cement paste (Pa.s)

η_o = viscosity of water (Pa.s) = 1.002 Pa.s (20° C)

C = percentage of absolute volume of cement

K_1 and K_2 are experimental constants which accommodate the shape of the agglomerated cement particles. They decrease with increasing cement volume concentration (V_c) and increase with increasing specific surface, with average values of $K_1 = - 15.6$ and $K_2 = 11.2$

If the mixing water temperature varies from 20° C, it will affect the plastic viscosity of cement paste. Therefore, they proposed the following equation to accommodate this variation

$$\Delta\eta_1 = q_1 e^{-\left(p_1 \frac{w}{C}\right)} \quad (2.19)$$

where $\Delta\eta_1$ = the increase in plastic viscosity due to temperature change (Pa.s/ c°)

$\frac{w}{C}$ = the water cement ratio

p_1 and q_1 = experimental constants, with $p_1 = 0.32$ and $q_1 = 3.25$

Note that $\Delta\eta_1$ is the increase in plastic viscosity per 1° C, hence for any temperature T greater than 20° C, $\Delta\eta_1$ must be multiplied by (T - 20) to obtain the change in plastic viscosity for that temperature.

Viscosity of mortar and concrete

The latter investigators studied the relationship between agglomerated shape factor and the fineness modulus for both fine and coarse aggregate and they found that the shape factor decreases with increasing fineness modulus for both fine and coarse aggregate. Therefore, the following equation was proposed for both mortar and concrete

$$\eta_{re} = \frac{\eta}{\eta_o} = \left(1 - \frac{1}{C} V_c\right)^{-(a\mu+b)} \quad (2.20)$$

where η_{re} = the relative viscosity of mortar or concrete

η = plastic viscosity of mortar or concrete (Pa.s)

η_o = plastic viscosity of cement paste in case of mortar or plastic viscosity of mortar in case of concrete (Pa.s)

C = solid volume ratio of fine aggregate in case of mortar or coarse aggregate in case of concrete

V_c = volumetric concentration of fine aggregate in case of mortar or coarse aggregate in case of concrete

μ = fineness modulus of fine aggregate in case of mortar or coarse aggregate in case of concrete

a and b = experimental constants, with $a = -0.57$ and $b = 3.4$ in case of mortar and $a = -0.89$ and $b = 9.31$ in case of concrete

Obviously, in this method the effect on absolute volume of adding the additives is very small and relatively negligible compared to the rest of the ingredients. This implies that the effect of additives is not considered.

Tanigawa et al (1993) also proposed the theoretical equation to estimate the plastic viscosity of fresh concrete from the relationship between the slump rate and the slump-flow. Following Bingham's constitutive model (Fung 1977), a relationship exists between the strain rate $\dot{\epsilon}_z$, and the stress-deviation $\bar{\tau}_z$,

$$\dot{\epsilon}_z = \frac{1}{2\eta} \left(1 - \frac{\tau_y}{\sqrt{\sigma J_2}} \right) \bar{\tau}_z \quad (2.21)$$

in which at height Z from the bottom of the cone the stress deviation and the quadratic invariant of stress deviation are given by :

$$\bar{\tau}_z = \frac{2}{3} \tau_z = \frac{2\alpha\rho g(Z-H)}{3} \quad (2.22)$$

$$\sqrt{\sigma J_2} = \tau_y = -\frac{\tau_z}{\sqrt{3}} = \frac{\alpha\rho g(H-Z_y)}{\sqrt{3}} \quad (2.23)$$

Substituting Eq. 2.22 and Eq. 2.23 into Eq. 2.21, yields

$$\dot{\epsilon}_z = \frac{\alpha\rho g(Z-Z_y)}{3\eta} \quad (2.24)$$

Integrating Eq. 2.24 with respect to Z_y , yields

$$Z_y = \frac{\alpha\rho g(-Z^2_y)}{3\eta} \quad (2.25)$$

Integration of Eq. 2.25 with respect to time, yields

$$Z_y = \frac{1}{\frac{\alpha \rho g}{6\eta} t + C} \quad (2.26)$$

where C is a constant.

Tanigawa et al (1992) proposed a relationship between Z_y and the slump at which all portions of the material become non-yielding,

$$Z_y = SL - sL_{(t)} \quad (2.27)$$

This implies that the boundaries of Z_y are given by:

$$Z_y = SL \quad @ \quad t = 0 \quad (2.28)$$

$$Z_y = 0 \quad @ \quad t = \infty \quad (2.29)$$

By substituting Eq. 2.28 into Eq. 2.26

$$C = \frac{1}{SL} \quad (2.30)$$

Also by substituting Eq. 2.27 and Eq. 2.30 into Eq. 2.26, one obtains

$$sL = SL - \frac{1}{\frac{\alpha \rho g}{6\eta} t + \frac{1}{SL}} \quad (2.31)$$

Banfill (1993) reported that the plastic viscosity values for flowing concrete and normal concrete were 20 and 100 Pa.s, respectively. Inadequate details were provided for the latter quantities.

Tanigawa et al (1986) showed some results of concrete plastic viscosity based on sL-t curve. For example, with W/C = 0.55, the slump and plastic viscosity were measured to be 95 mm and 220 Pa.s, and when W/C = 0.70, the slump and plastic viscosity were 197 mm and 60 Pa.s, respectively. Also Topcu and Kocataskin (1995) reported that with increasing W/C ratio, or increasing average aggregate size, the yield stress and plastic viscosity decrease.

The shear yield stress and plastic viscosity are affected by mixture composition, the amount and properties of individual ingredients (especially particle shape, maximum size, size distribution, porosity, and surface texture of the aggregate), the presence of admixture, the amount of mixing and the time elapsed following mixing (ACI 309.96).

2.5.2.3 Slump-flow

The slump flow value, SF, represents the final horizontal spread of the fresh concrete after the removal of the slump cone. Practically, it is not easy to measure slump flow. Therefore Tanigawa et al. (1994) derived a theoretical relationship between the slump value and the slump-flow value:

$$SL = H - \frac{12 \times 10^5}{SF^2} \quad (2.32)$$

where SL and H are in cm and SF is in mm.

This relationship is based on the final shape of material in the slump test, which is assumed to be the frustum of a cone. In other words, $\alpha = 7/12$ is experimentally valid

when the slump flow value is greater than 300 mm. They also established the relationship between the yield value and the slump-flow value:

$$\tau_y = \frac{9.12 \times 10^7}{SF^2} \quad (2.33)$$

where SF is in mm

Mori and Tanigawa (1987) found that the slipping frictional resistance which acts between the bottom plate in the slump test and the fresh concrete has less effect on the slumping value than on the flow value.

The preceding literature survey reveals the complex nature of fresh concrete and the quantification of its rheological properties. Clearly, any simple relationship that can be useful for practical applications would require simplifying assumptions which in turn may diminish its utility. Nevertheless, the establishment of relatively simple relationships between the rheological properties of fresh concrete and the quality of finished concrete is a valuable goal because faulty concrete work can be detected at the casting stage. The latter is the motivation for the present study.

3. EXPERIMENTAL STUDY OF COVERCRETE

3.1 Background and scope

Concrete mixture for house basements when poured into forms usually have W/C ratio of 0.8 - 0.9, and consistencies ranging from a 175 mm slump to fluid condition. Such fluid mixes are produced in order to obtain adequate compaction in the form without the additional cost of vibration. The resultant concrete manifests a host of defects, a high potential for cracking and a friable, highly porous surface layer. These defects are known to have a direct impact on the durability of concrete surface because they reduce its effectiveness as a barrier against the ingress of water and other deleterious agents (Orchard, 1973).

Concrete processing, such as consolidation and curing, is also known to influence the quality of concrete, particularly, the integrity of the concrete surface. Several factors such as cement type and content, water content, admixtures, aggregate type and ratio, forming materials, release agents, and type of vibratory equipment and intensity of vibration are believed to have influence on the finish concrete surface and its integrity. In this study, the effects of some of the foregoing parameters on the quality of covercrete of high W/C concrete were studied experimentally. In particular, the interplay of three parameters, mix design, formwork, and vibration were investigated in some detail.

3.2 Experimental outline

3.2.1 Concrete mix design

As shown in Table 3.1, six concrete mixes were prepared with the primary variables being the water cement ratio (W/C), sand to total aggregate ratio (S/A), water reducer (WRA) and air entrained agent (AEA). The mixtures were designed to simulate the workability and strength of concrete mixes used in the construction of residential basement walls and foundations. For each of the mixture proportions studied, the constituents were adjusted to give an average 28 day compressive strength of 20 MPa and a target minimum slump of 175 mm. This strength level and slump value fall within the range of the corresponding properties of basement concrete mixes.

The mixes consisted of Ordinary Portland Cement type 10 and local coarse and fine aggregates. The coarse aggregate used was crushed limestone, with maximum size of 25 mm, while the fine aggregate was silica sand with maximum size of 4.75 mm. The gradation analysis for the fine and the coarse aggregates was conducted according to ASTM C 33-(1985) and is given in Tables 3.2 and 3.3, and shown in Figures 3.1 and 3.2, respectively. The fineness modulus for the fine and coarse aggregates were calculated according to ASTM C 136-(1984) and the values are, respectively, 2.60 and 6.54. Further, EUCON Lignosulfonate water reducing admixture (WRA) and a synthetic detergent air entraining agent (AEA) were used in some mixes, together, or alone.

The concrete was mixed using a pan mixer according to ASTM C192-(1981). The specimens were cast and cured under controlled room temperature at 20° C and at a

relative humidity of 50 %. Three standard cylinder per mix were cast and cured according to ASTM C 192-(1981).

3.2.2 Formwork and sample geometry

Two geometrical shapes were chosen for the specimens, a wall shape and L-shape form, as illustrated in Figure 3.3. The dimensions of the wall and L-shape are given in Figure 3.3. The actual forms used in this study, as shown in Photos 3.4 and 3.5, were made of plywood or of plywood lined with a coating of 100 % solid urethane. It is part of this study's objective to evaluate the effects of form material facing on the surface condition of the hardened concrete, with particular emphasis on its integrity and mass transport properties.

3.2.3 Vibration

In general, the volume of entrapped air after placement ranges from 5 % to 20 %, depending on the mix design, type of formwork, amount and arrangement of reinforcing steel, and concrete placement method (ACI 309.1993). Removal of entrapped air is an integral part of the placement process in order to reduce both porosity and inhomogeneity in concrete. Vibration is used to minimize the presence of entrapped air in fresh concrete by breaking down its structure, permitting the mortar to fill any voids and to drive entrapped air bubbles to the concrete surface.

For this study, a 32 mm diameter poker vibrator with a frequency of 226 Hz, and a peak acceleration of 1.1g, was selected. The dynamic properties of the vibrator were

measured and the spectrum is given in Figure 3.6. The effectiveness of the selected vibrator to break down the structure of fresh concrete meets the requirements stipulated by Tattersall and Baker (1988).

The vibration period was selected to be 10 seconds on the wall shape forms and a total of 20 seconds for the L-shaped forms. In the latter case, vibration of equal duration (10 seconds) was applied at two positions as indicated in Figure 3.3.

3.3 Properties of fresh concrete

The properties of the mix design were evaluated prior to casting of test specimens. The slump test was carried according to ASTM C 143-(1990), and the slump values for Mixes 1 to 5 are reported in Table 3.4. The slump-flow represents the final horizontal spread of the fresh concrete after the removal of the slump cone. The measured values given in Table 3.4 were obtained by averaging the spread of material measured in two perpendicular directions.

The flow test was used to assess the fluidity of the mix and was performed in accordance with British Standard BS 1881: part 105 (1984). The air content and bleeding were measured according to ASTM C231-(1991b) and C 232-(1992), respectively. The density of fresh concrete was determined using ASTM C 138-(1981). The respective values are given in Table 3.4. It should be noted that the results indicated in Table 3.4 are the average of two repetitions, with a maximum difference of 4 % observed in the slump values of two repeat samples.

Table 3.1: Mix designs for basement concrete in the current investigation

Mix No.	Cement, (kg/m ³)	W/C	Coarse agg., (kg/m ³)	S/A, (%)	Density, (kg/m ³)	WRA, (ml/m ³)	AEA, (ml/m ³)
1 (A)	275	0.83	947	0.52	2333		
1 (B)	275	0.83	750	0.60	2338		
2 (A)	286	0.65	976	0.49	2376		
2 (B)	275	0.65	980	0.49	2377		
3 (A)	275	0.65	980	0.49	2318	687.5	
3 (C)	275	0.65	923	0.52	2292	687.5	
4	275	0.65	980	0.49	2257		137.5
5	275	0.65	923	0.52	2224	687.5	55

Table 3.2: Sieve analysis of the fine aggregate

Sieve size (mm)	Weight retained (g)	Cumulative percentage passing (%)	Cumulative percentage retained (%)
9.51	0.00	100.00	0.00
4.75	48.00	95.10	4.90
2.36	85.31	86.44	13.56
1.18	52.61	81.09	18.91
0.6	230.56	57.64	42.36
0.3	409.92	15.95	84.05
0.15	122.67	3.47	96.53
0.075	28.22	0.60	99.40
Pan	5.88	0.00	Fineness modulus 2.60

Table 3.3: Sieve analysis of the coarse aggregate

Sieve size (mm)	Weight retained (g)	Cumulative percentage passing (%)	Cumulative percentage retained (%)
25	0.00	100.00	0.00
19	41.00	97.09	2.91
12.5	380.10	70.08	29.92
9.5	369.70	43.80	56.20
4.75	576.60	2.81	97.19
2.36	32.60	0.50	99.50
1.18	1.70	0.38	99.62
0.6	0.10	0.37	99.63
0.3	0.50	0.33	99.67
0.15	0.2	0.32	99.68
0.075	0.7	0.27	99.73
Pan	3.8		Fineness modulus 6.54

Table 3.4: Properties of fresh concrete for mixes used in the study

Mix No.	Density, (kg/m ³)	Slump, (mm)	Slump-flow, (mm)	Flow test, (mm)	Air content, (%)	Bleeding, (%)
1 (A)	2333	250	488	710	0.5	21.1
1 (B)	2338	240	475	665	2	12.8
2 (A)	2376	170	270	573		
2 (B)	2377	165	245	510	2.5	5.3
3 (A)	2318	205	315	575	4.2	5.5
3 (C)	2292	168	293	540	5	4.2
4	2257	195	292	533	7.5	1.8
5	2224	200	318	594	7.8	2

Fig. 3.1: Grain size distribution of sand

Fig. 3.2: Grain size distribution of coarse aggregate

Fig. 3.3: Formwork dimensions and geometry used for the wall shape and L-shape specimens

Wood form

Lined form

Fig. 3.4: Photo of the wall-shape wood and lined forms

Wood form

Lined form

Fig. 3.5: Photo of the L-shape wood and lined forms

Fig. 3.6: Fourier spectrum of the poker vibrator

3.4 Evaluation of concrete mixture

3.4.1 General remarks

The amount of cement used in the mix design was less than the suggested amount of 320 kg/m^3 (ACI 301.1996) for a maximum aggregate size of 20 mm. The rationale for using 275 kg/m^3 cement and a range of 0.65 to 0.83 water to cement ratio was to be compatible with the current field practice and to maintain the same cost. It is recognized that as the W/C ratio increases, the quality and durability of concrete is expected to decrease (ACI 201.1992).

3.4.2 Slump

Although the target minimum slump was 175 mm, the measured slump values ranged from 165 mm to 250 mm. The mix design for those mixes whose slump was too

high was modified by increasing the total surface area of solids, i.e. the ratio of fine to the total aggregate. Water reducing admixture was added to increase the slump values for the 0.65 W/C mix design (Mix 3 (A)).

Closer examination of the slump values revealed that an increase of 3% in the ratio of fine to the total aggregate for mixture with $W/C = 0.65$ resulted in an 18% reduction in the slump, in contrast to a 4 % decrease only in the slump value of the mixture with $W/C = 0.83$ when its ratio of fine to total aggregate was increased by 8%. Further, the reduction of W/C ratio from 0.83 to 0.65 resulted in a 75 mm decrease in the slump value.

The slump values measured for Mix 3 (A) and 3 (C) indicate that a mixture becomes more sensitive to changes in the ratio of fine to total aggregate as the W/C is reduced. However, the workability is enhanced through the use of water reducing admixture. The same observation can be made for the air entraining agent by examining Mix 2 (B), 4 and 5. From the measured slump values, the following observations can be made:

1. A reduction in the W/C ratio resulted in a decrease in the slump value.
2. The slump value decreased as the ratio of fine to total aggregate was increased, with the most change experienced by the mixture with the lowest water to cement ratio.
3. The addition of either water reducing admixture or air-entraining agent produced a mix with higher slump value.

3.4.3 Slump-flow and flow

The slump-flow and flow values are a measure of concrete workability. The results in Table 3.4 show a similar trend for both the slump-flow and flow values as the mix design was modified. The plot of slump-flow versus slump in Figure 3.7 shows clearly the effect of W/C ratio. The result for Mixes 3 (A) and 4 show that the addition of admixtures has slightly larger impact on the slump value than on the slump-flow. Similarly, the increase in the ratio of fine to total aggregates, (compare Mixes 3 (C) and 5) largely affected the slump value, with relatively smaller increase in the measured slump-flow.

3.4.4 Air content

Mixes 1 (A), 1 (B) and 2 (B) are considered as non-air entrained concrete, and they contain less than the recommended total air content of concrete (ACI 211.1991) for the specified level of exposure and for the maximum size of aggregate (20 mm) used. Mixes 3 (A), 3 (C), 4, and 5 are considered as air-entrained concrete. Mixes 3 (A) and 3 (C) are suitable for moderate level of exposure while Mixes 4 and 5 are suitable for severe level of exposure. It should be noted that the addition of water reducing admixture increased the entrained air content.

3.4.4 Bleeding

Mix 1 (A) had the highest amount of bleeding, with approximately 15 mm of free water accumulating on the top surface of the concrete specimens, especially those

specimens cast in lined moulds. The amount of bleeding decreased when the sand to the total aggregate ratio was increased from 0.52 to 0.6, Mix 1 (B). The change in the mix design resulted in 8.3 percent less bleeding in Mix 1 (B) compared to Mix 1 (A). For a 0.65 W/C ratio, Mix 2 (B), approximately 5 mm free water was measured on the surface of concrete specimens. However, when Mix 3 (A) was vibrated, the amount of free water increased. As a result, the mix was modified by increasing the amount of sand to the total aggregate ratio from 0.49 to 0.52 to produce Mix 3 (C). The modification showed slight improvement over Mix 3 (A), with about 2 mm free water. A comparison between the measured slump values and the bleeding shown in Figure 3.8 indicates that the percent bleeding in general increases as the slump value increases, and that the addition of admixture increases the slump, with either a minimal decrease, or no change in the amount of free water measured at the top surface. Further, increasing the ratio of fine to total aggregates has minimal impact on the bleeding. From Figure 3.9, one can also observe that the amount of entrained air has no effect on the amount of bleeding.

Fig. 3.7: Relationship between slump value and slump-flow value for the test mixes

Fig. 3.8: Relationship between slump value and bleeding for the test mixes

Fig. 3.9: Relationship between air content and bleeding of the test mixes

4. RHEOLOGICAL PROPERTIES OF FRESH CONCRETE

4.1 Introduction

In spite of rapid advances in the concrete industry, still the most common method of testing fresh concrete workability is based on empirical methods such as the slump method first introduced by Abrams in 1918. In 1983, Tattersall and Banfill introduced the two-point test apparatus for measuring concrete workability. This contribution led to the development of a “Coaxial Cylinders Viscometer” for fresh concrete. Although extensive work has been carried out on the basis of this equipment (Tattersall, 1971; Murata et al., 1973; Uzomaka, 1974), the application of viscometer is still confined to the laboratory environment.

Research efforts, particularly in Japan, have resulted in the development of various types of equipment for testing the concrete rheology. Most notable is the work of Tanigawa et al. (1986, 1988 and 1992) on the estimation of rheological constants of fresh concrete by the slump and the flow tests. The slump and the slump-flow value were measured using an apparatus consisting of a displacement transducer and a slump cone. The apparatus, further modified by Chidiac (1997b), to measure the displacement of fresh concrete and the withdrawal rate of the slump cone, is called the Slump Rate Machine, SLRM. The slump cone in the SLRM meets the requirements of ASTM C 143-(1990). The Slump Rate Machine, SLRM, shown in Figure 4.1, is fully automatic and is controlled by a computer. A computer monitors and records all information necessary to estimate the yield stress and plastic viscosity of fresh concrete. Because of its simple

operation and its conformity to ASTM C 143-90, the SLRM was adopted for this study. This chapter begins by describing the design, operation, and calibration procedures for the SLRM. The methodology for estimating the rheology of fresh concrete is then presented, and the estimated rheological properties of fresh concrete are compared to those obtained via other methods reported in the literature. A comparative study between the rheological properties and the mix design is conducted in order to distinguish empirical methods of predicting the workability of fresh concrete from the corresponding analytical methods.

4.2 Slump Rate Machine, SLRM

4.2.1 General description

The Slump Rate Machine, SLRM, schematically illustrated in Figure 4.1, consists of (1) two displacement transducers for measuring the cone lifting displacement and slump displacement with time; (2) a slump cone for measuring the concrete slump and flow; (3) a computer and a data acquisition unit to monitor and record the readings of both transducers; and (4) an electric motor to control the withdrawal rate of the slump cone.

Fig. 4.1: Schematic view of the Slump Rate Machine, SLRM (Chidiac, 1997b)

4.2.2 Calibration and testing

The SLRM is fully automatic and controlled by a computer. However, the sensitivity and reproducibility of the cone withdrawal rate and the slump measuring rod need to be tested and calibrated. For compliance purposes, the cone lifting speed and the measured slump should comply with ASTM C 143-(1990) recommended values.

During the lifting of the cone, the interfacial friction generated between the fresh concrete and the slump cone can affect both the withdrawal rate and the reproducibility of the results. Two extreme conditions were investigated:

1. The lifting speed of an empty cone
2. The lifting speed of a weighted cone.

The results, as given in Table 4.1, show that the average speed of the lifting cone varies by 5, 8, and 13 percent when the weight of the cone is increased by 2, 4, and 8 kg, respectively. The reproducibility of the results was checked by repeating the test 7 times. As anticipated, the weight added to simulate the friction does affect the speed of the lifting cone, but it remains within the tolerated withdrawal range of 40 % stipulated in ASTM C 143-(1990) for the slump test (5 ± 2 s). Further, the results indicate that the average speed corresponding to power level 5 lies within the ASTM designation C 143-(1990) recommended values of 43 to 100 mm/s.

The SLRM measures the slump using a tracking steel rod that is continuously in contact with the fresh concrete. A 63.5 mm circular plate is attached to the contacting end of the rod for distributing the weight of the rod. The effect of the added weight on the slump values was determined, and the results are given in Table 4.2. Prior to the addition

of a counter weight, the weight of the steel rod resulted in an 83 percent difference between the SLRM values and the results obtained from a standard slump test. Accordingly, a 158 gm counter weight was added to the SLRM apparatus to ensure compliance of slump values with ASTM C 143-(1990).

Table 4.1: Calibration of the effect of lifting cone speed scale for SLRM

Power level	Average speed (mm/sec)			
	Free	2 kg	4 kg	8 kg
3	15.8	15	14.5	13.8
4	33.8			
5	81.2			
6	100.9			
7	114.7			
7.5	125.2	124.4		
8	140.1			
10	210.9			

Table 4.2: The effect of the tracking steel rod weight on concrete spreading

Mix Name	W/C	S/A	Slump cone, (mm)	SLRM		Percent difference
				Counter weight, (g)	Slump, (mm)	
A	0.50	0.41	76.2	free	139.7	83
B	0.51	0.41	45	210	41.4	-8
C	0.53	0.41	75	210	46.7	-38
D	0.60	0.41	139.7	210	126.1	-10
E	0.60	0.41	165	158	165	0
E*	0.60	0.41	141	158	145	3

* Mix E was re-mixed for 30 seconds before repeating the test

The results given in Table 4.2 represent the average of 2 repetitions with a maximum difference of less than 3%. The mix design used for the calibration of the SLRM consisted of 296 kg/m³ cement and 1172 kg/m³ coarse aggregate.

4.3 Measurement of the rheological properties

The SLRM machine was adopted as the apparatus for measuring and estimating the rheological properties of the design concrete mixes given in Table 3.1. The properties of interest are slump, shear yield stress, plastic viscosity and slump-flow.

4.3.1 Slump

The recorded SLRM measurements of the fresh concrete slump as a function of time are shown in Figure 4.2 while the measured average slump rate is shown in Figure 4.3. The average slump rate is equal to the total travel distance divided by total travel time. The measured slump time, average slump rate, and the corresponding values of slump are also summarized in Table 4.3.

Table 4.3: Measured slump time, average slump rate and slump

Mix Name	Slump time, (s)	Average slump rate, (mm/s)	Slump, (mm)		Percent difference
			cone	SLRM	
1 (A)	3.7	73.51	250	272	9
1 (B)	4.6	52.40	240	241	0
2 (A)	10.5	18.67	170	196	15
2 (B)	9.2	20.00	165	184	12
3 (A)	7.6	30.26	205	230	12
3 (C)	11	15.60	168	172	2
4	7.2	27.08	195	207	6
5	6.6	35.45	200	234	17

Fig. 4.2: Measured slump curves for Mixes 1 (A) to 5

Fig. 4.3: Measured average slump rate for Mixes 1 (A) to 5

A comparison between the slump values measured using SLRM, and those using the manual slump cone, Table 4.3, shows that the former are slightly larger. Maximum differences of 15 and 17 percent were obtained for Mixes 2 (A) and 5, respectively. Those values suggest that the counter weight used in the calibration of the SLRM may not have been sufficient.

The measured average slump rates, Figure 4.3, show that the rates for Mix 1 (A), 1 (B), 3 (A) and 5, are not smooth, and that the slump accelerates and decelerates during travel time of the concrete cone. For these mixes the initial high rate of slump is attributed to poor inter-particle cohesion due to excessive amount of free water. As the free water is allowed to escape and separate from the other components of the mix, the rate of slump decreases significantly.

4.3.2 *Shear yield stress*

It is recognized that the slump test is essentially a static test, primarily depending on the yield stress of the fresh concrete. Three previously proposed relationships between slump and shear yield stress were investigated, namely:

1. Tanigawa et al (1992)

$$\tau_y = \frac{\alpha \rho g (H - SL)}{\sqrt{3}} \quad (4.1)$$

2. Murata et al (1992)

$$\tau_y = 715 - 474 \log(100 SL) \quad (4.2)$$

3. Hu et al (1996)

$$\tau_y = (30 - 100SL) \frac{\rho}{27} \quad (4.3)$$

The relationship given by Murata et al. and Hu et al. are based on numerous experimental results, where the shear yield stress was measured by a coaxial cylinder viscometer and a BTRHEOM, respectively. The relationship given by Tanigawa et al. was derived from the principles of applied mechanics, and based on the assumption that the shape of the slumped material remains a simple cone. By further assuming that the material is incompressible, the value of the shape factor, α , was then calculated using the experimentally measured values for slump, SL, and the slump-flow SF, i.e.

$$\alpha = \frac{4V}{\pi SF^2 (H - SL)} = \frac{1 + a + a^2}{3} \quad (4.4)$$

The corresponding maximum and minimum computed values of α , shown in Table 4.4, are 1.05 and 0.53, respectively. The corresponding maximum and minimum values for a are 1.05 and 0.43, respectively. The average value of α may be taken as 0.87. Theoretically, it should be noted that the value of the parameter a larger than 1.0 implies that the top radius of the slump cone is greater than the bottom one. For fresh concrete with a large slump value, the cone tends to collapse into a shallow cylinder, thus resulting in a maximum value of a equal to 1.0. Thus for α values greater than 7/12, the geometry of the collapsed cone will take the form of a cylinder rather than a cone, with its diameter equal to the slump-flow (SF).

By applying Eq. 4.1, together with the measured slump value of the fresh concrete, the yield stress can be computed. As shown in Figure 4.4, α equal to 7/12, as suggested by Tanigawa et. al (1992), produces yield stress values that do not agree with those obtained from Eq. 4.4. The results shown in Figure 4.4 indicate that the yield stress values computed using a value of α in the range of 1.0 are in close agreement with those from Eq. 4.4. From Table 4.4 it can be observed that with the exception of Mix 1 (B) and 3 (C), the values of α are greater than 0.87. It should also be noted that Mix 1 (B) and 3 (C) have the highest sand to total aggregates ratio for the W/C ratio equal to 0.83 and 0.65, respectively. Thus increasing the ratio of sand to total aggregates increased the inter-particle cohesion, resulting in a reduction in the values of both the slump-flow and slump.

The results indicate that adapting a single value for the shape factor to compute the shear yield stress, as suggested by Tanigawa et al (1992), can not adequately represent the various mix proportions. As a result, substitution of Eq. 4.4 into Eq. 4.1 produces a relationship for the yield stress that is independent of the shape factor and inversely proportional to the square of the slump-flow, i.e.

$$\tau_y = \frac{4\rho g V}{\sqrt{3}\pi SF^2} \quad (4.5)$$

The relationship proposed by Murata and Kikukawa (1992) produces maximum and minimum shear yield stress values of 130 and 35 Pa, respectively. These maximum and minimum values, as shown in Table 4.5, correspond to slump values of 172 and 272 mm, respectively.

Hu et al.'s. (1996) empirical relationship shows that the yield stress is linearly proportional to the product of the slump and density. The corresponding results are given in Table 4.5 and shown in Figure 4.4. The results, shown in Figure 4.4, computed in accordance with

Eq. 4.1, are significantly larger in comparison to those computed using the empirical relationship suggested by Murata and Kikukawa (1992). However, the computed values using the Hu et al.'s relationship are found comparable to those obtained using Eq. 4.1. Further comparison shows the computed values are within the range of the typical values reported by Tanigawa (1986) and Banfill (1993). Figure 4.4 clearly displays the difference between the yield values obtained from Eq. 4.2 and those obtained from Eq. 4.1 and 4.3.

Table 4.4: Effect of shape factor on the yield stress value

Mix No.	Density, (kg/m ³)	Slump, (mm)	Slump-flow, (mm)	α	a	Yield stress, (Pa)			
						Eq. 4.1, Tanigawa et al. (1992)			
						Eq. 4.4	$\alpha=0.5$	$\alpha=0.87$	$\alpha=1.0$
1 (A)	2333	272	488	1.05	1.05	388	194	338	388
1 (B)	2338	241	475	0.53	0.43	411	206	358	776
2 (A)	2376	196	270	0.92	0.92	1292	646	1124	1404
2 (B)	2377	184	245	1.01	1.01	1570	785	1366	1570
3 (A)	2318	230	315	1.01	1.01	926	463	806	926
3 (C)	2292	172	293	0.64	0.58	1058	529	920	1653
4	2257	207	292	0.88	0.87	1049	525	913	1192
5	2224	234	318	1.05	1.05	872	436	759	872

Table 4.5: Comparison of estimated shear yield stress

Mix No.	Yield, (Pa)		
	Eq. 4.1	Eq. 4.2	Eq. 4.3
	Tanigawa et al. (1992)	Murata et al. (1992)	Hu et al. (1996)
1 (A)	388	35	242
1 (B)	411	60	511
2 (A)	1292	103	915
2 (B)	1570	116	1021
3 (A)	926	70	601
3 (C)	1058	130	1087
4	1049	92	777
5	872	66	544

Fig. 4.4: Relationship of shear yield stress to the slump and shape factor

4.3.3 Plastic viscosity

The evaluation of plastic viscosity is critical for predicting the consistency of high fluidity concrete. Following the literature survey, the two approaches proposed by Kikukawa et al. (1993) and Tanigawa et al. (1992) are further examined in this study. The two approaches are referred to as method A and method B, respectively. In the present study, a third approach, based on Tanigawa et al. (1992), is also proposed. This approach is referred to as method C.

Closer examination of Tanigawa et al. (1992) proposed relationship between Z_y and the slump, i.e.

$$Z_y = \frac{SL - sL_{(t)}}{100} \quad (4.6)$$

yields to zero height above which fresh concrete has yielded, i.e. complete collapse. Instead, the height should correspond to the relation previously given, i.e. $Z_y = H - SL$. Thus, a new relationship for Z_y is proposed as follows:

$$Z_y = H - sL_{(t)} \quad (4.7)$$

This implies that the boundaries of Z_y are given by

$$Z_y = H \quad @ \quad t = 0 \quad sL_{(t)} = 0 \quad (4.8)$$

$$Z_y = H - SL \quad @ \quad t \geq t_{slump} \quad sL_{(t)} = SL \quad (4.9)$$

The incorporation of the new boundaries for Z_y into Eq. 2.26 yields

$$sL = H - \frac{1}{\frac{\alpha \rho g}{6\eta} t + \frac{1}{H}} \quad (4.10)$$

It should be noted that Eq. 4.10 applies only during the slumping time and therefore is further modified to take into effect the slump time, i.e.

$$sL = H - \frac{1}{\frac{\alpha \rho g}{6\eta} t + \frac{1}{H}} \quad 0 \leq t < t_{slump} \quad (4.11)$$

$$sL = SL \quad t \geq t_{slump}$$

The initially computed plastic viscosity values using Eq. 4.11 are high in comparison with the values obtained from method B. The difference is attributed to the factor 100 introduced in the relationship between Z_y and the slump. To be consistent with the calibrated relationship of Tanigawa et al. (1992), a calibration factor of equal magnitude, 100, was introduced into Eq. 4.11, hence

$$sL = H - \frac{1}{\frac{\alpha \rho g}{600\eta} t + \frac{1}{H}} \quad 0 \leq t < t_{slump} \quad (4.12)$$

$$sL = SL \quad t \geq t_{slump}$$

Since Eq. 4.12 is consistent and continuous, it was further re-arranged to establish a relationship between the plastic viscosity and the slump, slump flow and the time of slump, i.e.

$$\eta = \frac{\rho g H V}{150\pi SL SF^2 t_{slump}} \quad (4.13)$$

It should be noted that Eq. 4.4 was used to account for the shape factor.

Computed values of slump versus time using method B, method C and the experimental data are shown in Figure 4.5 to Figure 4.12, for Mix 1 (A) to Mix 5, respectively. The computed plastic viscosity and the time of slumping are summarized in Table 4.6. The measured slump time are given in Table 4.3 while the computed ones are

reported in Table 4.6. The two time sets are found to be in excellent agreement, except for Mix 1 (B).

Examination of the slump curves shows that the proposed relationship gives representative slump curves for all the tested mixes, except for Mix 1 (A). The results are in excellent agreement with the measured slump curve, provided the shape of the curve is concave. For Mixes 1 (A), 1 (B), 3 (A), 4, and 5, one can observe a convex slump curve.

The computed values for plastic viscosity according to method A (Kikukawa et al., 1993) are 1.33 and 1.35 Pa.s for the W/C ratio of 0.83 and 0.65, respectively. These values are very low. The computed plastic viscosity according to method B (Tanigawa et al., 1992), are 75 Pa.s for W/C ratio of 0.83 and in the range of 100 to 300 Pa.s for the W/C ratio of 0.65. Referring to Figure 4.2, one can observe that the velocity of deformation of Mixes 2(A) and 2(B) exhibits similar trend, an indication that the plastic viscosity for both mixes are close to each other, with Mix 2(B) being slightly higher. Estimating the plastic viscosity of Mix 2 (B) by Method B gives a value approximately 200 percent greater than that of Mix 2 (A). Further, Mixes 3(A), 4 and 5 exhibited similar trend, but the estimated plastic viscosity showed a very wide range of variation. Revisiting the results obtained using method C, it can be observed that the predicted plastic viscosity for Mixes 2 (A) and 2 (B) are in close proximity with that of Mix 2 (B) being slightly larger. The plastic viscosity for Mixes 3 (A), 4 and 5 are 31, 33 and 21 Pa.s, respectively, values which follow the trend. The predicted plastic viscosity of 59 Pa.s for Mix 3 (C) corresponds to the low rate of slump.

One should note that these observations follow the theoretical definition of plastic viscosity which controls the flowing velocity of material in the slump test. Thus it increases with a decrease in the flowing velocity.

The proposed new relationship (Method C) has yielded a range of plastic viscosity values between 5 to 11 Pa.s for the W/C = 0.83 and a range of 21 to 74 Pa.s, for the W/C = 0.65. The computed plastic viscosity using methods C show very consistent results, and the computed slump curves are in agreement with the experimental data. Also the computed plastic viscosity values are within the range of plastic viscosity values reported by Tanigawa (1986) and Banfill (1993).

In general, since there are no standard methods to reliably quantify or measure the plastic viscosity of fresh concrete, and recognizing the wide range of variation from one method to another, which is due to variations in testing equipment and techniques, one should use calculated values of plastic viscosity as indicators of the rheological behavior of fresh concrete.

Table 4.6: Computed slump time and plastic viscosity values

Mix No.	Slump time, (s)	Method A, (Pa.s)	Method B, (Pa.s)	Method C, (Pa.s)	
				curve fitting	Eq. 4.13
1 (A)	4	1.33	75	5	5
1 (B)	7.5	1.33	75	11	7
2 (A)	10.3	1.34	100	59	60
2 (B)	10	1.35	300	74	68
3 (A)	8.9	1.35	300	31	26
3 (C)	11.1	1.35	300	59	59
4	7.5	1.35	100	33	32
5	6.5	1.35	150	21	21

Fig. 4.5: Experimental and computed slump curves for Mix 1 (A)

Fig. 4.6: Experimental and computed slump curves for Mix 1 (B)

Fig. 4.7: Experimental and computed slump curves for Mix 2 (A)

Fig. 4.8: Experimental and computed slump curves for Mix 2 (B)

Fig. 4.9: Experimental and computed slump curves for Mix 3 (A)

Fig. 4.10: Experimental and computed slump curves for Mix 3 (C)

Fig. 4.11: Experimental and computed slump curves for Mix 4

Fig. 4.12: Experimental and computed slump curves for Mix 5

4.3.4 Slump-flow

The slump flow values can be computed using the Tanigawa et al.(1994) proposed relationships, i.e.

$$SL = H - \frac{12 \times 10^5}{SF^2} \quad (4.14)$$

The slump flow value can also be computed by re-writing Eq. 4.4. as

$$SF = \sqrt{\frac{4V}{\pi\alpha(H - SL)}} \quad t > t_{slump} \quad (4.15)$$

The rate of slump-flow can be derived by substitute Eq. 4.12 into Eq. 4.15, which gives

$$sF_{(t)} = \sqrt{\frac{4V}{\pi\alpha} \left(\frac{\alpha\rho g}{600\eta} t + \frac{1}{H} \right)} \quad 0 \leq t \leq t_{slump} \quad (4.16)$$

Figure 4.13 shows a plot of the experimentally measured values and the computed values, using Eq. 4.14 and Eq. 4.16. One can observe that the computed values using the present study are in good agreement with the experimentally measured ones. The computed slump flow values with time using Eq. 4.16 are shown in Figure 4.14. The computed slump flow curves exhibit similar characteristics to those of the measured slump rate shown in Figure 4.2. The factors which influence the slump flow curves also influence the measured slump curves, and generally in the same manner.

Fig. 4.13: Relationship between slump value SL. and slump-flow value SF.

Fig. 4.14: Computed slump-flow for Mixes 1 (A) to 5

4.4 General observations

The results clearly indicate that an increase in the AEA, WRA and W/C values decrease the shear yield stress, the plastic viscosity, and the total time of slump. Further, one can observe that the plastic viscosity is equally affected by the changes in AEA, WRA and W/C. The water to cement ratio has the most influence over the shear yield stress, followed by the water reducer admixture and the air entraining agent. However, the air entraining agent has the most influence over the total time to slump in comparison to the WRA and W/C. The increase in the ratio of fine to total aggregate has a direct effect on the rheological properties. The plastic viscosity and the total time of slump are the most influenced by S/A, with the shear yield stress being marginally affected.

4.5 Concrete workability-a quantitative approach

Experimental observations have shown the inter-relationship between the slump, the slump-flow, the shear yield stress, the plastic viscosity, and the total time of slump. The observed inter-relations can be quantified by the following equations:

1. Shear yield stress versus slump-flow and density

$$\tau_y = \frac{4\rho g V}{\sqrt{3}\pi SF^2} \quad (4.17)$$

2. Slump flow versus slump, total time of slump and plastic viscosity

$$sF_{(t)} = \sqrt{\frac{4V}{\pi\alpha} \left(\frac{\alpha\rho g}{600\eta} t + \frac{1}{H} \right)} \quad (4.18)$$

3. Plastic viscosity versus slump, slump flow and total time of slump

$$\eta = \frac{\rho g H V}{150 \pi S L S f^2} t_{\text{slump}} \quad (4.19)$$

Assessment of workability in terms of the rheological properties, i.e. the shear yield stress and the plastic viscosity, calculated based on the slump, slump flow, density of fresh concrete, and time of slump measurements, can provide a powerful tool for control of concrete production. Using the above relationships, design curves can be established to control the quality of the fresh concrete as illustrated in Figure 4.15 and Figure 4.16. These curves can be used to determine the necessary slump and slump-flow for the required rheological properties, or to control the uniformity of the fresh mix to the required properties using the measured slump, and slump flow and time of slump. It should be noted that although the established curves may require further refinement and calibration, their benefits as a means to control the quality of fresh mix should not be overlooked.

Fig. 4.15: The effect of slump, slump-flow and density on shear yield stress

Fig. 4.16: The effect of slump, slump-flow and time of slump on plastic viscosity

5. MECHANICAL AND PHYSICAL PROPERTIES OF HARDENED CONCRETE

5.1 Background and scope

The microstructure analysis of the hardened concrete by Krijger (1987) showed that the condition, structure, and properties of the outside 50 mm of the concrete cover differ from those of the bulk. The results indicated a significant variability in properties of the covercrete, with the lowest quality being in the outermost layer. Further, the highest values for porosity and water uptake were recorded at the outermost layers. Macroscopic investigations into the durability of concrete have revealed that the W/C ratio, period of moist curing, and the workability of concrete are the parameters that have the most effect on the covercrete water uptake properties. The desired properties, in particular the quality of the hardened concrete, are contingent on the characteristics of the plastic state which affords proper compaction and homogeneity of the hardened mass.

In this study, the mechanical and physical properties of the basement concrete mixes were evaluated using destructive and non-destructive tests. The non-destructive evaluation consists of visual inspection of the concrete surface condition, surface air tightness, surface hardness and ultrasonic pulse velocity. The destructive tests conducted to quantify the properties of the hardened concrete are compressive strength, pull off tests, initial surface absorption, sorptivity and porosity.

The water uptake properties of the hardened concrete and the initial surface absorption and sorptivity of the covercrete are compared to those of the bulk. The comparison is performed to assess the durability potential of the concrete.

Although the latter may be a simplistic approach, it provides a strong indication of the effectiveness of covercrete as a barrier against air, water and/or ion penetration into the bulk of the concrete.

5.2 Non-destructive tests

Non-destructive evaluation involves tests that can be performed without causing any damage to the concrete substrate. The visual inspection was carried out to qualitatively evaluate the surface condition of the hardened concrete. The air permeability test is used to assess the air tightness of the covercrete. The hardness test gives the stiffness characteristic of the covercrete whereas the ultrasonic pulse velocity measures the variation in the elastic properties through out the bulk. The shrinkage test is expected to provide a measure of the concrete crack potential as it hardens.

5.2.1 Characterization of finished concrete surface

A visual inspection of the cast samples was conducted to qualitatively describe the finished concrete surface. Table 5.1 to Table 5.6 present the findings for the various mixes. Close examination of the surface conditions revealed that the concrete surface cast against wood reflected the grain pattern due to the differential absorption of the timber, and profiling of the grain pattern is shown in Figure 5.1, with small air pockets ranging

from 2 mm to 25 mm in diameter. The largest and smallest air pocket were visually identified and their maximum diameters were manually measured. The lined form produced smooth and gray colour surfaces. Bug-holes found on the surface of specimens cast in lined forms ranged from 2 to 20 mm in diameter. In addition a large number of air pockets of less than 2 mm were observed.

The influence of formwork surface absorbency upon the occurrence of blow holes is illustrated in Figure 5.2. Current practice indicates that the treated plywood with a suitable release agent gives a low degree of blow holes; this was confirmed in the present study (CIB report no. 5, 1966). Figure 5.2 also shows that non-absorbent form (lined forms) for mixes with high W/C ratio tend to aggravate the occurrence of blow holes. In general, the specimens from Mixes 1(B), 4 and 5, which were not vibrated, and which were cast in wood and lined forms, exhibited excessive amount of pin holes with a maximum diameter of 2 mm, as shown in Figure 5.3 to Figure 5.8. The degree of blow hole formation is categorized in Table 5.7. The results indicate that none of the mixes responded effectively to the consolidation efforts through vibration insofar as blow holes formation is concerned.

The amount of sand streaking is illustrated in Figure 5.9 which shows that Mixes 1(A), 1(B) and 2(B) had a high degree of sand streaking. Figure 5.10 and Figure 5.11 photographically confirm the latter assessment. This behavior is attributed to excessive bleeding which promotes sand streaking. Figure 5.12 indicates that a high amount of free water was observed during the casting of Mixes 1(A) and 1(B), especially in non-absorbent forms. This amount of free water is shown photographically in Figure 5.13 and

Figure 5.14. It was observed, however, that a concrete which contains an adequate amount of entrained air could prevent sand streaks, but high air content also led to a thickness of 10 mm laitance (Figure 5.15) especially in the case of vibrated concrete.

Figure 5.16 shows that insufficient amount of cement in the mix, or high sand/cement ratio, leads to honeycomb as in the case of Mixes 1(B) and 2(B), but good vibration tends to partly overcome this problem.

It is recognized that some of the observations in this section are subjective and may depend on the perspective of the observer. However, most of the subjective observations pertain to the relative characteristics of two or more specimens. For example it is easy to distinguish gray from dark gray, without any absolute reference.

Table 5.1: Surface condition for Mix 1 (A)

Shape	Vib.	Form	Air pocket	Sand streaks	Honey - comb	Hair crack	Surface texture colour	General observation
W	N	Wood	Few and small 15 per side 5mm in Ø	N	N	N	Slightly rough Dark green in colour	Laitance Bleeding
	N	Lined	Few and small 10 per side 3 mm in Ø	500 mm ²	N	N	Smooth, gray in colour	Laitance Excessive bleeding 15 mm free water
L	N	Wood	N	N	N	N	Slightly rough Dark green in colour	Laitance Bleeding
	N	Lined	Very small 20 per side 2 mm in Ø	N	N	N	Smooth gray in colour	Laitance Excessive bleeding 15 mm

Table 5.2: Surface condition for Mix 1 (B)

Shape	Vib.	Form	Air pocket	Sand streaks	Honey-comb	Hair crack	Surface texture colour	General observation
W	N	Wood	20 per side 5 mm in Ø	N	N	N	Slightly rough dark green in colour	Laitance
	N	Lined	Few large one with many small 20 per side 12mm in Ø	500 mm ²	3000 mm ²	N	Smooth gray in colour	Laitance
	Y	Wood	20 per side 5 mm in Ø	N	N	N	Slightly rough dark green in colour	Laitance
	Y	Lined	Too many small 80 per side 8 mm in Ø	1500 mm ²	N	N	smooth gray in colour	Laitance 5 mm free water
L	N	Wood	Too many small <3mm in Ø	Slightly sand streaks < 400 mm ²	N	N	Slightly rough dark green in colour	Laitance
	N	Lined	Few large & many small 5 per side 10mm in Ø <2mm in Ø	3000 mm ²	N	N	Smooth gray in colour	Laitance
	Y	Wood	Many small <2mm in Ø	N	N	N	Slightly rough dark green in colour	Laitance
	Y	Lined	40 per side 4mm in Ø	N	N	N	smooth gray in colour	Laitance Bleeding 5 mm

Table 5.3: Surface condition for Mix 2 (B)

Shape	Vib.	Form	Air pocket	Sand streaks	Honey-comb	Hair crack	Surface texture colour	General observation
W	N	Wood	15 per side 10mm in Ø	Slightly not significant	800 mm ²	N	Slightly rough green yellow	
	N	Lined	25 per side 8 mm in Ø	N	N	N	Smooth gray	
	Y	Wood	30 per side 3 mm in Ø	N	N	N	Slightly rough dark yellow & green	Slight laitance 2 mm free water In general good
	Y	Lined	50 per side 9 mm in Ø	N	N	N	Smooth gray	Laitance 2 mm Acceptable
L	N	Wood	20 per side 10mm in Ø	1000 mm ²	1500 mm ²	N	Slightly rough dark yellow to green	Not acceptable
	N	Lined	40 per side 10mm in Ø	2000 mm ²	2500 mm ²	N	Smooth gray	Not acceptable
	Y	Wood	15 per side 10mm in Ø	N	N	N	Slightly rough dark yellow to green	Slight laitance 2 mm In general good
	Y	Lined	60 per side 6 mm in Ø	N	N	N	Smooth gray	Laitance 2 mm Acceptable

Table 5.4: Surface condition for Mix 3 (C)

Shape	Vib.	Form	Air pocket	Sand streaks	Honey-comb	Hair crack	Surface texture colour	General observation
W	N	Wood	10 per side 7 mm in Ø	N	N	N	Slightly rough yellow to green	Slight bleeding in general good
	N	Lined	50 per side 8 mm in Ø	1000 mm ²	N	N	Smooth gray	Excessive bleeding acceptable
	Y	Wood	30 per side 10mm in Ø	N	N	N	Slightly rough yellow to green	Excessive bleeding
	Y	Lined	30 per side 15mm in Ø	N	N	N	Smooth gray	Excessive bleeding
L	N	Wood	60 per side 5 mm in Ø	N	N	N	Slightly rough light green	Slight bleeding In general good
	N	Lined	80 per side 14mm in Ø	N	N	N	Smooth gray	Excessive bleeding Acceptable
	Y	Wood	20 per side 25mm in Ø	N	N	N	Slightly rough Light green	Excessive bleeding
	Y	Lined	80 per side 20mm in Ø	N	N	N	Smooth gray	Excessive bleeding

Table 5.5: Surface condition for Mix 4

Shape	Vib.	Form	Air pocket	Sand streaks	Honey-comb	Hair crack	Surface texture colour	General observation
W	N	Wood	Small in Ø	N	N	N	Slightly rough light yellow to green	Excessive bleeding
	N	Lined	50 per side 7 mm in Ø numerous 0.5mm in Ø	N	N	N	Smooth gray	Excessive bleeding
	Y	Wood	30 per side 10mm in Ø	N	N	N	Slightly rough light yellow to green	Excessive bleeding 10 mm loose creamy mortar
	Y	Lined	50 per side 15mm in Ø	N	N	N	Smooth gray	Excessive bleeding 10mm loose creamy mortar
L	N	Wood	10 per side 3 mm in Ø	N	N	N	Slightly rough dark green	Excessive bleeding
	N	Lined	Few 13mm in Ø with many 0.5mm in Ø	1000 mm ² near to the corner	N	N	Smooth gray	Excessive bleeding
	Y	Wood	10 per side 3 mm in Ø	N	N	N	Slightly rough dark green	Excessive bleeding 10mm loose creamy mortar
	Y	Lined	30 per side 5 mm in Ø	N	N	N	Smooth gray	Excessive bleeding 10 mm loose creamy mortar

Table 5.6: Surface condition for Mix 5

Shape	Vib.	Form	Air pocket	Sand streaks	Honey - comb	Hair crack	Surface texture colour	General observation
W	N	Wood	50 per side 2 mm in Ø	N	N	N	Slightly rough dark green	
	N	Lined	Many small in size 30 per side 10mm in Ø	N	N	N	Smooth gray	Bleeding
	Y	Wood	50 per side 10mm in Ø	N	N	N	Slightly rough dark green	Excessive bleeding and air bubbles at surface
	Y	Lined	20 per side 12mm in Ø	N	N	N	Smooth gray	Excessive bleeding
L	N	Wood	Too many < 2mm in Ø	N	N	N	Slightly rough dark green	Laitance
	N	Lined	Large 5 per side 7mm in Ø Too many < 2mm in Ø	N	N	N	Smooth gray	Laitance
	Y	Wood	30 per side 6 mm in Ø	N	N	N	Slightly rough dark green	
	Y	Lined	40 per side 15mm in Ø	N	N	N	Smooth gray	

Table 5.7: The mixtures categorization with respect to blow holes

Mix No.	Blow Holes			
	Unvibrated		Vibrated	
	Wood	Lined	Wood	Lined
1(A)	M	M		
1(B)	M	M	M	H
2(B)	M	M	M	H
3(C)	H	H	M	H
4	L	M	M	H
5	H	M	H	M

Note: (L : 0~15 blow holes, M: 15~30 blow holes, H: > 30 blow holes per total surface area of the specimen)

Fig. 5.1: Surface photograph of the grain pattern obtained from plywood surface

Fig. 5.2: Effect of mould geometry and mould surface on amount of blow holes on concrete surface

Fig. 5.3: Photograph of concrete from Mix 1(B) cast in wood form

Fig. 5.4: Photograph of concrete from Mix 1 (B) cast in lined form

Fig. 5.5: Photograph of concrete from Mix 4 cast in wood form

Fig. 5.6: Photograph of concrete from Mix 4 cast in lined form

Fig. 5.7: Photograph of concrete from Mix 5 cast in wood form

Fig. 5.8: Photograph of concrete from Mix 5 cast in lined form

Fig. 5.9: Effect of mould geometry and mould surface on sand streaks on concrete surface

Fig. 5.10: Photograph of Mix 1 (B) vibrated concrete cast in lined form

Fig. 5.11: Photograph of concrete from Mix 3 (A) cast in lined form

Fig. 5.12: Effect of mould geometry and mould surface on amount of free water on concrete surface

Fig. 5.13: Photograph of free water on the surface of Mix 1 (A) cast in lined form

Fig. 5.14: Photograph of free water on the surface of Mix 1 (A) cast in wood form

Fig. 5.15: Photograph of creamy mortar on the surface of Mix 4

Fig. 5.16: Effect of vibration and form finish on honeycomb of concrete surface

5.2.2 Surface hardness

The rebound test is a non-destructive test that is currently used by the industry for assessing the integrity of concrete. For the present design mixes, the tests were conducted in accordance with ASTM C 805-1985 and the results are summarized in Table 5.8. The data represents the average of nine readings in each case.

Based on the results in Table 5.8, it is difficult to deduce any direct relationship and/or trend between the rebound number and the various parameters considered in the current mixes.

Table 5.8: Results of rebound number

Mix No.	Statistical analysis	Results			
		Unvibrated		Vibrated	
		Wood	Lined	Wood	Lined
1 (A)	Mean	12.72	15.22		
	S.D	2.85	1.40		
1 (B)	Mean	11.83	9.44	12.22	11.72
	S.D	2.15	1.06	1.83	1.67
2 (B)	Mean	16.44	17.50	16.94	16.94
	S.D	2.31	1.59	2.14	1.29
3 (C)	Mean	14.17	17.00	16.67	15.72
	S.D	2.36	2.06	2.87	1.99
4	Mean	14.89	11.56	16.33	14.22
	S.D	1.41	1.58	2.06	2.92
5	Mean	11.06	12.28	13.50	12.22
	S.D	2.07	2.40	2.15	2.26

5.2.3 Pulse velocity

Concrete pulse velocity is often used to assess the quality of concrete insofar as the existence of flaws and damage are concerned. The tests here were conducted in

accordance with ASTM C 597 (1983). In the current study, the ultra-sound device, “Pundit”, was used to assess the quality of the different hardened concrete mixes. The pulse velocity results, summarized in Table 5.9, show that the concrete with $W/C = 0.65$, cast in lined form and vibrated had the highest pulse velocity. It appears that consolidation has some effect because the vibrated concrete has generally higher pulse velocity than the unvibrated concrete. Furthermore, with the exception of Mix 4, the vibrated lined form specimens had relatively higher pulse velocity than the vibrated wood form specimens. It is recognized that the preceding observations are not definitive conclusions because they are based on the comparison of the average pulse velocity of the various specimens. In fact, the recorded standard deviation values in Table 5.9, could alter some of these conclusions. Further work is needed to definitively establish a relationship between some of the present test parameters and the pulse velocity of the specimens.

A plot of recorded pulse velocities versus concrete density is shown in Figure 5.17. It can be observed that in general the denser mixes have higher pulse velocity. Further, the effect of the concrete air content on the pulse velocity is noticeable because generally the mixes with higher air content have both lower density and lower measured pulse velocity.

In summary, the concrete density has effect on the pulse velocity, and more importantly, the results reveal that generally consolidated concrete has higher pulse velocity. This observation agrees with the knowledge that the use of vibration reduces voids and air-pockets and improves the compactness of concrete.

Table 5.9: Pulse velocity of the hardened concrete

Mix No.	Sample No.	Pulse velocity, km/s			
		Unvibrated		Vibrated	
		Wood	Lined	Wood	Lined
1 (A)	V1	3.96	4.33		
	V2	4.05	4.37		
	Avg.	4.00	4.35		
	S.D	0.06	0.03		
1 (B)	V1	4.09	3.69	3.97	4.08
	V2	4.12	3.73	4.07	4.12
	Avg.	4.10	3.71	4.02	4.10
	S.D	0.02	0.03	0.07	0.03
2 (B)	V1	4.29	4.44	4.28	4.41
	V2	4.37	4.35	4.38	4.50
	Avg.	4.33	4.39	4.33	4.45
	S.D	0.06	0.06	0.07	0.06
3 (C)	V1	4.21	4.25	4.12	4.33
	V2	4.11	4.33	4.19	4.43
	Avg.	4.16	4.29	4.15	4.38
	S.D	0.07	0.06	0.05	0.07
4	V1	3.87	3.89	4.14	4.07
	V2	3.94	4.02	4.10	4.23
	Avg.	3.91	3.95	4.12	4.15
	S.D	0.05	0.09	0.03	0.11
5	V1	3.88	3.99	3.86	4.10
	V2	3.86	4.03	4.10	4.24
	Avg.	3.87	4.01	3.98	4.17
	S.D	0.01	0.03	0.17	0.10

Fig. 5.17: Influence of density and air content on pulse velocity

5.2.4 Shrinkage

The shrinkage properties of the designed mixes were determined in accordance with ASTM C157-(1980). Due to the limited availability of moulds, the evaluation was restricted to two specimens per mix, and the results are summarized in Table 5.10. Fig. 5.18 illustrates the effect of W/C ratio on the extent of shrinkage. It can be observed that despite the higher W/C ratio for mixes 1 (A) and 1 (B), they did not experience the highest shrinkage, while Mix 5, which had a lower W/C ratio, yielded the highest shrinkage. Further examination of the results show that the effect of adding AEA to the mixture has significant effect on the amount of shrinkage. Fig. 5.18 shows that for a given cement content, an increase of W/C ratio from 0.65 to 0.83, i.e. from Mix 2 (B) to Mix 1 (A), the drying shrinkage increased by 270 percent. The addition of water reducing-admixture to Mix 3 (C) and air-entraining admixture to Mix 4 increased the shrinkage value by

45% and 80%, respectively, in comparison to Mix 2 (B). Furthermore, one can observe that the addition of both WRA and AEA, resulted in an abrupt increase in the shrinkage value and it appears that they have more significant effect than changing the water/cement ratio.

Table 5.10: Shrinkage of concrete after 28 days, %

Mix No.	Sample No.		Avg.	S.D
	1	2		
1 (A)	0.0585	0.0998	0.0792	0.0292
1 (B)	0.0519	0.0592	0.0555	0.0052
2 (B)	0.0262	0.0158	0.021	0.0074
3 (C)	0.0201	0.0218	0.0209	0.0012
4	0.0323	0.0701	0.0512	0.0267
5	0.1079	0.1107	0.1093	0.002

Fig. 5.18: Influence of W/C ratio and aggregate content on shrinkage

5.3 Destructive tests

Destructive tests, such as compressive strength tests and pull off tests were conducted to quantify the properties of the hardened concrete. Destructive tests were needed also to evaluate the physical properties of the concrete, particularly the absorption and porosity.

5.3.1 *Compressive strength*

5.3.1.1 *Cylinder compressive strength*

Three 150 x 300 mm standard cylinders were cast for each concrete mix, and were cured for 28 days according to ASTM C 39-1984. Prior to testing, the cylinders were capped with a sulfur compound and the test procedure was conducted according to ASTM C 39-1984. The 28 day compressive strength, including standard deviation for the three specimens of each mix, are given in Table 5.11. As expected, Figure 5.19 shows that mixes with lower W/C have higher compressive strength. Further, it would appear, based on the average compressive strength values, that the addition of air entraining agent resulted in a small reduction in the cylinder compressive strength while the addition of WRA caused a small increase in strength. From Figure 5.19, one can observe that mixes with higher air content have generally a lower compressive strength.

Table 5.11: Compressive strength of concrete cylinders, (MPa)

Mix No.	Sample No.			Avg.	S.D
	1	2	3		
1 (A)	17.60	18.80	20.50	18.90	1.46
1 (B)	15.36	13.64	14.05	14.35	0.90
2 (B)	27.40	26.40	28.10	27.40	0.75
3 (A)	26.74	27.08	26.47	26.70	0.31
3 (C)	33.00	28.30	29.40	30.20	2.46
4	21.00	22.40	19.60	21.00	1.40
5	23.50	23.40	23.10	23.30	0.21

Fig. 5.19: Influence of W/C ratio and air content on cylinder strength

5.3.1.2 Core compressive strength

Several cores normal to the direction of casting were extracted from the hardened concrete specimens in order to evaluate the effect of the form lining material on the properties of the hardened mix. The 28 days compressive strength, as well as the average and the standard deviation, for the specimens of each mix are given in Table 5.12. The results are found to be consistent with the maximum standard deviation of 3.61 MPa noted for Mix 4. To visualize the various effects, the average compressive strength are shown in Figure 5.20.

The results confirm that generally mixes with low W/C have higher strength values. The addition of water reducing admixture increased the compressive strength while adding air entraining agent decreased the strength. These observations are consistent with those made about the cylinder compressive strength. Finally, the consolidated concrete had on the average slightly higher compressive strength.

For the mixes with $W/C = 0.65$ W/C, one can observe that generally the lined form specimens have slightly higher compressive strength than the wood form specimens, provided the mixture was not consolidated. The addition of air entraining agent resulted in higher compressive strength for vibrated and unvibrated wood form specimens. Further, when both admixtures were added to the mixture, the vibrated lined specimens yielded the highest compressive strength. Once again the differences in the strength values are not large enough to arrive at definitive conclusions about the effect of form lining on core strength. Much more work is needed before any recommendation can be made with respect to the form lining effect.

Further examination of the results shows that the ratio of core strength to the standard cylinder strength of the same age is always more than one. The difference is attributed to the orientation of the cored specimens and the size of the cylinder. The cores avoid the areas of bleeding channels, a phenomenon known to affect the standard cylinder strength. In addition, during the preparation of the cylinder, bleeding water was observed at the surface of the specimens. Finally, the core were 100 × 200 mm cylinders while the test cylinders for compressive strength were 150 × 300 mm.

Fig. 5.20: Relationship between core strength and W/C ratio

Table 5.12: Compressive strength of concrete cores

Mix No.	Sample No.	Cores compressive strength, MPa			
		Unvibrated		Vibrated	
		Wood	Lined	Wood	Lined
1 (A)	1	20.67	20.39		
	2	26.19	26.05		
	3	24.00	25.84		
	Avg.	23.62	24.09		
	S.D	2.78	3.21		
1 (B)	1	23.79	15.01	23.93	27.11
	2	22.58	17.27	23.79	23.86
	3	23.29	16.64	20.95	23.36
	Avg.	23.22	16.31	22.89	24.78
	S.D	0.60	1.17	1.68	2.04
2 (B)	1	28.31	28.52	33.41	26.33
	2	28.46	30.01	29.45	31.71
	3	28.18	31.71	30.16	28.18
	Avg.	28.30	30.08	31.00	28.74
	S.D	0.14	1.60	2.11	2.73
3 (C)	1	31.57	33.84	31.71	31.08
	2	31.01	32.28	36.53	33.34
	3	31.50	31.50	32.42	31.57
	Avg.	31.36	32.54	33.56	32.00
	S.D	0.31	1.19	2.60	1.19
4	1	26.69	20.18	31.57	21.45
	2	24.56	24.78	31.43	28.10
	3	25.63	23.50	27.47	27.18
	Avg.	25.63	22.82	30.16	25.58
	S.D	1.06	2.38	2.33	3.61
5	1	25.41	29.10	24.00	29.17
	2	28.46	25.63	27.82	27.40
	3	25.41	23.57	27.82	28.03
	Avg.	26.43	26.10	26.55	28.20
	S.D	1.76	2.79	2.21	0.90

5.3.2 Pull off tests

The pull off test, an indication of concrete cover tensile strength, is carried out to evaluate the quality of the finished concrete surface. Pull off tests were performed on the wall shape forms of the present mixes in accordance with BS 1881 : part 207 : 1992. The average pull off strength and standard deviation corresponding to each mix are given in Table 5.13. The same results are graphically represented in Figure 5.21.

For mixes with $W/C = 0.83$, one can observe that specimens cast in wood form have slightly higher strength than those cast in lined form, provided the mixture was not vibrated. For vibrated mixes with $W/C = 0.83$, specimens cast in lined form produced somewhat higher values. When comparing the recorded results for mixes with 0.83 W/C to mixes with 0.65 W/C , the trend is reversed. The addition of water reducer admixture and air entraining agent to the mixture enhanced the strength, most notably for those specimen cast in the wood form.

The preceding observations are rather preliminary, and due to the limited number of test specimens and the limited statistical analysis, may not reflect the actual influence of the different parameters under consideration. Many detailed studied are needed to establish definitively their true effect.

Table 5.13: Pull off strength

Mix No.	Sample No.	Pull off strength, MPa			
		Unvibrated		Vibrated	
		Wood	Lined	Wood	Lined
1 (A)	1	2.95	3.32		
	2	2.81	2.77		
	3	3.41	2.49		
	Avg.	3.06	2.86		
	S.D	0.31	0.42		
1 (B)	1	3.00	2.21	1.66	2.67
	2	3.00	2.40	1.94	2.67
	3	2.72	2.07	3.09	2.54
	Avg.	2.91	2.23	2.23	2.63
	S.D	0.16	0.16	0.76	0.08
2 (B)	1	1.75	2.35	2.03	2.58
	2	1.98	2.77	1.89	3.60
	3	1.66	2.86	2.07	1.80
	Avg.	1.80	2.66	2.00	2.66
	S.D	0.17	0.27	0.10	0.90
3 (C)	1	3.46	2.67	2.86	3.32
	2	2.95	2.86	1.84	3.09
	3	1.89	2.91	3.23	2.54
	Avg.	2.77	2.81	2.64	2.98
	S.D	0.80	0.12	0.72	0.40
4	1	3.46	2.54	2.77	3.09
	2	4.52	2.58	3.55	2.58
	3	3.87	2.77	3.46	2.81
	Avg.	3.95	2.63	3.26	2.83
	S.D	0.54	0.12	0.43	0.25
5	1	3.14	2.67	3.83	2.95
	2	2.21	2.81	3.74	3.09
	3	2.49	2.44	3.23	2.21
	Avg.	2.61	2.64	3.60	2.75
	S.D	0.47	0.19	0.32	0.47

Fig. 5.21: Relationship between W/C ratio and pull off strength

5.3.3 Mass transport

It is recognized that the mass transport properties of concrete are a measure of its durability potential. This observation is based on the fact that the penetration of air/water or deleterious chemicals is controlled by the mass transport properties of cover concrete. In this study, the focus will be on assessing the properties of the cover, namely air tightness, initial surface absorption and sorptivity.

5.3.3.1 Surface air tightness

Surface air tests were conducted on the test specimens according to the SCHUPACK Tester Procedure (Appendix B). The surface air tightness was measured in two orthogonal directions, which will be referred to as the face and the side, respectively. The results of 18 tests, i.e. mean and standard deviation, for each mix are given in

Table 5.14 and illustrated graphically in Figure 5.22. The results in Figure 5.22 show a trend between air leakage and the form surface finish in practically all cases. We can see that in many cases the lowest air leakage is exhibited by the specimens which were cast in lined forms. On the other hand, no trend can be established for the effect of vibration on the air tightness, but in the cases of Mixes 1 (B), 3 (C) and 4, the vibrated concrete had practically the same air leakage, irrespective of the type of form. Similarly, the unvibrated concrete with the high W/C ratio of 0.83 had relatively higher air leakage than the unvibrated concrete with W/C ratio of 0.65.

The results in Figure 5.22 seem to indicate that the W/C ratio has some influence on air permeability; higher W/C ratio produces greater air leakage. This observation is consistent with observations by others (Neville, 1981; Dhir et al., 1987, 1989a; Figg, 1989; Long et al. 1995). The present test results also revealed that the side of the specimens had in general higher air leakage than the face, perhaps due to restrictions imposed by the corner effect. As for the effect of form finish and vibration, the specimens from the lined forms showed relatively better surface air tightness than those cast in wood forms.

Table 5.14: Surface air tightness

Mix No.	Face or side	Statistical analysis	Air tightness $\left(\frac{\text{kPa}}{\text{s}}\right)$			
			Unvibrated		Vibrated	
			Wood	Lined	Wood	Lined
1 (A)	F	Mean	1.23	1.25		
		S.D	0.22	0.24		
	S	Mean	1.16	1.15		
		S.D	0.27	0.18		
1 (B)	F	Mean	1.10	1.30	1.11	1.00
		S.D	0.20	0.17	0.33	0.26
	S	Mean	1.16	1.41	1.13	1.00
		S.D	0.26	0.00	0.27	0.22
2 (B)	F	Mean	1.02	0.71	1.16	0.92
		S.D	0.31	0.45	0.37	0.31
	S	Mean	1.31	0.96	1.25	1.04
		S.D	0.07	0.36	0.16	0.38
3 (C)	F	Mean	0.94	0.45	1.02	0.49
		S.D	0.24	0.29	0.30	0.36
	S	Mean	1.01	0.37	0.93	0.60
		S.D	0.22	0.29	0.22	0.39
4	F	Mean	0.58	0.54	0.75	0.49
		S.D	0.16	0.21	0.35	0.34
	S	Mean	0.84	0.51	0.88	0.79
		S.D	0.33	0.15	0.23	0.42
5	F	Mean	1.14	0.41	0.76	0.53
		S.D	0.34	0.22	0.17	0.24
	S	Mean	0.82	0.49	1.12	0.86
		S.D	0.23	0.11	0.30	0.41

Fig. 5.22: Relationship between face surface air tightness and W/C ratio

5.3.3.2 Initial Surface Absorption (ISA at 10 minute)

The procedure adopted to measure the initial surface absorption is given in Appendix B. For this study, however, a comparison between the properties of the cover and those of the bulk is also sought. The cored cylinders, 200 mm high by 100 mm in diameter, were sawed at mid-height to produce two samples. The original concrete surface of the first half was tested, together with the newly exposed concrete surface of the second half. The former specimen produces the properties of the cover, the latter represents the bulk of the concrete. Only two samples were tested for each mix due to the limited number of extracted cores. The average of the two specimens is given in Table 5.15 and shown in Figure 5.23. The results clearly show that regardless of the form type the ISA at 10 minute values of the concrete surface are always higher (on the average by 138 percent) than the corresponding ISA at 10 minute of concrete bulk.

It would appear that the cover ISA at 10 minute from the lined form is on the average 25 percent higher than the cover ISA at 10 minute from the wood form, while the bulk ISA at 10 minute from wood form is on the average 85 percent higher than those of the lined form. Further comparison shows that vibration and form finish have relatively more effect on the ISA at 10 minute of bulk concrete than that of the cover, with the exception of Mix 1 (B).

In the context of residential basement concrete walls, it would appear that if unvibrated concrete is used, then the unlined exposed wood form finish would produce better surface insofar as ISA at 10 minute is concerned. These results are attributed to the higher water concentration on the surface of the lined form. It should be noted that this conclusion does not coincide with the results recorded for the surface air tightness of the concrete.

Table 5.15: Initial surface absorption at 10 minute

Mix No.	Vib.	Form	ISA at 10 min ml / m ² s		Percent difference, %				
			Cover	Bulk	Cover/ Bulk	Cover	Bulk	Cover	Bulk
						Wood/ Lined	Wood/ Lined	Un-vib/ Vib.	Un-vib/ Vib.
1 (A)	N	wood	1.24	0.63	97	-5	3		
		lined	1.31	0.61	115				
1 (B)	N	wood	1.51	0.65	132	-28	-45	3	3
		lined	2.11	1.19	77			31	133
	Y	wood	1.46	0.63	132	-9	24		
		lined	1.61	0.51	216				
2 (B)	N	wood	0.7	0.76	-8	-38	36	-42	58
		lined	1.12	0.56	100			10	17
	Y	wood	1.2	0.48	150	18	0		
		lined	1.02	0.48	113				
3 (C)	N	wood	0.7	0.33	112	-38	22	-13	-20
		lined	1.13	0.27	319			-7	-29
	Y	wood	0.8	0.41	95	-34	8		
		lined	1.21	0.38	218				
4	N	wood	0.54	0.5	8	-57	4	-49	11
		lined	1.27	0.48	165			2	55
	Y	wood	1.06	0.45	136	-15	45		
		lined	1.24	0.31	300				
5	N	wood	0.83	0.41	102	-28	-7	0	0
		lined	1.15	0.44	161			-11	2
	Y	wood	0.83	0.41	102	-35	-5		
		lined	1.28	0.43	198

Fig. 5.23: Relationship between W/C ratio and ISA at 10 minute

5.3.3.3 Sorptivity

Sorptivity, similar to the initial surface absorption, is a property associated with capillary effects and is defined as the gradient of volume of water absorbed per unit area of section surface and the square root of the absorption time. The procedure followed to measure the sorptivity is given in Appendix B. Figure 5.24 and Figure 5.25 show that the gradient is linear between 1 hour and 24 hours.

The results for the ISA at 10 minute test were used and the average values are tabulated in Table 5.16. It should be noted that the recorded water sorptivity values given in Table 5.16 are within the range of the values reported by Hall (1989). The bulk sorptivity is found on the average 36 percent lower than the surface sorptivity for every

mix tested. The same trend is observed for the ISA at 10 minute as was noted for the sorptivity, with the exception of Mix 5 where the use of vibration resulted in a decrease in the sorptivity of the concrete cover

Hall (1989) has suggested that the sorptivity may be estimated directly from the ISA at 10 minute (ISA_{10}). Using the least square method, a linear relationship was derived for both the bulk and concrete cover and is given below

$$S_{cov} = 0.7281ISA_{10} - 0.3262 \quad (R^2 = 0.7009) \quad (5.1)$$

$$S_{bulk} = 1.091ISA_{10} - 0.1636 \quad (R^2 = 0.6849) \quad (5.2)$$

where S is in $mm/h^{0.5}$ and ISA_{10} in $ml/m^2.s$

The results for the tested mixes are illustrated in Figures 5.26 and 5.27. Figure 5.28 indicates a significant difference between the computed values based on Hall's equation and the present test data. The difference may be attributed to different composition, initial moisture condition, and curing of the present specimens from those used by Hall. Although these factors affect both ISA at 10 minute and sorptivity, the former is believed to be less susceptible since it represents a discrete value with a short absorption time period. Although ISA at 10 minute values can be used to quantitatively compare different concretes, the sorptivity is a better indicator to quantify the capillarity of the concrete cover.

Fig. 5.24: Volume of absorbed water per unit area vs. square root of time for sample cast in lined forms

Fig. 5.25: Volume of absorbed water per unit area vs. square root of time for sample cast in wood forms

Table 5.16: Sorptivity of concrete

Mix No.	Vib.	Form	Sorptivity, mm/h ^{1/2}		Percent difference, %				
					Cover/ Bulk	Cover	Bulk	Cover	Bulk
			Cover	Bulk		Wood/ Lined	Wood/ Lined	Un-vib./ Vib.	Un-vib./ Vib.
1 (A)	N	wood	0.73	0.61	20	-14	-9		
		lined	0.85	0.67	27				
1 (B)	N	wood	0.96	0.69	39	-32	-40	14	-8
		lined	1.42	1.15	23			63	69
	Y	wood	0.84	0.75	12	-3	10		
		lined	0.87	0.68	28				
2 (B)	N	wood	0.3	0.3	0	-40	-21	-3	43
		lined	0.5	0.38	32			6	15
	Y	wood	0.31	0.21	48	-34	-36		
		lined	0.47	0.33	42				
3 (C)	N	wood	0.22	0.13	69	-31	-32	-39	-67
		lined	0.32	0.19	68			-18	-30
	Y	wood	0.36	0.39	-8	-8	44		
		lined	0.39	0.27	44				
4	N	wood	0.25	0.31	-19	-11	15	-11	107
		lined	0.28	0.27	4			-22	35
	Y	wood	0.28	0.15	87	-22	-25		
		lined	0.36	0.2	80				
5	N	wood	0.41	0.21	95	-7	-34	37	-30
		lined	0.44	0.32	38			10	33
	Y	wood	0.3	0.3	0	-25	25		
		lined	0.4	0.24	67

Fig. 5.26: Relationship between sorptivity and ISA at 10 minute for concrete cover

Fig. 5.27: Relationship between sorptivity and ISA_{10} for concrete bulk

Fig. 5.28: Computed sorptivity vs. ISA at 10 minute for concrete cover

5.3.4 Capillary porosity

The capillary porosity of the four cores taken from the hardened concrete specimens was evaluated according to the procedure in Appendix (B). The results are given in Table 5.17. The results show that the measured porosity for $W/C = 0.83$ specimens to be in the range of 9 % to 12 %, and between 7 % to 10 % for specimens with a $W/C = 0.65$. These values are slightly lower than those reported by Hall (1989). He reported porosity values ranging from 13 % to 14 % for $W/C = 0.65$ and 0.85, respectively. In this study, the capillary porosity value for the unvibrated specimens cast

in wood forms was found to be lower than the values for the specimens cast in lined forms, while the reverse trend was observed for vibrated specimens cast in lined forms, with the exception of Mix 5.

Table 5.17: Porosity of concrete

Mix	Vib.	Form	Capillary Porosity, %	Percent difference, %	
				Wood/ Lined	Un-vib./ Vib.
1 (A)	N	wood	9.18	-5	
		lined	9.69		
1 (B)	N	wood	10.62	-10	-2
		lined	11.82		12
	Y	wood	10.89	3	
		lined	10.59		
2 (B)	N	wood	9.32	1	-1
		lined	9.27		-3
	Y	wood	9.41	-1	
		lined	9.53		
3 (C)	N	wood	7.5	-2	-15
		lined	7.65		0
	Y	wood	8.87	16	
		lined	7.67		
4	N	wood	8.14	-7	1
		lined	8.71		17
	Y	wood	8.02	8	
		lined	7.43		
5	N	wood	7.95	-8	5
		lined	8.64		-8
	Y	wood	7.57	-19	
		lined	9.37		

5.4 Correlation of mass transport and mechanical properties

5.4.1 Air tightness versus pull off strength

In Figure 5.29 the surface air leakage is plotted against the pull-off strength for the test specimens. It should be pointed out that both tests are used to assess the quality of the surface concrete, but the pull-off test is destructive while air leakage test is non-destructive. Overall, Figure 5.29 appears to show some relation between surface air leakage and pull off, i.e. the surface air leakage decreased with increased pull off strength when concrete was vibrated. The results of the specimens from the lined form do not show any trend. Lined forms and vibration appear to influence the air leakage rather than pull off strength.

Fig. 5.29: Relationship between face surface air tightness and pull off results.

5.4.2 Pull off strength versus core strength

To determine whether there is any relation between the pull off strength and the core strength, we plotted in Figure 5.30 the two strengths for the several mixes used in the current study. There does not appear to be any systematic relation between the core strength and the pull-off strength. This suggests that a high strength concrete does not necessarily imply a high strength and peel resistant surface.

Fig. 5.30: Relationship between core strength and pull off results

5.4.3 Rebound number versus pull off and compressive strength

Figures 5.31 and 5.32 compare the rebound number and the corresponding pull off and compressive strength, respectively. It can be observed in this Figures that generally the increased rebound number of the vibrated concrete specimens leads to a

corresponding increase in pull off and compressive strength. The latter statement needs to be fully confirmed by further testing and analysis.

Fig. 5.31: Relationship between rebound number and pull off strength

Fig. 5.32: Relationship between rebound number and compressive strength

5.4.4 ISA at 10 minute versus core strength and pull off strength

Figure 5.33, compares the ISA at 10 minute and the corresponding pull off strength of each of the test specimens. Overall it can be stated, based on the results in Figure 5.33, that higher pull off strength generally leads to low ISA at 10 minute value. Although the latter is not true in every case, it appears to be generally true. Figure 5.34 shows the variation of ISA at 10 minute values for the bulk concrete and core compressive strength, for the specimens from the same mixes. Once again from this figure it can be stated that generally ISA at 10 minute decreases with increase in the core strength.

Fig. 5.33: Relationship between surface ISA at 10 minute of concrete cover and pull off strength

Fig. 5.34: Relationship between ISA at 10 minute of bulk concrete and core strength

5.4.5 Sorptivity versus pull off and compressive strength

Figure 5.35 shows the relationship between sorptivity and pull off strength. From this figure it can be stated that for vibrated concrete some relationship exists between its sorptivity and pull-off strength. Lined forms and vibration appear to influence sorptivity more than the pull off strength. Figure 5.36 shows that in general the cover sorptivity decreases with increasing strength. of course, this trend is not true in every case.

Fig. 5.35: Relationship between cover sorptivity and pull off strength

Fig. 5.36: Relationship between cover sorptivity and compressive strength

5.4.6 Capillary porosity versus air tightness

Figure 5.37 compares the porosity and the corresponding surface air leakage of the test specimens. Overall it can be stated, based on the results in Figure 5.37, that higher

surface air leakage leads to higher porosity value. Although the latter is not true in every case, it appears to be generally true.

Fig. 5.37: Relationship between surface air tightness and capillary porosity

5.4.7 Capillary porosity versus sorptivity

It can be stated based on the results plotted in Figure 5.38 that cover sorptivity increases with increasing capillary porosity.

Fig. 5.38: Relationship between capillary porosity and cover sorptivity

It is recognized that the preceding conclusions are tentative and based on limited observations. However, they provide the basis for further investigation into the development of non-destructive test methods for evaluating the durability of concrete and its resistance to intrusion of chemicals and deleterious solutions.

6. RELATIONSHIP BETWEEN RHEOLOGY OF FRESH CONCRETE AND THE PROPERTIES OF HARDENED CONCRETE

6.1 Introduction

It is anticipated that the development of a quantitative method of measuring the workability of concrete by computing its rheological properties would also lead to the establishment of better control of concrete production and possibly in substantial savings. In this chapter, the rheological properties of fresh concrete, namely its plastic viscosity and yield stress, as presented in Chapter 4, are correlated to those physical and mechanical properties of hardened concrete that were given in Chapter 5. It should be pointed out that the term correlation in the present context is not intended to connote any statistical significance.

6.2 Correlation of mass transport and physical properties

6.2.1 Surface air tightness

Figures 6.1 and 6.2 show the variation of air permeability with plastic viscosity and yield, respectively. It would appear from Figure 6.1 that generally the air leakage for the concrete cover decreases first then increases with increased plastic viscosity. The range between 20 and 60 Pa.s produces the lowest value of air leakage. A similar observation can be made from Figure 6.2 for the yield, where an improved air leakage value occurs between 900 and 1100 Pa. Such trend follows the expectation that generally

concrete with low viscosity and yield results in porous concrete while that with high viscosity and yield will contain air cavities.

Fig. 6.1: Surface air tightness versus plastic viscosity

Fig. 6.2: Surface air tightness versus yield stress

6.2.2 Sorptivity

Plots of water sorptivity versus the plastic viscosity and yield values are shown in Figures 6.3 and 6.4, respectively. The results indicate some difference between mixes with 0.83 and 0.65 W/C. The rheological values that do not fit the trend correspond to mixes whose total aggregate content are different from the majority of the mixes. The rheological properties for the concrete mixes that do not contain admixture are re-plotted in Figures 6.5 and 6.6. In general, it is observed that sorptivity decreases as the plastic viscosity and yield stress increase. Close examination reveals that sorptivity increase slowly when plastic viscosity exceeds 60 Pa.s. Similar trends can be noted in Figure 6.4. Further testing is obviously needed to verify the current data. However, the results indicate that it is possible to have unvibrated concrete with relatively low sorptivity provided its plastic viscosity is maintained in the range of 20 to 60 Pa.s and its yield stress in the range of 900 to 1100 Pa. The proposition of controlling the quality of hardened concrete through rheological properties of fresh concrete has potential.

Fig. 6.3: Water sorptivity versus plastic viscosity

Fig. 6.4: Water sorptivity versus yield stress

Fig. 6.5: Water sorptivity for mixes (that do not contain admixtures) versus plastic viscosity

Fig. 6.6: Water sorptivity for mixes (that do not contain admixtures) versus yield stress

6.2.3 Shrinkage

The effects of W/C ratio on the amount of drying shrinkage is well known. The percentage of drying shrinkage versus plastic viscosity and yield value are plotted in Figure 6.7 and Figure 6.8, respectively. There is a distinct trend which show that the drying shrinkage decreases with increasing plastic viscosity and yield stress. The linear relationships shown in the figures can be expressed as.

$$\text{Shrinkage}(\%) = -0.001\eta + 0.0888 \quad (R^2 = 0.6) \quad (6.1)$$

$$\text{Shrinkage}(\%) = -0.00004\tau_y + 0.0944 \quad (R^2 = 0.3) \quad (6.2)$$

where η and τ_y are in Pa.s and Pa, respectively. It should be noted the above best fit equations do not apply to actual structures. They were derived here to test the sensitivity of shrinkage to the rheological properties.

Fig. 6.7: Shrinkage versus plastic viscosity

Fig. 6.8: Shrinkage versus yield stress

6.3 Mechanical properties

6.3.1 Core strength

As shown in Figures 6.9 and 6.10 the core compressive strength increases as the values for plastic viscosity and yield stress increase. Clearly some of the data does not exactly follow that trend, but closer examination of the two plots reveals that the relation between the plastic viscosity and the core compressive strength is similar to that between the yield value and the core strength. This further illustrates the relation between the rheological properties and the hardened concrete properties. Moreover, one can observe that for mixes whose plastic viscosity is greater than 60 Pa.s, which correspond to mixes whose yield stress is greater than 1100 Pa, the core strength of the concrete begins to decrease. This trend is similar to that noted for the transport properties.

Fig. 6.9: Core strength versus plastic viscosity

Fig. 6.10: Core strength versus yield stress

6.3.2 Pull off strength

The pull-off strength is an indication of the quality of the concrete surface finish. The plotted values of pull-off strength versus the plastic viscosity and the yield values are shown in Figure 6.11 and Figure 6.12, respectively. From the results it can be stated that on the average the pull off strength has the highest value when the plastic viscosity is between 20 and 60 Pa.s and the yield is between 900 and 1100 Pa. Although the pull-off strength of the concrete is more affected by factors such as curing condition, form type and level of vibration, nevertheless the effects of the rheological properties can also be noted.

Fig. 6.11: Pull off strength versus plastic viscosity

Fig. 6.12: Pull off strength versus yield stress

6.3.3 Pulse velocity

The measured pulse velocity across concrete is a function of its elastic properties and density. As illustrated in Figures 6.13 and 6.14, the rheological properties appear to affect the pulse velocity. One can observe that the value of the pulse velocity increases as both the values of yield stress and plastic viscosity increase.

Although it is not possible to derive a simple relationship between the rheological properties and the pulse velocity, the results demonstrate that the rheological properties may be used to control both the quality and the elastic properties of the hardened concrete.

Fig. 6.13: Pulse velocity versus plastic viscosity

Fig. 6.14: Pulse velocity versus yield stress

6.4 Closure

It is not the objective of this study to derive exact relationships between the rheological properties of fresh concrete and the mechanical and physical properties of the hardened paste. However, the present results show the inter-relationship between the two sets of properties. It can also be concluded that a range for plastic viscosity between 20 to 60 Pa.s and the yield stress between 900 to 1100 Pa can be used as a guide to control the quality of high W/C concrete mixes. Similar findings are expected to apply to other concrete mixes.

Clearly, the present study is a preliminary attempt at investigating the relationship between the traditional quality control and evaluation methods of concrete and the methods based on rheology of fresh concrete mixes. Further detailed investigation is needed to fully explore the underlying relations which could be used to control the quality of the finished concrete via some intrinsic properties of the fresh mix. Consequently, any statement made on the basis of the present test results may be used as a guide to establish the relevant test parameters for future tests concerning this topic.

7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The principal objective of this study was to experimentally evaluate the influence of mix proportions, formwork and consolidation on concrete, with particular emphasis on the concrete cover. Furthermore, it was the objective of the study to investigate and validate the relation between the mechanical and physical properties of hardened concrete and the rheological properties of fresh mix. To meet these objectives, an apparatus was adapted, constructed and calibrated to quantify the slump test data. To relate this data with the rheological properties, a theoretical model was modified and applied. The rheological properties of fresh concrete were then compared to the mechanical and physical properties of hardened concrete. The mass transport properties of covercrete; namely, the air tightness and absorption, were measured to evaluate the effect of mix proportions, vibration, and formwork finish on the finished concrete cover. An attempt was made to relate the rheological properties of the mix to some of the mechanical and mass transport properties of the cover and the bulk concrete.

7.2 Conclusions

Based on the results of the current study, the following conclusions are drawn:

1. The Slump Rate Machine (SLRM) is a convenient and reliable device for measuring the slump, slump rate and flow properties of concrete mixes in a consistent fashion.

2. The present test data suggest that the yield stress is proportional to the product of slump and density and inversely proportional to the square of the slump flow. The relationships are as follows:

$$\tau_y = \frac{\alpha \rho g (H - SL)}{\sqrt{3}}$$

$$\tau_y = \frac{4 V \rho g}{\pi S F^2 \sqrt{3}}$$

3. The plastic deformation is related to the plastic viscosity and the slump time, in addition to the density and the cone height. An expression was developed to explicitly relate slump rate to the above parameters in a mix as given below:

$$sL_{(t)} = H - \frac{1}{\frac{\alpha \rho g}{600 \eta} t + \frac{1}{H}} \quad 0 \leq t < t_{slump}$$

$$sL_{(t)} = SL \quad t \geq t_{slump}$$

4. The plastic viscosity and yield value increase with decreasing water/cement (W/C) ratio.
5. For the same W/C ratio, higher sand/total aggregate ratio appears to produce higher yield stress and viscosity.
6. For the same W/C ratio, the addition of admixtures, such as water reducing (WRA) and air entraining admixture (AEA) result in a reduction in plastic viscosity and yield stress.
7. It was observed that mixes with yield values less than 411 Pa tend to promote bleeding. To be in the range of flowing concrete, the plastic viscosity should be from

11 to 74 Pa.s which correspond to a range of yield values of 411 to 1570 Pa. Such mixes would neither cause bleeding nor would they produce dry mixes.

8. In the absence of SLRM equipment, based on the findings of the present study, the yield stress and plastic viscosity, respectively, can be obtained or controlled using design curves derived from the following relationships:

$$\tau_y = \frac{4 V \rho g}{\pi SF^2 \sqrt{3}}$$

$$\eta = \frac{\rho g H V}{150 \pi SL SF^2} t_{slump}$$

$$SF = \sqrt{\frac{4 V}{\pi \alpha (H - SL)}}$$

9. The surface air leakage was found to increase with increasing W/C ratio. The lowest surface air leakage was exhibited by the specimens of vibrated concrete cast in lined forms.
10. The present results suggest that the range of plastic viscosity between 20 and 60 Pa.s and similarly yield stress between 900 and 1100 Pa produce the lowest air leakage.
11. It was observed that an increase in plastic viscosity and yield value causes the ultrasonic pulse velocity of hardened specimens to increase. Furthermore, concrete specimens cast in lined forms and vibrated had the highest pulse velocity
12. The core strength increases as the yield and plastic viscosity increase, up to a plastic viscosity and yield stress of 60 Pa.s and 1100 Pa, respectively. Beyond the latter values the compressive strength begins to decrease.
13. Vibration of the mix increases its core strength.

14. The pull off strength has the highest value when the plastic viscosity is between 20 and 60 Pa.s and the yield value is between 900 and 1100 Pa.
15. Measured ISA at 10 minute and water sorptivity increase with increasing W/C ratio.
16. Generally vibration decreases both ISA at 10 minute and water sorptivity, regardless of the type of forming materials.
17. It was observed that the ISA at 10 minute test values from the lined form are on the average 25% higher than the cover ISA at 10 minute from the wood form.
18. Sorptivity was found to be a variable quantity, depending on the time of measurement from the start of the test. Consequently, by not specifying the time at which the value is measured, one obtains substantially different values for different time periods. This difference makes direct comparison of data difficult. Therefore, in this study sorptivity is redefined as the linear part of the cumulative absorbed volume of water per unit area versus a specific period of time. Here, water sorptivity is defined as the slope of the secant line between one hour and 24 hour measurements on the water absorption versus time curve.
19. A correlation between ISA at 10 minute (ISA_{10}) and water sorptivity (S) was derived that can be used to estimate the latter,

$$S = 0.7281 \times ISA_{10} - 0.3262$$
20. It was observed that the plastic viscosity and yield stress vary inversely with the water sorptivity, provided the plastic viscosity and yield stress are less than 60 Pa.s and 1100 Pa, respectively. The lowest water sorptivity was exhibited by the specimens cast in wood form, regardless of vibration effect.

21. The capillary porosity of concrete was found to be in the range of 7 to 12 %. Non-consolidated concrete cast in lined form had slightly higher values for porosity in comparison to those cast in wood forms and the reverse trend was observed for vibrated specimens cast in lined forms.
22. High percentage of shrinkage was obtained in specimens made with mixes which contained both WRA and AEA at the same time. These admixtures increased shrinkage abruptly and had a more significant effect than the W/C ratio.
23. The percentage of shrinkage was found to decrease with increasing yield and plastic viscosity; also it was found to be more sensitive to changes in the plastic viscosity than yield stress.
24. Visual inspection of the concrete surface revealed that concrete surface cast against plywood, profiled the grain pattern and had rough texture, but with small amount of air pockets, ranging from 2 to 25 mm in diameter. Lined form produced smooth surface, but with numerous surface air pockets with a maximum size of 2 mm in diameter. In general, the lined form was found to produce more sand streaks and slightly larger amount of air pocket with a maximum diameter of 20 mm, regardless of vibration effect. The preceding relations need to be confirmed by further testing.

7.3 Recommendations

In this study, the conclusions are drawn for a small sample of high W/C concrete mixes. However, the results strongly suggest that rheological properties can be quantified or controlled using the simple SLRM apparatus. This finding needs further evaluation with different W/C concrete mixtures.

The observed inter-relationship between rheological properties and mechanical and physical properties of concrete can serve as an inexpensive tool to control the quality of the concrete. Further testing is required to explore the application of the conclusion to other concrete mix designs.

The present study investigated in a preliminary fashion the effects of mix proportions, vibration and form type on the properties of covercrete. More testing is needed to further investigate these parameters, but one should also study the effect of curing conditions.

Before any field application of new methods of improving the concrete properties, large scale field trials need to be implemented to address practical concerns and limitations, including the effect of structural element type, location, size and equipment limitation.

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Appendix A

Measured water uptake of concrete specimens

Time,	Water uptake, gr							
Minute	Wood				Lined			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.35	2.68	0.93	2.25	1.03	3.43	0.79	1.75
2	1.88	3.75	1.42	2.56	1.51	4.34	1.21	2.37
5	2.86	5.21	1.72	3.88	2.63	5.89	1.89	3.67
10	3.61	7.03	2.30	4.63	3.10	7.35	2.65	4.97
15	4.47	8.17	2.89	5.72	3.61	8.67	3.18	5.94
30	5.84	10.61	3.73	7.33	4.97	11.56	4.28	7.75
60	7.47	13.35	4.37	8.70	5.67	13.15	5.62	9.87
120	9.67	16.98	5.09	9.61	6.59	14.45	7.34	12.65
180	11.11	19.14	6.60	12.50	8.92	18.68	8.50	14.80
240	12.50	21.04	7.33	14.72	10.67	21.23	9.46	16.51
300	13.70	22.48	8.41	16.04	12.02	23.29	10.27	17.86
360	14.60	23.85	8.76	17.39	13.18	25.02	11.13	19.01
600	18.29	28.08	9.52	18.82	14.35	26.43	13.61	23.38
1440	26.05	36.02	11.11	21.64	17.91	31.24	18.82	30.69
1800	29.03	38.82	16.07	29.09	27.18	41.18	20.80	33.34
2880	35.95	44.52	17.26	30.45	29.58	44.28	25.07	38.12
3240	38.18	46.04	25.02	40.35	45.12	59.05	26.39	40.17
5760	52.40	56.17	34.56	49.13	59.87	69.44	33.87	48.77
8640	60.85	61.30	45.70	51.68	66.99	72.34	40.23	54.09
14400	67.72	64.49	50.53	52.30	69.38	73.92	50.63	57.95
18720	68.99	66.09	53.60	52.55	70.53	74.91	53.50	59.32
23040	69.28	66.99	54.77	52.97	71.35	75.75	54.95	60.05
28800	69.70	68.00	55.60	53.14	71.60	76.06	56.65	61.03
31680	69.94	68.33	56.70	53.56	71.79	76.39	57.40	61.15
37440	70.36	68.79	56.57	53.46	72.01	76.60	58.38	61.72
43200	70.48	69.00	57.27	53.36	72.15	76.86	59.10	62.04
51840	70.73	69.00	57.85	52.94	72.58	77.16	59.59	62.05
59040	71.02	68.94	58.13	52.38	72.78	77.44	59.89	62.24

Table A.1: Water uptake of concrete specimens from Mix 1 (A)

Time,	Water uptake, gr							
Minute	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.38	2.79	1.12	3.12	1.32	2.94	1.36	2.92
2	1.71	3.81	1.39	3.81	1.80	3.82	1.45	3.66
5	2.47	5.70	2.09	4.97	2.38	5.36	2.16	5.13
10	3.34	7.44	2.75	6.72	3.19	7.23	2.67	6.55
15	3.96	8.93	3.07	7.49	3.85	8.41	2.98	7.41
30	5.32	12.29	4.30	9.51	5.10	11.02	4.11	9.31
60	7.16	15.10	5.02	10.88	6.94	14.16	5.03	10.55
120	9.49	19.14	5.66	11.95	9.51	18.42	5.70	11.70
180	11.36	21.89	7.20	14.52	11.82	21.23	8.23	14.89
240	12.91	24.19	8.51	16.74	13.26	23.39	9.87	16.62
300	13.97	26.13	9.40	18.32	14.78	25.08	11.22	18.20
360	15.13	27.54	10.11	19.32	16.24	26.75	12.21	19.60
600	19.41	33.34	10.98	20.57	21.07	32.22	16.83	24.73
1440	28.27	44.67	11.93	22.39	31.83	42.93	25.34	32.96
1800	31.45	48.06	18.35	30.74	35.79	45.89	27.86	35.29
2880	39.85	56.49	19.88	32.46	45.98	54.07	35.16	41.07
3240	42.79	59.57	24.51	37.28	49.22	56.59	37.05	42.82
5760	49.26	64.95	25.68	38.35	58.47	62.48	51.05	52.82
8640	67.17	72.61	33.84	46.22	76.09	70.38	60.62	59.03
14400	74.22	75.75	41.15	52.59	82.00	73.94	69.42	62.29
18720	75.71	77.14	51.97	58.08	82.96	75.55	71.41	64.19
23040	76.46	78.56	55.53	59.02	83.65	76.54	71.60	65.21
28800	76.69	79.08	57.83	59.66	83.75	77.13	72.03	66.77
31680	76.80	79.11	59.44	60.55	83.18	77.36	72.12	67.35
37440	76.94	79.38	59.72	60.78	83.14	77.17	72.44	67.93
43200	76.86	79.59	60.11	61.26	83.02	77.55	72.63	68.55
51840	76.69	79.83	60.36	61.34	82.97	77.64	72.62	68.88
59040	76.46	79.99	60.39	61.34	82.81	77.66	72.23	69.16

Table A.2: Water uptake of concrete specimens from Mix 1 (B) cast in wood form

Time, Minute	Water uptake, gr							
	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.76	3.58	2.80	3.26	0.61	3.54	0.84	2.57
2	2.32	5.06	3.58	4.51	0.91	4.46	1.08	3.52
5	3.31	7.22	5.26	6.99	1.66	6.29	1.76	5.26
10	4.13	10.07	7.07	9.79	2.33	8.19	2.47	6.95
15	5.13	11.58	8.23	11.77	2.79	9.36	2.98	8.12
30	7.08	15.64	11.24	16.04	3.97	11.77	4.04	10.33
45	8.35	18.54	15.37	21.94	5.41	14.98	5.56	12.73
60	9.39	20.23	21.25	28.50	7.47	18.57	7.61	16.53
120	13.37	26.34	25.61	32.97	8.97	20.74	9.28	18.51
180	15.80	30.71	29.14	36.69	10.18	22.63	10.67	20.57
240	18.20	34.33	32.36	39.62	11.33	24.44	11.75	22.29
300	20.42	37.21	35.30	42.48	12.66	25.87	12.82	23.69
360	22.11	39.68	45.87	51.03	14.94	30.50	16.67	28.37
600	26.59	45.96	70.41	69.95	22.55	39.84	24.62	37.11
1440	45.30	64.85	75.52	74.58	25.01	42.69	27.33	39.97
1732	51.05	69.22	82.75	79.31	41.85	58.96	34.80	46.42
4320	72.57	77.03	84.25	80.20	50.79	69.69	36.81	48.42
8640	80.59	79.47	86.96	84.26	64.80	73.07	50.42	59.33
14400	82.32	80.66	88.36	85.96	68.67	74.66	60.62	66.25
18720	83.24	81.39	90.07	87.42	70.15	75.49	68.71	69.81
24480	83.26	81.63	90.70	88.43	71.86	76.47	71.23	71.85
28800	83.33	81.67	91.04	88.48	72.42	76.63	71.84	73.18
31680	83.44	81.89	91.66	88.92	73.33	76.98	72.58	74.68
36000	83.05	81.99	92.17	89.21	74.00	77.17	72.61	74.87
37440	82.87	82.04	92.44	89.49	74.29	77.47	72.69	75.37
41760	82.73	81.97	92.66	89.71	74.41	77.50	72.76	75.54
50400	82.41	81.82	92.68	89.84			72.60	75.79
57600	82.27	81.14	93.20	89.92			73.14	75.93

Table A.3: Water uptake of concrete specimens from Mix 1 (B) cast in lined form

Time,	Water gain, gr							
Minute	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.98	1.24	0.89	1.54	1.29	2.74	1.03	2.66
2	2.60	1.45	1.19	2.24	1.30	3.67	1.36	3.34
5	3.76	2.02	1.59	3.02	1.59	4.94	1.86	4.29
10	4.97	2.59	2.15	4.02	2.07	6.02	2.40	5.24
15	5.61	3.01	2.45	4.92	2.38	6.55	2.74	5.98
30	7.23	3.88	3.16	6.36	3.20	8.14	3.84	7.27
60	8.55	4.66	3.70	7.31	3.82	9.49	4.46	8.20
120	9.87	5.11	4.33	8.40	4.05	10.36	4.81	9.09
180	12.78	6.78	5.19	10.61	5.50	12.92	6.41	10.49
240	14.78	8.07	5.89	12.23	6.39	14.34	7.46	11.76
300	16.35	8.79	6.47	13.54	6.88	15.47	8.53	12.68
360	17.87	9.70	6.95	14.64	7.49	16.41	9.12	13.43
600	18.70	10.26	7.38	15.55	8.09	17.18	9.51	14.49
1440	22.03	12.33	8.84	17.97	9.69	19.69	11.34	16.70
1800	28.08	16.27	11.46	23.01	13.36	25.07	15.42	21.50
2880	29.47	17.68	12.61	25.14	14.45	27.14	17.03	24.09
3240	33.25	20.90	14.06	27.95	17.29	29.87	19.43	27.11
5760	34.06	21.62	14.36	28.39	17.79	30.43	20.26	27.92
8640	36.28	24.14	15.29	30.92	19.79	32.69	22.19	30.64
14400	42.07	30.89	18.54	36.71	25.85	37.41	27.97	38.87
18720	43.30	32.74	19.02	37.98	27.45	38.23	29.23	40.57
23040	46.10	37.59	20.77	41.35	32.18	40.16	33.12	45.74
28800	46.94	40.82	22.07	43.69	35.23	40.89	36.04	48.98
31680	47.78	43.51	22.89	45.29	38.04	41.55	38.55	51.38
37440	48.25	46.77	23.92	47.16	41.06	42.09	41.10	53.70
43200	48.65	47.74	24.63	48.02	42.54	42.38	42.35	54.96
51840	48.86	48.66	25.21	48.72	43.38	42.33	43.25	55.83
59040	48.94	49.40	25.23	48.95	44.39	42.40	43.69	55.97

Table A.4: Water uptake of concrete specimens from Mix 2 (B) cast in wood form

Time,	Water uptake, gr							
Minute	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.01	2.15	1.1	2.46	1.27	1.82	0.76	2.68
2	1.4	2.9	1.46	3.32	1.46	2.52	1.19	3.22
5	2	3.97	2.16	4.31	1.79	3.08	1.63	4.29
10	2.48	5.01	2.76	5.56	2.36	4.22	2.18	5.39
15	2.95	5.79	3.18	6.51	2.76	5.04	2.56	6.09
30	4.06	7.41	4.09	8.42	3.44	6.33	3.41	7.58
45	4.64	8.74	4.7	9.83	4.05	7.44	4.07	8.71
60	5.24	9.79	5.39	10.96	5.9	7.98	4.43	9.59
120	5.7	12.55	6.94	14.07	6.93	10.08	6.18	12.37
180	6.78	14.26	8.16	15.98	7.64	11.19	7.26	14.17
240	7.92	15.51	9.07	17.33	8.36	12.3	7.94	15.52
300	8.69	16.55	10.12	18.45	9.19	13.21	8.57	16.5
360	9.59	17.43	10.52	19.5	9.89	14.07	9.39	17.6
600	12.1	19.87	12.58	22.19	10.95	16.3	11.44	17.95
1440	16.19	25.09	17.15	27.42	15.1	21.69	15.99	26.17
1732	17.36	26.38	18.72	28.8	15.93	23.99	17.95	27.74
4320	20.3	29.9	22.21	32.05	18.76	27.13	20.68	31.57
8640	21.17	30.59	23.04	32.4	19.68	28.03	21.49	32.46
14400	23.16	32.85	25.53	34.54	21.09	30.86	23.77	34.76
18720	29.18	38	33.35	39.55	27.12	38.55	30.73	43.87
24480	30.77	39.33	35.31	40.69	28.45	40.26	32.26	44.31
28800	34.79	42	40.6	43.81	32.74	44.59	37.28	44.85
31680	37.27	43.47	44.01	45.34	35.67	47.94	40.7	47.6
36000	39.55	44.73	46.82	46.34	37.77	50.68	43.39	49.43
37440	42.12	45.87	49.78	47.35	40.82	53.19	46.35	51.42
41760	43.02	46.47	50.81	47.83	41.96	54.47	47.83	52.29
50400	43.91	46.71	51.63	48.05	42.92	55.25	48.68	52.92
57600	44.56	47.17	51.86	48.15	43.41	55.79	49.41	54.02

Table A.5: Water uptake of concrete specimens from Mix 2 (B) cast in lined form

Time, Minute	Water uptake, gr							
	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	0.60	1.43	0.98	1.40	0.59	2.30	0.84	1.34
2	0.78	1.77	1.14	1.89	0.97	2.88	1.07	1.57
5	0.98	2.08	1.40	2.83	1.38	3.82	1.51	2.31
10	1.37	2.87	1.72	3.71	1.73	4.75	2.06	2.74
15	1.67	3.23	2.05	4.55	2.12	5.64	2.47	3.23
30	3.16	4.28	2.62	5.44	2.74	6.97	3.19	3.90
60	3.32	5.45	3.09	6.15	3.11	7.79	4.28	5.03
120	3.59	6.02	3.22	6.65	3.45	8.50	5.80	6.44
180	4.55	7.75	4.36	8.07	4.46	10.20	6.76	7.77
240	5.12	8.99	4.81	9.13	5.08	10.98	7.60	8.29
300	5.73	9.89	5.32	9.94	5.64	11.85	8.60	8.96
360	5.98	10.35	5.84	10.37	6.12	12.41	9.13	10.11
600	6.32	11.04	6.40	11.04	6.42	13.07	11.86	11.92
1440	7.11	12.44	7.26	12.67	7.21	13.90	16.07	16.03
1800	10.20	17.22	10.66	16.76	10.14	17.61	18.10	17.34
2880	11.14	18.37	11.39	17.34	10.99	18.37	21.56	20.10
3240	13.89	21.44	13.56	19.73	13.45	20.93	22.92	21.24
5760	14.26	21.60	14.12	20.38	13.71	21.38	28.52	23.29
8640	16.54	23.79	17.79	23.14	15.66	23.27	32.88	27.74
14400	24.36	31.01	20.19	24.90	21.72	30.04	40.27	30.49
18720	25.41	32.21	24.82	27.43	22.61	30.83	43.98	31.72
23040	28.19	34.14	27.31	28.34	25.00	33.14	46.78	32.45
28800	29.97	35.34	29.10	28.83	26.48	34.48	49.68	32.87
31680	32.43	36.76	31.48	29.33	28.08	35.62	50.66	32.94
37440	33.27	37.13	32.50	29.36	28.85	36.21	52.39	33.04
43200	34.10	37.63	34.27	29.65	29.51	36.69	53.49	32.86
51840	35.32	38.08	35.96	29.96	30.66	37.49	54.39	32.73
59040	36.57	38.83	37.83	30.01	31.57	38.06	54.65	32.66

Table A.6: Water uptake of concrete specimens from Mix 3 (C) cast in wood form

Time, Minute	Water uptake, gr							
	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	0.47	1.84	0.48	2.65	0.55	2.92	0.76	2.68
2	0.49	2.35	0.67	3.57	0.7	3.69	1.19	3.22
5	0.81	3.16	1.11	4.8	0.94	4.89	1.63	4.29
10	1.07	3.98	1.45	6.64	1.43	5.98	2.18	5.39
15	1.23	4.56	1.69	7.49	1.62	6.66	2.56	6.09
30	1.76	5.6	2.24	9.09	2.15	8.15	3.41	7.58
45	2.07	6.09	2.6	10.15	2.5	9.04	4.07	8.71
60	2.32	6.69	2.91	11.02	2.86	9.91	4.43	9.59
120	3.17	7.67	4.3	13.29	3.52	11.34	6.18	12.37
180	3.7	8.83	5.1	14.8	4.12	12.69	7.26	14.17
240	4.18	9.2	5.68	16.02	4.26	13.54	7.94	15.52
300	4.6	9.65	6.12	16.87	4.87	13.89	8.57	16.5
360	4.75	10.16	6.34	17.64	5.01	14.62	9.39	17.6
600	5.53	11.02	7.03	19.34	5.34	14.79	11.44	17.95
1440	7.9	13.77	9.96	24.53	8.24	19.17	15.99	26.17
1732	8.5	14.47	10.99	25.74	9.14	20.34	17.95	27.74
4320	10.58	16.63	13.3	28.95	11.11	22.11	20.68	31.57
8640	10.66	17.17	13.82	29.55	11.47	22.69	21.49	32.46
14400	12.16	18.35	15.86	31.67	12.85	24.23	23.77	34.76
18720	16.37	21.74	23.15	38.4	18.27	30.21	30.73	43.87
24480	16.82	21.86	23.9	39.28	19.08	31.01	32.26	44.31
28800	18.43	23.16	26.82	41.05	21.15	33.16	37.28	44.85
31680	19.23	23.55	28.6	42.29	22.47	34.5	40.7	47.6
36000	20.23	24.16	30.67	43.76	24	35.85	43.39	49.43
37440	20.8	24.39	31.66	44.3	24.98	36.61	46.35	51.42
41760	21.23	24.71	32.57	44.94	25.57	37.05	47.83	52.29
50400	21.89	24.98	33.82	45.51	26.81	38.04	48.68	52.92
57600	22.76	25.46	35.1	46.21	28.22	38.91	49.41	54.02

Table A.7: Water uptake of concrete specimens from Mix 3 (C) cast in lined form

Time,	Water uptake, gr							
Minute	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.07	1.29	0.91	0.42	1.38	2.37	0.85	3.06
2	1.37	1.79	1.18	0.64	1.57	2.90	1.11	3.44
5	1.84	2.77	1.86	1.11	2.20	4.14	1.78	3.87
10	2.29	3.62	2.36	1.47	2.28	5.10	1.95	4.90
15	2.65	4.45	2.86	1.80	2.37	5.93	2.23	5.69
30	3.28	5.46	3.73	2.47	3.09	7.26	3.11	7.05
60	4.26	6.65	4.78	3.39	3.77	8.48	3.39	7.79
120	5.39	8.12	6.13	4.32	4.10	8.63	3.66	8.53
180	6.38	9.10	7.27	5.09	4.94	10.57	5.07	10.53
240	6.92	9.83	7.94	5.65	5.50	11.63	5.65	11.98
300	7.46	10.46	8.65	5.91	5.95	12.68	6.13	13.16
360	8.22	10.89	9.35	6.49	6.80	13.32	6.87	14.20
600	9.88	12.78	11.53	8.09	7.13	14.21	7.25	14.85
1440	12.95	15.63	15.39	9.72	7.72	16.00	8.63	17.11
1800	14.02	16.64	16.94	10.68	10.58	21.11	12.10	22.08
2880	16.56	18.82	20.02	12.13	11.58	22.01	13.11	23.57
3240	17.74	19.61	21.38	13.19	13.33	24.93	17.94	29.44
5760	19.72	22.30	27.33	16.02	13.58	25.59	22.67	34.17
8640	25.72	24.15	31.90	17.61	16.51	29.49	27.19	37.98
14400	31.51	27.28	39.75	19.97	18.44	31.82	29.37	39.68
18720	35.00	28.33	43.76	20.78	21.88	35.51	31.29	41.11
23040	37.89	29.15	46.75	21.56	23.42	36.79	32.48	41.93
28800	40.70	30.03	48.70	22.01	24.79	37.88	32.98	42.22
31680	41.73	30.26	49.20	22.15	26.49	38.92	33.84	42.88
37440	43.58	30.87	50.02	22.25	27.16	39.16	34.18	42.97
43200	44.35	31.41	50.33	22.62	28.45	39.90	34.74	43.17
51840	44.88	31.57	50.58	22.61	29.64	40.24	35.50	43.64
59040	45.17	31.72	50.78	22.84	30.95	40.50	35.97	43.36

Table A.8: Water uptake of concrete specimens from Mix 4 cast in wood form

Time, Minute	Water uptake, gr							
	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.04	2.88	1.30	2.34	0.78	2.42	0.39	1.75
2	1.45	3.58	1.61	2.73	1.25	3.40	0.55	2.64
5	1.75	4.81	1.87	4.21	1.32	4.92	0.92	3.73
10	2.30	6.20	2.23	5.71	1.63	6.36	1.28	5.32
15	2.76	7.06	2.60	7.16	1.95	7.30	1.45	6.27
30	3.61	8.83	3.27	8.08	2.62	8.92	1.98	8.22
45	4.74	11.10	3.49	8.72	3.14	9.86	2.43	9.65
60	6.10	13.70	3.62	10.65	3.49	10.54	2.80	10.14
120	7.11	15.40	4.09	11.59	4.69	12.59	3.74	12.40
180	8.18	17.08	5.36	12.06	5.35	13.81	4.12	13.68
240	8.62	17.96	5.83	12.50	5.62	14.95	4.66	14.58
300	9.30	18.90	7.14	13.31	5.97	15.85	5.02	15.28
360	11.64	22.19	7.31	13.72	6.46	16.25	5.39	15.96
600	15.59	26.89	8.19	14.91	7.24	17.81	5.87	16.97
1440	16.81	28.28	11.69	19.36	10.42	22.42	8.75	21.55
1732	20.12	31.14	12.36	20.23	11.16	23.37	9.36	22.73
4320	21.41	32.43	14.29	22.40	14.79	28.23	11.23	25.51
8640	23.71	33.83	14.90	23.14	18.33	32.54	11.60	26.30
14400	31.57	39.72	18.17	26.14	22.06	36.68	12.71	27.66
18720	39.18	44.05	20.59	28.03	23.36	38.49	17.19	33.92
24480	43.69	46.20	24.91	30.81	24.72	40.43	17.74	34.51
28800	47.66	48.03	27.42	32.66	25.51	41.33	19.38	36.23
31680	50.92	49.26	29.42	33.74	26.15	42.05	20.46	37.34
36000	51.85	49.64	31.99	34.99	27.10	42.93	21.31	37.99
37440	52.67	49.91	32.94	35.44	27.03	42.97	21.70	38.49
41760	53.36	50.22	34.92	36.43	27.83	43.67	22.18	38.75
50400	54.12	50.57	36.58	36.98	28.57	44.13	22.69	39.19
57600	54.55	50.32	38.30	37.57	28.93	44.00	23.45	39.74

Table A.9: Water uptake of concrete specimens from Mix 4 cast in lined form

Time, Minute	Water uptake, gr							
	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	1.21	1.73	0.79	1.30	0.64	1.39	0.90	2.20
2	1.52	2.25	0.98	1.72	0.95	1.93	1.13	2.41
5	1.70	3.31	1.50	2.56	1.36	3.03	1.64	2.93
10	2.12	4.33	1.76	3.44	1.82	4.01	1.96	3.81
15	2.39	4.96	1.96	4.22	2.14	4.79	2.11	4.19
30	2.98	6.69	2.35	6.32	2.85	5.98	2.76	5.64
60	3.82	7.72	3.17	8.14	3.59	7.54	3.13	6.34
120	3.88	8.78	3.90	10.41	4.78	9.18	3.62	7.04
180	5.02	10.32	4.70	12.00	5.75	10.29	4.32	8.91
240	5.53	11.53	5.26	13.15	6.25	11.07	5.14	9.85
300	6.21	12.57	5.40	14.00	6.79	11.98	5.56	10.68
360	6.59	13.49	5.66	14.67	7.32	12.30	6.04	11.71
600	7.07	14.31	7.33	17.16	9.79	14.34	6.28	12.05
1440	8.17	16.05	9.53	21.06	12.81	17.01	7.40	13.68
1800	11.44	20.25	10.28	21.93	14.38	18.21	10.82	17.59
2880	12.35	21.25	12.27	24.20	16.70	19.97	11.68	18.93
3240	14.40	23.63	13.15	25.47	18.10	20.80	16.11	23.91
5760	15.12	24.35	14.03	26.31	22.71	23.51	20.32	27.46
8640	18.16	27.35	18.06	30.38	26.58	25.03	24.22	30.25
14400	20.38	28.91	21.18	32.66	32.79	27.83	25.84	30.99
18720	24.18	31.15	22.99	33.80	35.96	28.80	27.39	31.56
23040	26.13	31.78	24.55	35.31	38.58	29.75	28.55	32.13
28800	27.73	32.08	25.74	35.93	41.55	30.51	29.01	32.17
31680	29.60	32.19	26.25	36.09	42.42	30.60	29.86	32.16
37440	30.36	32.26	26.54	36.14	44.09	31.35	30.26	32.54
43200	31.76	32.08	27.10	36.40	45.41	31.29	30.58	32.30
51840	33.22	31.94	27.75	36.55	45.80	31.24	31.26	32.08
59040	34.56	31.61	28.72	36.58	46.38	31.29	31.51	31.95

Table A.10: Water uptake of concrete specimens from Mix 5 cast in wood form

Time, Minute	Water uptake, gr							
	Un-vibrated				Vibrated			
	L-shape		Wall		L-shape		Wall	
	Bulk	Cover	Bulk	Cover	Bulk	Cover	Bulk	Cover
1	0.96	2.51	0.91	2.27	0.96	2.61	0.91	2.54
2	1.20	3.14	1.01	2.79	1.11	3.30	1.33	3.42
5	1.39	4.13	1.38	4.32	1.56	4.64	1.69	4.74
10	1.78	5.18	2.36	5.61	1.92	5.79	2.14	6.27
15	2.06	6.16	3.32	6.41	2.31	6.63	2.41	7.58
30	2.62	8.06	3.60	8.68	2.99	8.34	3.25	9.23
45	3.46	9.18	3.92	9.95	3.30	9.10	4.20	11.50
60	4.57	9.88	4.66	11.31	3.73	9.94	5.38	14.40
120	5.36	12.09	6.31	13.65	4.72	12.11	6.40	15.94
180	5.88	13.53	7.54	14.98	5.47	13.59	7.18	17.22
240	6.37	14.96	8.13	16.10	6.06	14.55	7.61	18.14
300	6.80	15.80	8.59	17.15	6.53	15.23	8.24	18.97
360	8.76	16.56	9.04	18.09	6.89	16.18	10.51	21.89
600	11.45	18.14	10.16	20.64	8.08	18.01	13.88	26.89
1440	12.55	23.20	15.05	25.77	11.36	22.69	15.74	28.39
1732	14.77	24.33	16.18	27.09	12.13	23.43	18.24	31.79
4320	15.79	27.05	22.18	33.73	14.48	26.09	19.96	33.16
8640	17.90	27.77	28.26	39.03	14.91	26.65	23.97	35.51
14400	22.70	31.56	34.29	44.11	18.56	30.06	28.45	42.03
18720	27.13	34.11	36.78	46.21	20.83	32.30	34.76	47.50
24480	30.00	37.96	39.50	48.00	25.07	35.44	38.12	50.37
28800	32.47	40.00	40.87	49.22	27.36	37.20	40.78	52.55
31680	34.77	41.62	41.45	49.67	28.99	38.35	44.00	54.14
36000	35.79	43.20	41.68	50.19	31.04	39.41	45.12	54.30
37440	36.45	43.76	42.54	50.21	31.80	39.84	47.33	54.64
41760	37.70	44.64	43.15	50.51	33.33	40.56	48.56	54.48
50400	38.95	45.19	43.66	50.34	34.88	41.51	50.13	54.42
57600	40.01	45.57	43.47	49.89	36.44	41.92	51.17	54.30

Table A.11: Water uptake of concrete specimens from Mix 5 cast in lined form

Appendix B

Surface absorption and air permeability test methods

A) Surface water Absorption

A cylindrical core, with height/diameter ratio of 2 was cored from each specimen. The cylinder was allowed to stand for period of time at room temperature of 20° C and relative humidity of 50 % until the weight variations was less than 0.1 % over 24 hrs. The cylinders were subsequently cut at mid-height into two discs of equal thickness. One disc was tested by exposing its outer circular surface to water/air while the other half was tested by exposing its cut surface to the same elements. The former half is referred to as cover while the latter half is called “bulk” in the present study. Prior to exposure to the elements, each disc perimeter was sealed using a single coat high gloss urethane (AM13166 resin and cure). The disc was in contact with water at one end and open to the air at the other. The sample rested on a wire mesh in a water container to allow free access of water to inflow surface, the water level was kept 10 mm above the base of the specimen (Hall, 1989).

After coming into contact with concrete, due to capillary action the water will have penetrated to some depth $i_{(t)}$ where t is the contact time, and will have gained weight $m_{(t)}$. Figure B.1 shows a typical relationship of water gain versus time. This data can be used to approximately estimate the depth of penetration $i_{(t)}$. The initial surface absorption (denoted by ISAT) is defined as the rate of water gain per unit cross sectional area.

Another property is the so-called sorptivity defined as the gradient of the straight part of absorbed volume of water per unit area versus square root of time curve as shown in a typical relationship in Figure B.2 for one of the mixes tested here. Finally, we estimated the capillary porosity by determining the water gain in the fully saturated specimens

Fig. B.1: Typical relationship of water gain versus time

Fig. B.2: Typical relationship of absorbed volume of water per unit area versus SQRT(Time) curve

B) Air Permeability

It was stated in the literature review in this thesis that the permeability of concrete is a key property which is believed to influence the durability of concrete structures. Currently there is no standardized test for measuring the permeability of concrete. Many techniques have been developed to measure the properties related to permeability. Some of the tests currently in use provide a qualitative assessment between different mix designs. One of the simplest technique is the SCHUPACK Concrete “Tightness” tester as shown in Figure B.3, developed to fill a need in the concrete industry to have an easy non-destructive method of determining the “Tightness” of a constructed surface. In fact concrete cubes or cylinders do not reflect the interplay of the different parameters of structural elements. The technique of providing representative cores drilled from concrete structures will alter the moisture content of the concrete. Therefore, by using SCHUPACK Concrete “Tightness” tester, one overcomes the above problem. The test is also inexpensive, simple, quick and the same specimen can be tested repeatedly without delay.

SCHUPACK Concrete “Tightness” Tester Procedure:

The SCHUPACK test is described in detail by SCONTEC. For the sake of completeness a brief description is given below:

- Brush the selected spot, removing all loose material.
- Place the vacuum head of diameter 100 mm, over the test area and evacuate.
- When the system reaches maximum vacuum, above (85 kPa), record the starting vacuum, turn the three way valve to test and start timing.

- Record the level of vacuum after 1 minute.
- The difference between the level of vacuum after 1 minute and starting vacuum will give the rate of vacuum decay. This rate gives a relative reading of the porosity of the surface condition. The tester should be calibrated prior to initial use each day or when questionable results are obtained. To check the system, place the vacuum head on a smooth non-permeable surface, such as steel or formica, evacuate the system to maximum vacuum. If 88 kPa or over is reached and holds, the system is in good order. If the leakage over 2 minutes drops the vacuum below 78 kPa, the gasket should be replaced, If this does not solve the problem, then the tester could have a leak.

Fig. B.3: Air tightness tester

IMAGE EVALUATION TEST TARGET (QA-3)

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