EVALUATION OF PUMPABILITY OF CONCRETE

K.D.N. Perera

178002L

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Department of Civil Engineering

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Kurugamage Dilini Nuwanthika Perera

178002L

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where acknowledgement is made in the text.

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The above candidate has carried out research for the Masters under my supervision.

Name of the supervisor: Prof. S. M. A. Nanayakkara

Signature of the Supervisor: Date:

DEDICATION

To my beloved parents, my loving husband and family for their overwhelming support and courage extended to me throughout this research project

And

To Prof. S. M. A. Nanayakkara, Dr. (Mrs.) M. T. P. Hettiarchchi and all of my dear teachers, who are the reasons behind my every successful step

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Evaluation of Pumpability of Concrete

ABSTRACT

Current guidelines and practices at construction sites on concrete pumping has not been based on theoretical understanding of pipe flow of fresh concrete. In fact, only the slump value is monitored at construction sites, even-though any single point test is insufficient to represent flow curve properties of fresh concrete.

Based on flow curves of concrete and basic rheological properties, a theoretical model for horizontal straight flow has been developed and validated in previous studies. Yet, properties of concrete flow at horizontal and vertical bends, tapered sections and vertical lengths had to be investigated. In this research study, experimental investigations were carried out at two high rise building construction sites which included monitoring rheology of fresh concrete with ICAR plus concrete rheometer and pressure at some points of the concrete pumping pipe line with a pressure transducer and several strain gauges. In the horizontal straight section, theoretical pressure drop based on sheared plus plug flow condition could reasonably estimate the actual pressure drop with a 20% margin. Pressure drop at a horizontal bend was in between 0.5 to 1.7 bar while in a vertical bend it was around 6 bar. Pressure drop in the vertical straight length was equal to the pressure needed to overcome the self-weight only. Hence, concrete pumping pressure could be estimated within 20% margin.

Moreover, understanding on the influence of mix design parameters on concrete rheology is much useful for deciding the mix proportions of concrete at the mix design stage. A series of laboratory experiments were conducted at paste and mortar phases of concrete. Correct admixture concentration, increase of w/c ratio, decrease of fine aggregate volume concentration and round shape fine aggregates over angular shape found to be improving the rheological properties and hence the pumpability of concrete.

Key words: fresh concrete rheology, concrete pumping, concrete pipe flow

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACI	-	*American Concrete Institute*
JSCE	-	*Japan Society of Civil Engineers*
rpm	-	*revolutions per minute*
SYS	-	*Static Yield Stress*
DYS	-	*Dynamic Yield Stress*
PV	-	*Plastic Viscosity*
CA	-	*Coarse Aggregate*
FA	-	*Fine Aggregate*
w/c	-	*Water to Cement ratio by weight*
CCC	-	*Colombo City Centre*
OPC	-	*Ordinary Portland Cement*
PCE	-	*Poly Carboxylic Ether*
PLC	-	*Portland Limestone Cement*
MS	-	*Manufactures Sand*

CHAPTER 1: INTRODUCTION

1.1 Background

High rise buildings and apartment towers in highly congested urban areas have become the new trend in Sri Lanka. During the past decade, the construction industry kept recording more and more high-rise buildings such as World Trade Centre (152 m), Lotus Tower (290 m), Colombo City Centre (183 m) and so on. Almost all these sky scrapers are designed to be constructed with reinforced concrete. When it happens to transport fresh concrete to such excessive heights, pumping concrete is essential. Often, problems arise at the construction site regarding the pumpability of concrete in such situations.

The main issues with pumping concrete are designing the mix proportions in order to get better consistency and cohesiveness and prediction of required pressure so that the pump capacity can be decided. Even though, pumpability of concrete has been investigated in large number of research studies { (Choi, Roussel, Kim, & Kim, 2013b) and (Feys, Khayat, Perez-Schell, & Khatib, 2015)}, these studies have not been able to address the issues in practical concrete pumping procedures and evaluation of pumpability concrete.

Furthermore, sufficient amount of field investigations had not been carried out to match the laboratory level researched knowledge with actual concrete pumping operations. For instance, it has been investigated on flow characteristics of fresh concrete pipe flow in a horizontal straight pipe section { (Kaplan, Lerrard, & Sedran, 2005); (Choi, Kim, & Kwon, 2013a) & (Feys, Khayat, & Khatib, 2016)}. In fact, pressure versus flow rate relationships have been established in terms of the dimensions of the pipe and the rheological properties of concrete. Yet, the rheological properties of concrete are not evaluated or considered at the design stage of mix proportions or at the site when concrete pumping takes place. Hence, a huge knowledge gap exists between the current understanding and the current practices of concrete pumping.

On the other hand, the scope of researched knowledge has to be extended. In fact, fresh concrete pipe flow has to be investigated further to establish flow characteristics with respect to horizontal and vertical bends of different radii, vertical straight sections and tapered sections. Unless the researched knowledge is extended for the above cases, an actual concrete pumping operation cannot be theoretically analysed. Therefore, it is essential to extend the scope of current research investigations to cover the scenarios exist in an actual concrete pumping operation.

1.1.1 Current practices in Sri Lanka

At the most of high rise building constructions in Sri Lanka, placing concrete is done by pumping. Although, transporting concrete to higher floors is still carried out by sending buckets of concrete from a crane, only small range of concrete operations can be survived with such method. Concrete pumping has become an essential task in medium and large scale projects at which hundreds of cubic meters of concrete being placed. Hence, to ensure a smooth pumping operation at the site, determination of pumpability of fresh concrete is one of the highest priorities at the concrete mix-design stage.

The general practice is ordering concrete from a batching plant and get it transported to the site by trucks. The concrete operations may even last for 10-12 hours depending on concrete volume that is to be pumped, dimensions of the pipeline circuit, efficiency of the pumps and the crew, efficiency of transportation from batching plant to the site and on various other factors. Commonly, pumpable concrete is designed to stay in fresh state for about 3 to 4 hours. Therefore, continuous communication between site and batching plant is very important. Construction site informs time to time how much concrete they should be supplied by next hour.

Most often, especially when the concrete pumping operation lasts for hours, placing concrete at night time is practised. There are number of favourable factors for choosing night time over day time for concreting work. Firstly, at night time temperature rise in fresh concrete is minimal compared to that in the day time. Excessive temperature rise in concrete, which is a quite common issue with concreting in a tropical country like Sri Lanka, causes several problems such as thermal cracks and delayed ettringite formation (Nanayakkara, 2013). Therefore, night time concreting is advantageous. In addition, compared to day time, roads are free of traffic so that the delays in transporting can be avoided when night time is chosen. Furthermore, at the construction site, it is quite busy in the day time with all the other types of operations, whereas, at night time most of the other teams are not working and the concreting crew can work at the site more efficiently.

To ensure pumpability of concrete, it is vital to keep monitoring the fresh concrete properties of the concretes. As a tradition, even for high-slump or self-compacting concretes, only the slump or slump flow value is being specified and monitored. In this case, it should be highlighted that, to describe concrete pumpability, the flow-ability of concrete should be examined and the flow characteristics of fresh concrete material cannot be explained with a single point test (Tattersall, 1975). At least a two point test is required.

However, still only the single point tests are used to specify and monitor fresh concrete properties in current practice. Hence, in the Sri Lankan construction industry, selection of a pumpable concrete for a certain application is a trial and error process.

1.1.2 Guidelines

Several professional institutions have proposed guidelines addressing concrete pumping practices including ACI Guidelines on concrete pumpability (Bognacki, et al., 1996) and JSCE Guidelines for Concrete (Tamon & Hiroshi, 2010). These two guidelines have presented methods to predict pressure loss in concrete pumping pipe line based on the slump value of concrete. Furthermore, necessary recommendations such as facilitating the lubrication layer in pipe line, maintaining the continuity of flow at concrete pumping, cleaning of pipe circuit, preplanning for pumpability and safety have also been stated.

1.1.2.1 *ACI Guidelines*

ACI Guidelines (ACI 304.2R) on concrete pumpability recommend to choose mix proportions based on the mix designs used in successful concrete pumping operations (Akers, et al., 1996). Guidelines have not established a specific procedure for mix design to address fresh concrete properties other than slump value to meet pumpability requirements.

However, it has been proposed a set of graphs ACI 304.2R (see Figure 1-1) to select the suitable slump value for the trial mix, with respect to flow-rate, pipe diameter, pipe line length and pressure head. In addition to those parameters, allowances for vertical run and bends have been recommended. In addition, limiting values for fineness moduli, coarse aggregate content and the gradation of aggregates have been specified.

Once the mix proportion is decided to obtain a suitable slump value, a full scale trial has to be carried out at the site before actual pumping is done. Since, the mix design can be finalized only after this trial pumping, ACI guidelines on concrete pumpability have not eliminated the need of trial testing for concrete pumpability.

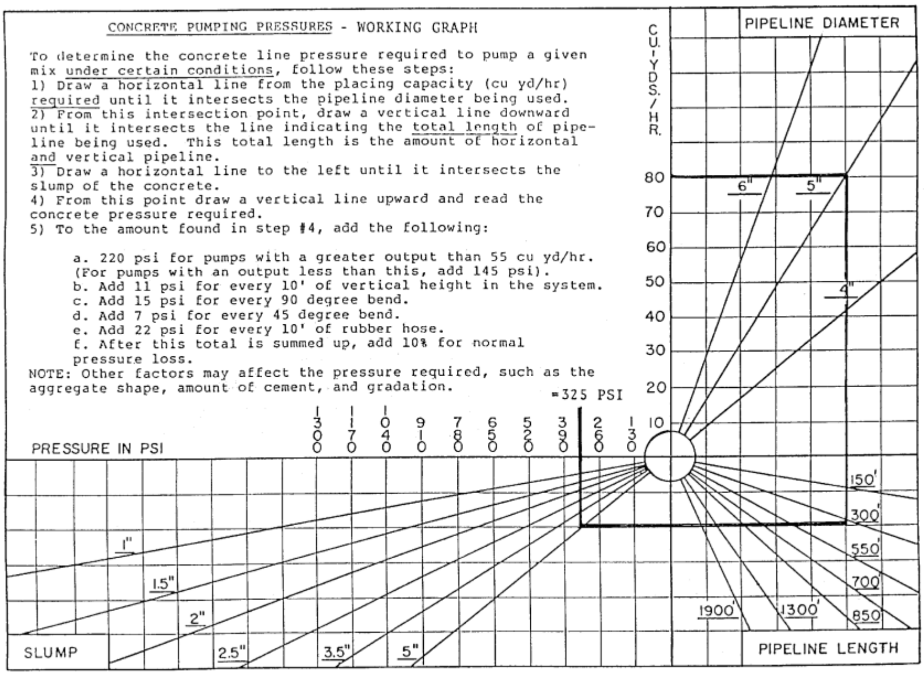

Figure 1-1: Estimation of Concrete Pumping Pressure
Source: (Bognacki, et al., 1996)

1.1.2.2 *JSCE Guidelines*

JSCE guidelines (Tamon & Hiroshi, 2010) have specified desirable ranges for slump (8 to 18 cm) and powder content (270 to 300 kg/m^3) to obtain a pumpable concrete mix. As per the guidelines, slump loss due to temperature, time elapsed from mixing, transporting and pumping should be taken into consideration when deciding the slump value of a pumpable concrete.

Furthermore, pressure loss per horizontal meter run at concrete pumping operation has been related to the slump and maximum size of aggregate as shown in Figure 1-2. In order to estimate the pumping pressure, equivalent lengths corresponding to the pressure drop at a bend or vertical pipe length have been proposed (see Table 1-1).

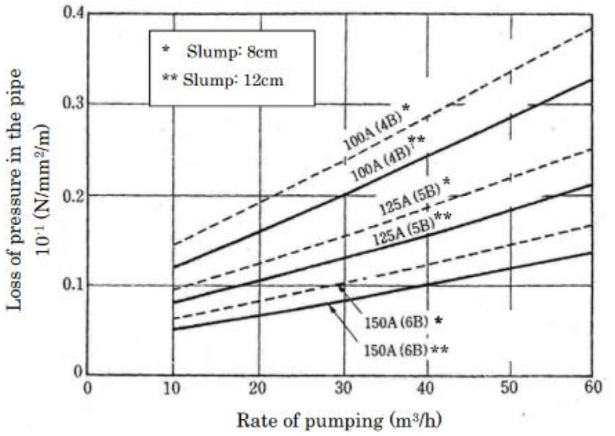

Figure 1-2: Pressure loss per meter run
Source: (Tamon & Hiroshi, 2010)

Equivalent horizontal pipe lengths proposed by JSCE guidelines has been presented in Table 1-1.

Table 1-1: Equivalent Horizontal Pipe Length
Source: (Tamon & Hiroshi, 2010)

Item	Unit	Nominal diameter of pipe	Equivalent horizontal pipe length* (m)
Vertical pipe	1 meter	100A(4B) 125A(5B) 150A(6B)	3 4 5
Tapered pipe**	1 piece	175A(4B)->150A 150A(5B)->125A 125A(6B)->100A	3
Bent pipe	1 piece	90 ° r=0.5 m r=1.0 m	6
Flexible hose	5~8 m/one piece		20

* The value for the pumping of the normal concrete
** The value for Tapered pipe with 1m of the length as the standard, and established on the basis of the diameter of the smaller pipe

However, when it is necessary to go for a mix in which the slump and powder contents are out of the specified range, guidelines recommends to conduct a full scale trial pumping allowing actual conditions at the construction site.

1.1.3 Studies on concrete pumpability

A considerable number of studies have been conducted on pumpability of concrete. According to the studies, there are basically four fresh concrete properties that define the pipe flow characteristics of concrete (Feys, Khayat, & Khatib, 2016) & (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001). Those are; the viscosity (μ_p) and yield stress (τ_0) of concrete and the viscous constant (η_{ll}) and the yield stress $(\tau_{0,ll})$ of the lubrication layer. Here the viscous constant is referred to the viscosity $(\mu_{p,ll})$ of lubrication layer divided by the lubrication layer thickness (e) in concrete pipe flow. In forthcoming chapters, the theoretical background of the concrete pipe flow has been described in more details.

A theoretical model for concrete line pressure (in a horizontal concrete pipe flow), has been investigated in a number of research projects { (Kaplan, Lerrard, & Sedran, 2005); (Choi, Kim, & Kwon, 2013a); (Choi, Roussel, Kim, & Kim, 2013b); (Feys, Khayat, & Khatib, 2016) & (Feys, Khayat, Perez-Schell, & Khatib, 2015)}. In this model, the pressure corresponding to a certain flow rate can be predicted once the above four fresh concrete properties, pipe line diameter and length are known.

To measure the rheological properties of concrete and lubrication layer, various types of apparatus have been introduced over last few decades. Rheological properties of concrete, i.e. yield stress and viscosity of concrete, can be determined from a concrete rheometer. A special rheometer which is designed to measure the lubrication layer properties, which are the yield stress and viscous constant of the lubrication layer material is generally called as a concrete tribometer. In such an apparatus, there is a mechanism to enable formation of a lubrication layer between bulk concrete material and a steel surface of the instrument and then the rheology of that layer is measured.

However, the above described theoretical approach is not yet applied in practical applications in the construction industry. The main reason seems to be is that studies on rheology and pumpability of concrete have been progressed independently in lab scale, yet adequate investigations have not been implemented in upgrading the current practices of concrete pumping with the updated research knowledge.

1.2 Problem Statement

Despite the fact that current understanding on fresh concrete properties (rheology) and pumpability of concrete, current practice at the construction industry does not address the effect of fresh concrete properties on concrete pumpability. In addition, since concrete pipe flow had been studied only for the case of horizontal straight pipe section, pressure drops corresponding to horizontal and vertical bends, tapered sections and vertical sections have to be investigated in order to predict concrete pumping pressure based on concrete rheology and pipe network details. Furthermore, influence of mix design parameters on concrete rheology has to be investigated in order to decide mix proportions of concrete at the mix design stage.

1.3 Objective

(1) Establish a model to predict concrete pumping pressure at the construction site, from the rheological properties of concrete

(2) Identify the variations of rheological properties of concrete with respect to the mix proportion parameters of the concrete

1.4 Research Plan

The focus of the research study was to develop a model to estimate concrete pumping pressure from rheological properties of concrete and to find relationships of mix design parameters on those rheological properties. To achieve the first objective, a set of field tests had been carried out at a high rise building construction project. Secondly, some lab experiments were carried out to derive correlations of mix design parameters on concrete rheology. Figure 1-3 demonstrates the research plan.

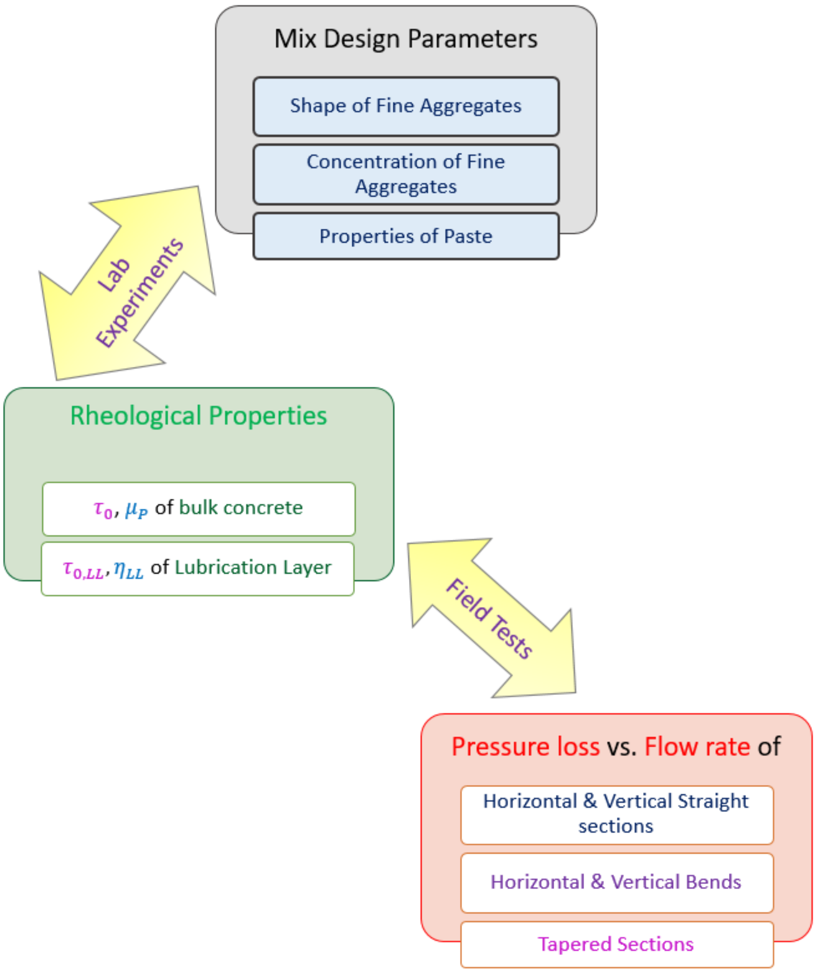

Figure 1-3: Research Plan

1.5 Guide to Thesis

As per the flow chart shown in Figure 1-4, this research project included an extensive literature review and theoretical investigation followed by a set of field and laboratory experiments to achieve the research objectives.

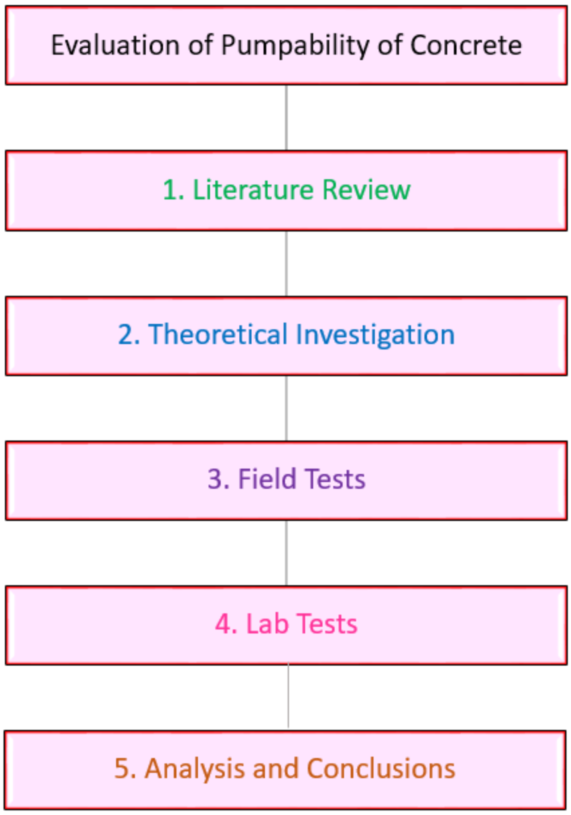

Figure 1-4: Guide to Thesis

1.5.1 Literature Review

As the first step, an extensive literature review was conducted to understand the current knowledge, involved parameters, available instruments and existing research gaps to be filled. A detailed presentation of the state of art on concrete pumpability has been included in this report as chapter 2.

1.5.2 Theoretical Investigation

A considerable theoretical knowledge had been developed through past research on concrete pipe flow. In fact several flow curves for fresh concrete and lubrication layer had been proposed. Moreover, theoretical model for horizontal straight pipe flow has been presented. Chapter 3 of this report describes the theoretical understanding with illustrations of velocity, stress, strain and shear rate distributions over pipe cross section.

1.5.3 Field Tests

There were two basic objectives in this research project. As described in the research plan; field tests were planned and conducted to fulfil the first objective, which is to establish a model to predict pressure drop versus flow rate relationship based on rheological properties of concrete.

Field tests were carried out at two high rise apartment tower construction projects. Those tests included testing concrete samples with ICAR plus rheometer, pressure transducer and strain gauge measurements for pipe line pressure at some sections. Chapter 4, on experimental investigations contain details on conducted field tests.

1.5.4 Lab Experiments

A set of lab experiments were carried out to find the effect of mix design parameters on rheological properties of concrete, which is the second objective of the research. Experiments were planned and conducted for paste and mortar phases of concrete. Details have been presented in Chapter 4.

1.5.5 Analysis and Conclusions

Analysis of Lab tests was quite straight forward. The measurements taken of rheological properties of samples were compared against different mix design parameters.

Field tests involved measurements of pressure transducer and strain gauges recorded by a dynamic data logger other than the rheological properties. Analysis of the results have been presented in detail in Chapter 5.

Finally, a couple of conclusions could be made based on experimental investigations and analysis. Those conclusions have been summarised in Chapter 6 in this report.

CHAPTER 2: LITRATURE REVIEW

2.1 Flow Characteristics

Fresh concrete behaves as a suspension of coarse aggregates in mortar phase or as coarse and fine aggregates suspending in paste phase; where the effect of shear thinning and thixotropic effect are some of the main features of the fresh concrete rheology (Roussel N. , 2016).

2.1.1 Behaviour of Suspensions

Flow characteristics of a suspension is very much dependent on the volume fraction (ϕ) of the elements in suspension and the maximum packing fraction (ϕ_m) (Krieger & Dougherty, 1959). When the volum fraction of suspending elements are quite low (ie: less than 2%), suspending particals would not collide with each other, hence, the suspension would behave as a Newtonian suspending liquid with increased viscosity. In case of higher volume fractions of suspending particals, particle interaction cannot be avoided. Therefore, the behaviour is influenced by both suspending particals and liquid.

2.1.2 Shear Thinning Effect

Shear thinning is the phenomena of decreasing the viscosity of a liquid as the applied shear rate is increased. Roussel (Roussel N. , 2016) has stated this by a mathematical expression as $d\eta/d\dot{\gamma} < 0$; where symbols η and γ are referred to the viscosity and shear strain of the media. Figure 2-1 shows the effect of shear thinning graphically.

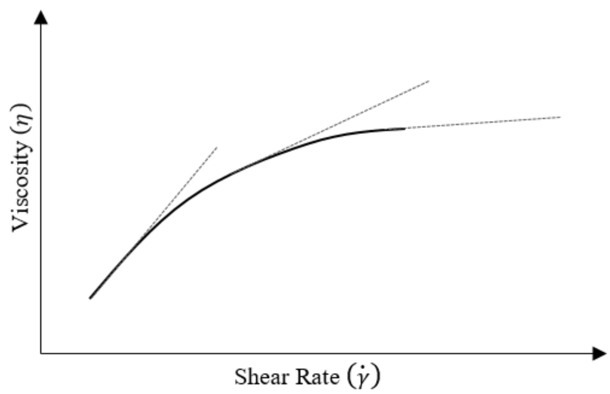

Figure 2-1: Shear thinning effect

Based on an experimental investigation on rheological properties of fresh mortar with glass fibres, shear thinning effect has been observed in fibre-free mortars where the addition of glass fibre had influenced the mortars to be shear thickening fluids (Jiao, Shi, Yuan, Zhu, & Schutter, 2019).

2.1.3 Thixotropic Behaviour

Varying the viscosity of a fluid over time, when the applied shear rate remain constant is explained as the thixotropic behaviour. Roussel (Roussel N. , 2016) has expressed this mathematically as $d\eta(\dot{\gamma})/dt \neq 0$. Reversible dispersion-flocculation of cement particles and irreversible bonds created with hydration reactions cause time dependent behaviour or the thixotropy of fresh concrete (Li, Cao, & Guo, 2018). Hence, hydration of cement, physical flocculation of cementitious particles and agitation have been considered for the thixotropic model developed for fresh concrete by Li (Li, Cao, & Guo, 2018). Moreover, studies have been conducted to investigate the effect of thixotropy on the concrete pumping pipe line pressure (Tan, Cao, Zhang, Wang, & Deng, 2015). According to the literature, flocculation rate (A_{thix}) has also been proposed to classify self-compacting concrete with respect to the thixotropic behaviour (Roussel N. , 2006). In addition to above literature, there are other research studies which have addressed this time dependent behaviour of fresh concrete (Lowke, 2018); (Roussel, Ovarlez, Garrault, & Brumaud, 2012).

2.2 Theoretical Understanding on Concrete Pipe Flow

Large number of experimental research studies have been carried out to investigate the fresh concrete pipe flow. When concrete is being pumped through a pipe line, formation of a lubrication layer between the pipe wall and bulk concrete has been well understood (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001); (Choi, Kim, & Kwon, 2013a); (Choi, Roussel, Kim, & Kim, 2013b). Meanwhile, flow curves for both concrete and lubrication layer have been studied and several models have been proposed in literature (Banfill, 2006); (Nehdi & Rahman, 2004) (Peng, Deng, Liu, Yuan, & Ye, 2014) & (Vance, Sant, & Neithalath, 2015). However, Bingham's model is the mostly accepted flow curve for fresh concrete and lubrication layer. Kaplan's theoretical model for fresh concrete pipe flow is based on the approximation of fresh concrete flow curves based on the Bingham's model.

2.2.1 Lubrication layer

The phenomena of the slip layer has been first recognized by Alekseev in 1952 (Kwon, Jang, Kim, & Shah, 2016). Bleeding of water and paste in concrete phase (Secrieru, Cotardo, Mechtcherine, Lohaus, & Schrofl, 2018), shear induced particle migration (Choi, Kim, & Kwon, 2013a) and the pipe wall – concrete interface effect (Ngo, Kadri, Bennacer, & Cussigh, 2010) influence the formation and existence of lubrication layer or the slip layer. Studies on fresh concrete pipe flow claim that the lubrication layer material can be considered as similar to the constituent mortar (Choi, Roussel, Kim, & Kim, 2013b). Rheology of lubrication layer has been tested by wet screening the mortar from 5 mm sieve out of pumped concrete (Kwon, Jang, Kim, & Shah, 2016).

The rheological parameters concerned with lubrication layer are the yield stress and viscous constant, where the viscous constant is referred to the plastic viscosity divided by the lubrication layer thickness (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001); (Choi, Roussel, Kim, & Kim, 2013b); (Feys, Khayat, Perez-Schell, & Khatib, 2015). Among these parameters, yield stress and plastic viscosity can be determined with a rheometer; while the measuring of lubrication layer thickness is little complicated.

However, some experiments have been carried out on velocity graphs using an ultra-sonic velocity profiler and concluded that the thickness of lubrication layer does not depend on the pipe line length, design strength of fresh concrete or the coarse aggregate size. Moreover, the lubrication layer thickness has been observed to be nearly constant and equal to 2 mm (Choi M. S., Kim, Jang, & Kwon, 2014). Recent studies have also confirmed that the assumption of a 2 mm lubrication layer thickness in the case of a tribometer measuring system is adequate for predicting concrete pumping (Kim, Kwon, Jang, & Choi, 2018).

2.2.2 Flow Curves

A number of flow curve models have been considered in literature (Banfill, 2006) for cement phase and fresh concrete. Almost all of the adopted models for fresh concrete flow characteristics have been considered yield stress effect (Roussel N. , 2006).

Herschel-Bulkley model {equation (1)}, Bingham Model {equation (2)} and Casson model {equation (3)} are the flow curves that have been taken into consideration most often. Fresh concrete rheology and the rheology of cement based materials have been experimentally evaluated against above three models in several research studies (Güneyisi, Gesoglu, Naji, & İpek , 2016); (Nehdi & Rahman, 2004); (Peng, Deng, Liu, Yuan, & Ye, 2014); (Vance, Sant, & Neithalath, 2015).

Herschel-Bulkley Model	$\tau = \tau_0 + k\dot{\gamma}^n$	*(1)*
Bingham Model	$\tau = \tau_0 + \mu\dot{\gamma}$	*(2)*
Casson Model	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu\dot{\gamma}}$	*(3)*

Herschel-Bulkley model could be well fitted to experimental data over decades of shear rate test results while Bingham model and Casson model may be fitted only over a very limited range of shear rates (Roussel N. , 2016).

2.2.3 Theoretical model by Kaplan

Theoretical expressions have been derived and validated for horizontal straight pipe sections in literature (Kaplan, Lerrard, & Sedran, 2005) & (Feys, Khayat, Perez-Schell, & Khatib, 2015). Bingham's model has been the flow curve basis for both lubrication layer and bulk concrete when deriving the theoretical expressions. Simplicity and convenience of the Bingham's model and the reliability over Newtonian fluid model caused it to be the most accepted flow curve model for lubrication layer and fresh concrete.

Kaplan (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001) has derived expressions for plug flow and sheared flow of concrete which has been experimentally validated in few research studies for different types of concrete with horizontal straight pipe sections. The expressions are stated in chapter 3. Kaplan had conducted experiments using a 148 m long pipe circuit along with pressure gauges and strain gauges to measure pressure drops in horizontal straight sections and an electromagnetic flow rate meter.

Feys (Feys, Khayat, Perez-Schell, & Khatib, 2015), Choi (Choi M. S., Kim, Jang, & Kwon, 2014) and Mechtcherine (Mechtcherine, Nerella, & Kasten, 2014) are some of the researchers whose studies were based on Kaplan's equations.

2.3 Apparatus for Testing on Rheology of Concrete

Since, the theoretical models are based on Bingham's model for lubrication layer and bulk concrete, evaluation of rheology is referred to the determination of two constants in Bingham's model, which are the yield stress and plastic viscosity. The two variables in the Bingham's model are the shear stress and shear rate. Hence, the measuring technique of rheological properties should have a mechanism to apply shearing to a concrete sample and measuring the applied shear stress versus obtained shear rate values.

Different types of concrete rheometers have been developed to evaluate the rheology of concrete. Technique of rheometers can be varied from parallel plates to rotating impellers or rotating vanes or coaxial cylinders.

When the rheology of lubrication layer is concerned, the thickness of the lubrication layer is a very important parameter. Thickness of slip layer can either be assumed as 2 mm (Choi M. S., Kim, Jang, & Kwon, 2014); (Kim, Kwon, Jang, & Choi, 2018) or the viscous constant has to be measured. The viscous constant of the lubrication layer is the division of plastic viscosity by the layer thickness. Therefore, it is necessary to evaluate viscous constant and the yield stress of lubrication layer. Concrete tribometers have been developed using various techniques to assess the lubrication layer parameters.

2.3.1 Rheometers

There are different rheometers that have been developed to evaluate Bingham parameters (i.e. yield stress and plastic viscosity) of fresh concrete. In concrete rheometers, ribs are located at the rheometer – concrete sample interface to avoid formation of slip layer. BML rheometer (Ireland), IBB rheometer (Canada), CEMAGREF-IMG rheometer (France) and Two-Point Test (UK) had been brought together and compared the performance in ACI 236-A project (Brower & Ferraris, 2003).The two rheometers, ConTec Viscometer 5 (Choi, Roussel, Kim, & Kim, 2013b) and ICAR rheometer (Feys, Khayat, Perez-Schell, & Khatib, 2015) are being used in the recent and current research studies extensively. Pictures of those concrete rheometers have been presented in Figure 2-2, Figure 2-3 and Figure 2-4.

Figure 2-2: ConTec Viscometer 5
Source: (Feys, Khayat, Perez-Schell, & Khatib, Development of a tribometer to characterize lubrication layer properties of self-consolidating concrete, 2014)

Figure 2-3: ICAR plus Rheometer

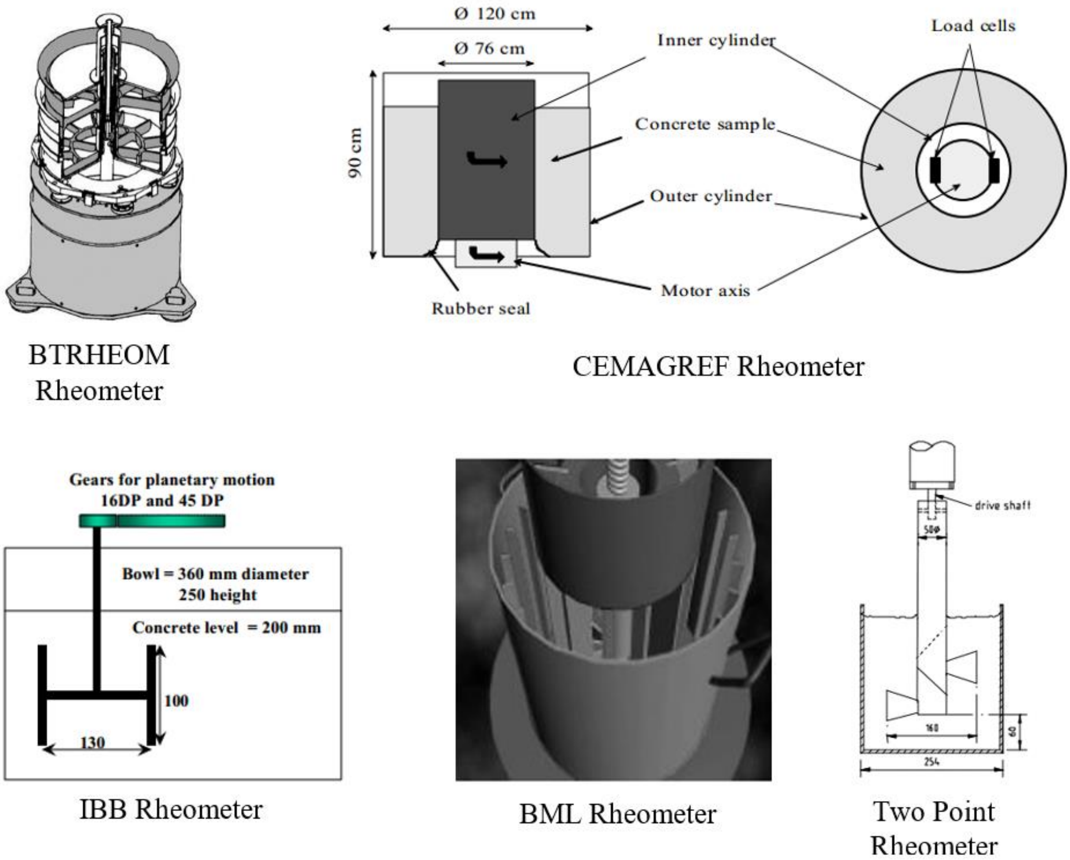

Figure 2-4: Some Concrete Rheometers from literature
Source: (Ferraris, et al., 2000)

In each of these rheometers, the rotating impeller or vanes or the coaxial cylinder is applying shear to the concrete sample at few different rates. The applied torque on the sample is related to the applied shear stress based on the geometry of the rheometer while the rotation rate (rpm value) is related to the shear rate. When a set of shear stress versus shear rate values are available, assuming a linear relationship, the interception (yield stress) and gradient (plastic viscosity) can be calculated (Perera, Nanayakkara, & Dasanayaka, 2017).

2.3.2 Tribometers

Coaxial cylinders is the most widely used mechanism for concrete tribometers. In fact, the first tribometer by Kaplan (Kaplan, Lerrard, & Sedran, 2005), Chapdelaine's tribometer (Jolin, Burns, Bissonnette, Gagnon, & Bolduc, 2009), new tribometer by Feys (Feys, Khayat, Perez-Schell, & Khatib, 2015) and the tribometer developed by Ngo (Ngo, Kadri, Bennacer, & Cussigh, 2010) are some of the coaxial cylinders tribometers found in literature. Figure 2-5, Figure 2-6 and Figure 2-7 contain pictures of some coaxial cylinder type concrete tribometers.

Figure 2-5: Tribometer by Feys
Source: (Feys, Khayat, Perez-Schell, & Khatib, Development of a tribometer to characterize lubrication layer properties of self-consolidating concrete, 2014)

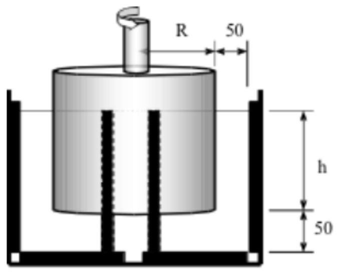

Figure 2-6: Chapdelain's Tribometer
Source: (Jolin, Burns, Bissonnette, Gagnon, & Bolduc, 2009)

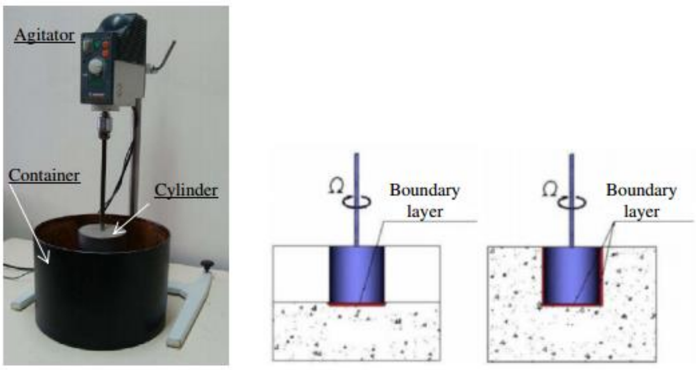

Figure 2-7: Tribometer by Ngo
Source: (Ngo, Kadri, Bennacer, & Cussigh, 2010)

Unlike concrete rheometers, the interface of tribometer – concrete is smooth so that the steel-concrete interface which is the actual condition in concrete pipe flow is facilitated. Since the surface is smooth, formation of slip layer has been encouraged when one of the cylinders rotate at a certain rotation rate.

Bingham's fundamental equation can be slightly modified to incorporate the lubrication layer thickness as described in chapter 3. Therefore, the variables concerned are the velocity difference of the lubrication layer and the shear stress. Hence, applied torque could be converted to the shear stress applied and rotation rate to the relative velocity of outer most lubrication layer with respect to the inner most layer. Same as the method of rheometers, the interception and gradient of shear stress versus relative velocity can be considered as the yield stress and viscous constant of the lubrication layer.

Furthermore, tribometers like SLIPER (Mechtcherine, Nerella, & Kasten, 2014) has been developed which simulate the plug flow of concrete and predicts the pressure versus flow-rate relationship using the Kaplan's model for plug flow in fresh concrete pipe-flow. A picture of the SLIPER tribometer has been presented in Figure 2-8.

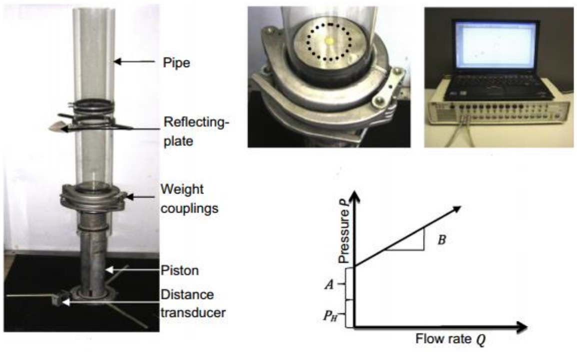

Figure 2-8: Sliding Pipe Rheometer
Source: (Mechtcherine, Nerella, & Kasten, 2014)

2.4 Factors affecting Pumpability of Concrete

Kaplan's model has become the basis of current knowledge and research interests on pumpability of concrete (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001); (Feys, Khayat, & Khatib, How do concrete rheology, tribology, flow rate and pipe radius influence pumping pressure, 2016); (Choi, Kim, & Kwon, Prediction on pipe flow of pumped concrete based on shear-induced partical migration, 2013a); (Mechtcherine, Nerella, & Kasten, 2014). With expected ideal conditions, parameters related to concrete pumpability are;

1. Applied Pressure (Pump Capacity)
2. Operating Flow-rate
3. Pipe Length and Radius
4. Rheological Properties of Bulk concrete and Lubrication Layer

Rheological properties of Lubrication Layer are referred to the yield stress and viscous constant. Viscous constant depends on both plastic viscosity and layer thickness. Pipe wall material has some effect on lubrication layer thickness (Ngo, Kadri, Bennacer, & Cussigh, 2010).

In addition to the length and radius of pipe line, details of bends, tapered sections and potential height difference between inlet and outlet also influence the pipe flow parameters of fresh concrete. Equivalent lengths have been stated in JSCE guidelines (Tamon & Hiroshi, 2010) to consider the pressure drops at bends, tapered sections and vertical lengths. ACI guidelines (Bognacki, et al., 1996) have proposed pressure drop constants for bends, vertical lengths and rubber hoses irrespective of operating flow-rate. However, (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001) and Chapdelaine (according to (Roussel N. , 2016)) have concluded that bends and reducers had not cause significant pressure loss based on their experimental studies on concrete pipe flow with Conventional Vibrated Concrete. In contrary, Feys had observed considerable pressure drops at 90^o and 180^o bends than straight sections from his experimental work, though he has not produced values (Roussel N. , 2006).

Another important factor that needs to be considered is the time dependant behaviour or the thixotropic effect. Research work related to thixotropy have been presented in section 2.1.3 of this chapter.

Shear thinning and shear thickening phenomena also influence the pumping characteristics of fresh concrete. As stated in section 2.1.4, shear thinning effect of concrete has been addressed in several research studies. In contrary, some research work has found that fresh concrete has shear thickening effect with certain admixtures

(Ma, Feng, Long, & Xie, 2016). Similarly, (Feys, Verhoeven, & Schutter, 2009) has explained the shear thickening effect in self-compacting concrete which cause the flow curve to be non-linear.

CHAPTER 3: THEORY OF CONCRETE PIPE-FLOW

3.1 Introduction

Theoretical and experimental investigations have been carried out in several research projects on fresh concrete pipe-flow { (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001); (Choi, Kim, & Kwon, 2013a) & (Feys, Khayat, & Khatib, 2016)}. This chapter describes the current understanding of the pipe flow mechanism of fresh concrete.

It is the theoretical model proposed by (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001) that has obtained a considerable attention of the researchers who work on pumpability of fresh concrete. As fresh concrete is pumped through a pipeline, a lubrication layer will be formed just inside the pipe wall. Figure 3-1 shows a schematic diagram of the layers formed at fresh concrete pipe flow. Generally, the flow characteristics of lubrication layer is much higher than that of the bulk concrete material.

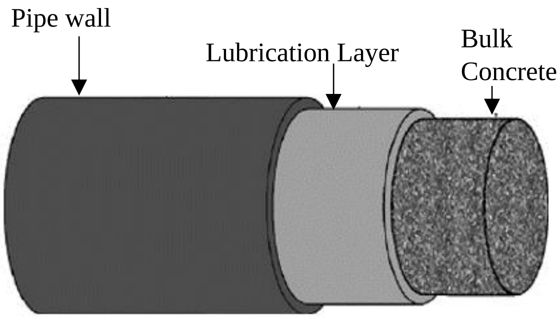

Figure 3-1: Schematic pattern of concrete flow in pipe source: (Choi, Roussel, Kim, & Kim, 2013b)

The concrete pipe flow can be of two types depending on the pressure applied per meter run of pipe flow and the fresh concrete properties. When the applied pressure on pipe flow is comparatively low to make bulk concrete sheared, but is sufficient to induce shear in lubrication layer, plug flow of concrete occurs. On the other hand, when the applied pressure is adequate to induce shear in bulk concrete material as well, sheared flow occurs.

Kaplan's model on concrete pipe flow includes equations for both plug flow and sheared flow of concrete. This model has been developed, using Bingham's fluid model for the flow curves of both lubrication layer and bulk concrete.

3.2 Flow curves of concrete

Flow properties of any kind of liquid can be explained from its flow curve. Generally, flow curve of a liquid is expressed as the relationship of shear stress to shear strain or shear strain rate between the layers. For a better understanding of the theoretical derivation, shear stress, shear strain and shear rate can be described using the Figure 3-2.

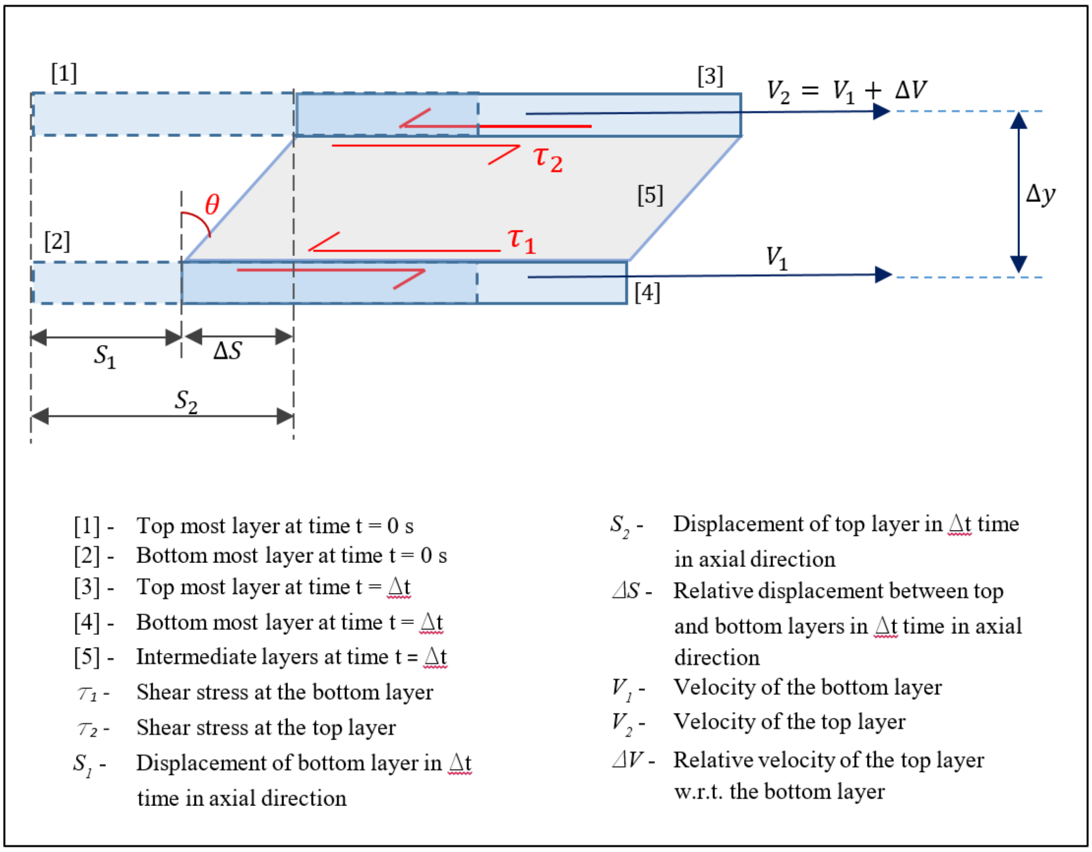

Figure 3-2: Shearing between layers of a fluid

When fluid material starts to flow, Shear stress (τ) varies over transvers direction y as shown in Figure 3-2. Then the fluid layers start to flow in different speeds corresponding to the applied shear stress at each layer. Variation of fluid layer speed over the transverse direction cause the shear strain and shear rate distribution between layers.

Shear strain (γ) is referred to the gradient of relative axial displacement (ΔS) of layers over the perpendicular distance(Δy). Equation (4) is for the shear strain in a material flow;

$$\gamma = dS/dy \tag{4}$$

Differentiation of shear strain over time is defined as the shear strain rate. Commonly, shear strain rate is called the shear rate in literature. Hence, shear rate $(\dot{\gamma})$ can be expressed as;

$$\dot{\gamma} = \frac{d}{dt}\left(\frac{dS}{dy}\right)$$

$$= \frac{d}{dy}\left(\frac{dS}{dt}\right)$$

$$= \frac{d}{dy}(V)$$

Therefore, shear rate is the axial velocity gradient over perpendicular distance between layers, as expressed in equation (5).

$$\dot{\gamma} = dV/dy \tag{5}$$

Flow curve of concrete has been approximated to a number of mathematical models in various research studies. Besides, Bingham fluid model is the most famous and most adopted model for fresh concrete flow characteristics. In fact, both lubrication layer and bulk concrete are assumed to be Bingham fluids.

Unlike Newtonian fluids like water or most of the liquids, Bingham fluid has a yield stress value. This means when stress is applied on a Bingham fluid it can sustain stresses up to a certain extent without being sheared. The minimum stress that should be applied to cause the fluid shear is referred to the yield stress of that liquid. This scenario is almost similar to the static friction which has to be overcome to make an object slip over a certain surface.

Figure 3-3 below is the flow curve of the Bingham fluid.

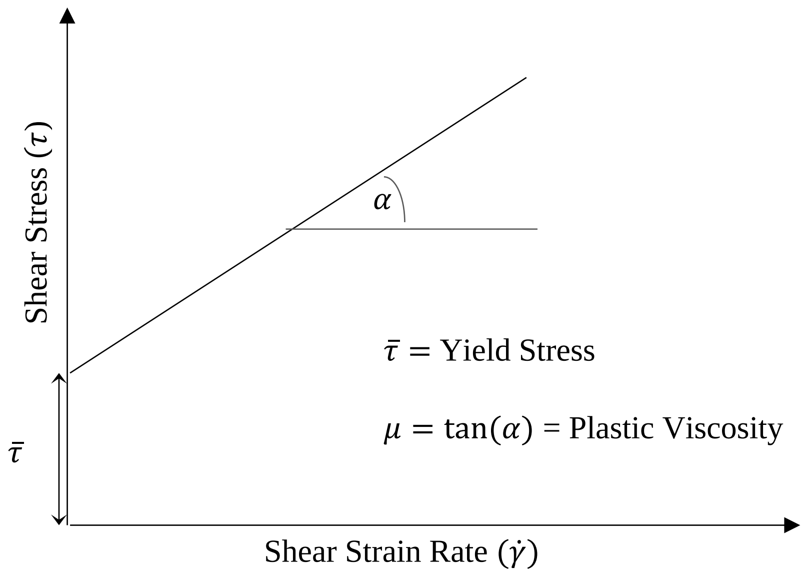

Figure 3-3: Bingham Fluid Model

Mathematically the flow curve of a Bingham fluid can be expressed as Equation (6);

$$\tau = \bar{\tau} + \mu\dot{\gamma} \tag{6}$$

The relationship of 'shear stress' applied versus the 'shear strain rate' is approximated to a linear variation when fresh concrete is modelled as a Bingham fluid. The interception of the graph between shear stress and shear strain rate is the yield stress of the fluid, where the gradient is defined as the plastic viscosity of that liquid.

3.2.1 Flow curve of bulk concrete

Applying Bingham model for bulk concrete material flow curve for bulk concrete can be illustrated as Figure 3-4;

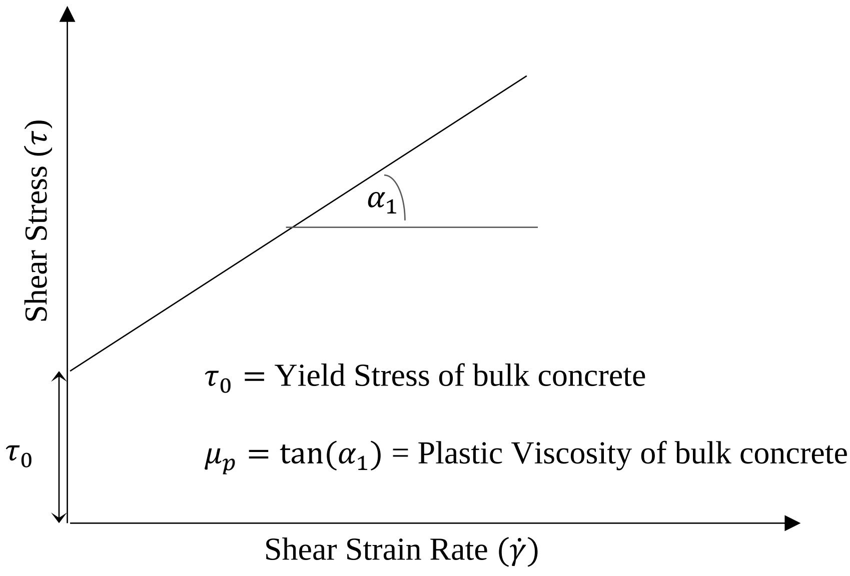

Figure 3-4: Flow curve of Bulk Concrete

Similarly, the flow curve of bulk concrete can be expressed as Equation (7);

$$\tau = \tau_0 + \mu_p \dot{\gamma} \tag{7}$$

As a convention, throughout studies on concrete pumpability τ_0 (Pa) symbolises the yield stress of bulk concrete. At the same time, μ_p $(Pa.s)$ denotes the plastic viscosity of concrete. These two properties are the two rheological properties of bulk concrete that influence the flow characteristics of fresh concrete. Additionally, there exist the properties of the lubrication layer which also contribute to the flow characteristics of fresh concrete.

3.2.2 Flow curve of lubrication layer

Same flow curve of the Bingham model can be adopted for the lubrication layer material as well as shown in Figure 3-5;

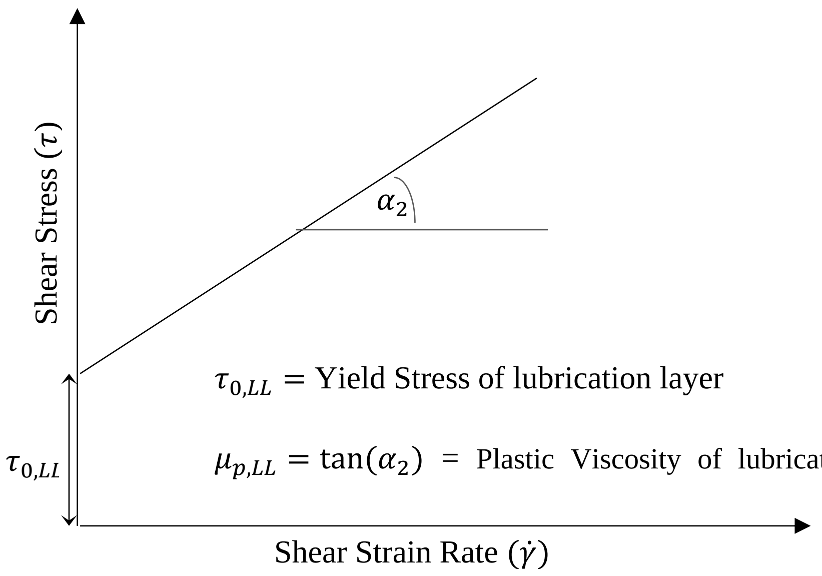

Figure 3-5: Flow curve of Bulk Concrete

Mathematical expression may be stated as Equation (8);

$$\tau = \tau_{0,LL} + \mu_{p,LL}\dot{\gamma} \tag{8}$$

In addition to the yield stress and viscosity of the lubrication layer, there is another important parameter. That is the thickness of lubrication layer when the concrete is pumped through a pipe line. Hence, the thickness of lubrication layer has to be incorporated in the flow curve equation in order to derive expressions for fresh concrete pipe flow.

Lubrication layer and the related parameters are shown in Figure 3-6.

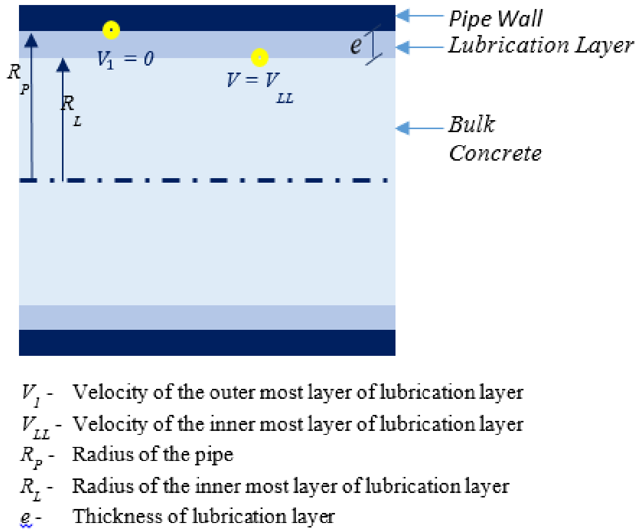

Figure 3-6: Lubrication Layer

The thickness of this lubrication layer is very small so that the applied shear stress at the lubrication layer in fresh concrete pipe flow can be considered same from R_L to R_P (Kaplan, Sedran, Lerrard, Vachon, & Marchese, 2001). With that reasonable assumption, the shear rate in lubrication layer is constant and that is equal to the velocity difference of outer and inner most layers of lubrication layer divided by the lubrication layer thickness.

$$\dot{\gamma} = \frac{d}{dt}.\frac{dx}{dy} = \frac{d}{dy}.\frac{dx}{dt} = \frac{\Delta V}{\Delta y} = \frac{V_{LL}}{e}$$

$$\dot{\gamma} = \frac{V_{LL}}{e} \qquad (9)$$

By substituting for the shear rate in lubrication layer with Equation (9) in Equation (8), characteristic flow curve of lubrication layer can be expressed as in Equation (10);

$$\tau = \tau_{0,LL} + \eta_{LL} V_{LL} \qquad (10)$$

Here, $\eta_{LL} = \frac{\mu_{p,LL}}{e}$ is called the Viscous Constant of the Lubrication Layer.

3.3 Mechanism of concrete pipe flow

Formation of lubrication layer influence the flow characteristics of fresh concrete pipe flow to a great extent. The literature (Choi, Kim, & Kwon, 2013a) elaborates how shear induced particle migration helps the formation of lubrication layer and how the lubrication layer thickness is limited due to increase of viscosity at the centre with particle migration.

It is necessary to consider the shear stress distribution over pipe cross section. Consider a cylindrical element of radius r and length l of which the pressure difference between two circular planes is ΔP as shown in Figure 3-7.

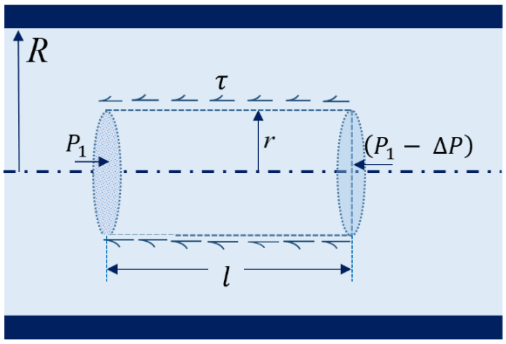

Figure 3-7: Shear stress applied at r distance to the centre line

At steady flow, forces acting on cylindrical element should be balanced,

$$\{P_1 - (P_1 - \Delta P)\} \times \pi r^2 = \tau \times 2\pi r \times l$$

$$\Delta P \times r = \tau \times 2l$$

Hence, the shear stress applied at an r distance from the centre line can be expressed as in Equation (11);

$$\tau = \frac{\Delta P}{2l} \times r \qquad (11)$$

Furthermore, variation of shear stress, shear strain and shear rate can be sketched as shown in Figure 3-8.

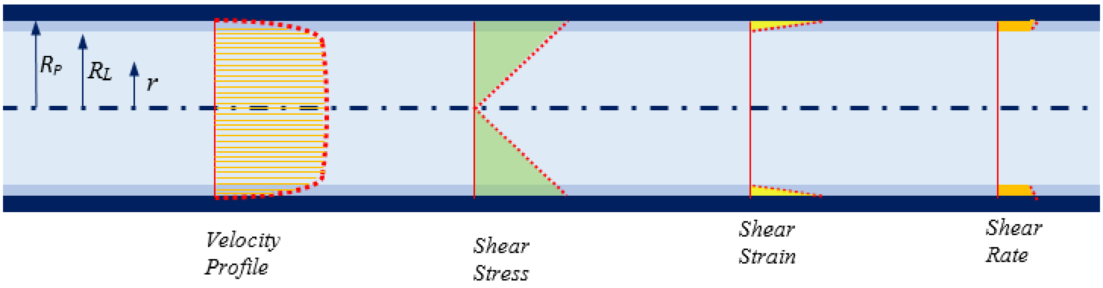

Figure 3-8: Shear stress, shear strain and shear rate of plug flow

It has been considered the plug flow of concrete in Figure 3-8. In case of sheared flow, shear strain and shear rates are not zero in the bulk concrete region. However, the values corresponding to bulk concrete are less than that of lubrication layer. Graphs corresponding to sheared plus plug flow are shown in Figure 3-9.

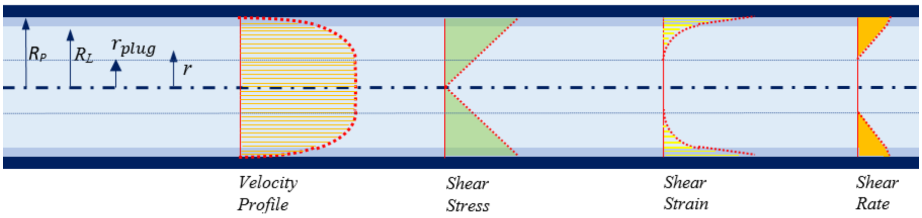

Figure 3-9: Shear stress, shear strain and shear rate in case of sheared plus plug flow condition

As presented in Figure 3-8 and Figure 3-9, shear stresses are maximum near the pipe wall. Hence the resulting shear strains and shear strain rates are also maximum.

When the shear strains near pipe wall is comparatively larger than at the central region, the axial velocity varies along the transverse direction. Since CA (coarse aggregate) particles are relatively larger than fines, each CA particle included in several layers. However, CA particles cannot deform to match the different strains in each layer. Hence, CA particles would choose to migrate to the central region, where the differential shear strain or the shear rate is relatively low. In that case only the mortar phase is left near the pipe wall – concrete interface. At that point the lubrication layer is formed between pipe wall and bulk concrete. After the lubrication layer has been formed, the rheology of lubrication layer is much better that the bulk concrete so that the shear strains and shear rates in this region are further influenced. Due to higher shear strains and shear rates, migrated CA would not go into the lubrication layer region again.

However, as the CA particles concentrate toward the centre, the viscosity of the central bulk concrete material is increased. That increased viscosity resists against the thickening of lubrication layer. Therefore, the thickness of the lubrication layer is limited to a certain value.

Choi (Choi, Roussel, Kim, & Kim, 2013b) has conducted some experimental investigations on lubrication layer properties using an ultrasonic velocity profiler. With their numerical analysis, lubrication layer properties have been similar to the properties of constitutive mortar of the pumped concrete. Further, the thickness of the lubrication layer has found to be not influenced by the flow rate but only the mix design details. The thickness of the lubrication layer is generally 2 mm.

The rheological properties or the dynamic yield stress and plastic viscosity of lubrication layer are considerably low than that of the bulk concrete. Plug flow of concrete occurs when the applied shear stress at pipe wall due to the applied pressure gradient is greater than the yield stress of lubrication layer yet that is lower to the yield stress of bulk concrete. As the applied pressure is increased and τ_w is greater than the yield stresses of both lubrication layer and the bulk concrete, the bulk concrete also starts to shear. However, the shear stress is reduced when it comes nearer to the central axis so that there will be a cylindrical section around central axis still moving as a plug. The radius of the plug is related to the pressure gradient in concrete pipe flow.

Figure 3-10 explains the remaining shear stress available for inducing shear, after compensating for the yield stresses of lubrication layer and bulk concrete

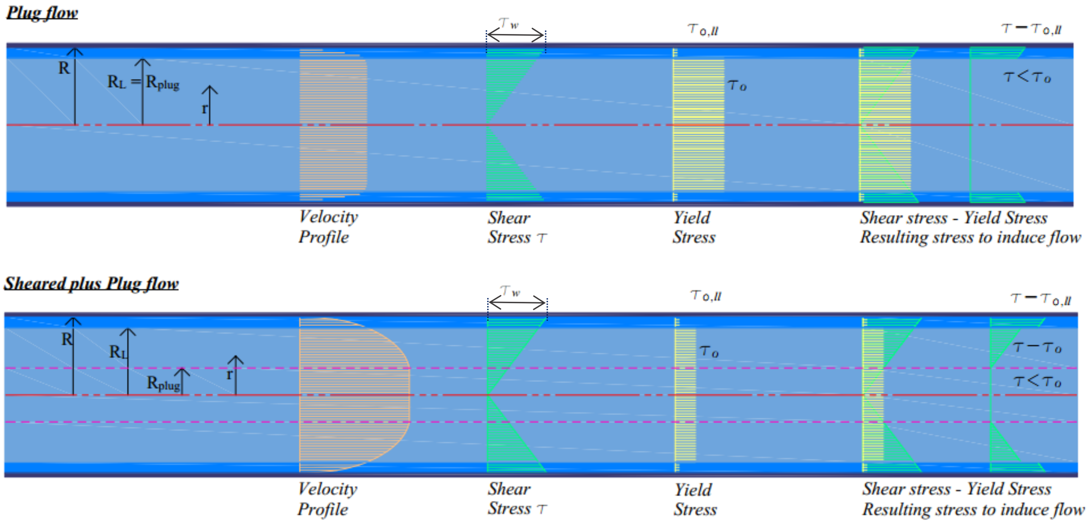

Figure 3-10: Resulting shear stress to induce fresh concrete pipe flow

3.4 Theoretical model for concrete pipe flow

In section 3.3, it has been clearly described the formation of lubrication layer and when plug flow occurs and when does the sheared plus plug flow occur.

Kaplan has derived theoretical equations for plug flow and sheared flow of concrete considering both lubrication layer and bulk concrete are Bingham's fluids.

Pressure loss versus flow rate relationship for plug flow and sheared flow of fresh concrete pipe flow can be expressed as in Equation (12) and (13) respectively;

$$\Delta P = \frac{2L}{R}\left(\frac{Q}{3600\pi . R^2}\eta_{LL} + \tau_{0,LL}\right) \tag{12}$$

$$\Delta P = \frac{2L}{R}\left(\frac{\frac{Q}{3600\pi . R^2} - \frac{R}{4\mu_p}\tau_{0,LL} + \frac{R}{3\mu_p}\tau_0}{1 + \frac{R}{4\mu_p}\eta_{LL}}\eta_{LL} + \tau_{0,LL}\right) \tag{13}$$

Theoretical derivations for Equations (12) and (13) have been presented in Appendix-I.

In equation (10), when Kaplan has derived the relationship of pressure loss versus flow-rate, it had been considered that all the layers of bulk concrete would be sheared as shown in Figure 3-11.

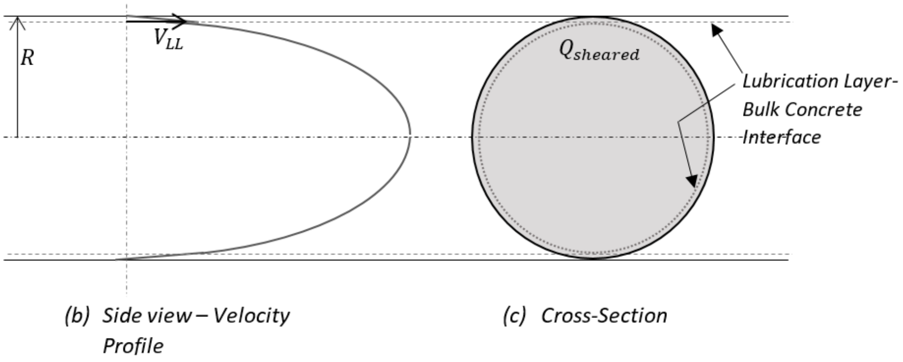

Figure 3-11: Velocity Profile for Sheared flow model by Kaplan

However, since bulk concrete has considerable yield stress value, there would be a portion of bulk concrete at the centre which moves as a plug as shown in Figure 3-12. This mechanism of sheared plus plug flow has been theoretically explained in section 3.2.

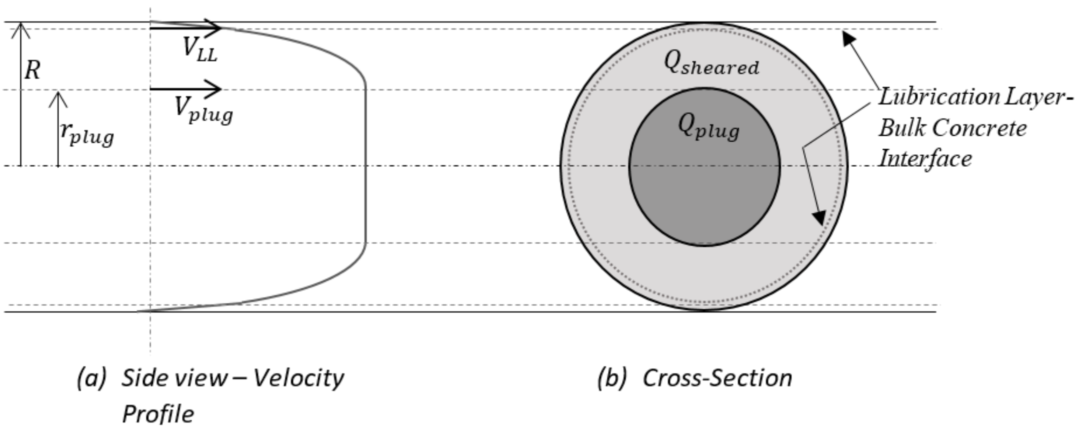

Figure 3-12: Velocity profile for sheared plus plug flow

Flow-rate corresponding to sheared plus plug flow condition can be expressed as in Equations (14), (15) and (16). Derivation of these equations are given in Appendix-II.

$$Q_{sheared} = 2\pi \left[\frac{1}{2} . \left\{ \frac{\Delta P . R^2}{4L\, \mu_p} - \frac{\tau_0 R}{\mu_p} + V_{LL} \right\} \left\{ R^2 - {r_{plug}}^2 \right\} + \frac{\tau_0}{3\mu_p} \left\{ R^3 - {r_{plug}}^3 \right\} - \frac{\Delta P}{16L\, \mu_p} \left\{ R^4 - {r_{plug}}^4 \right\} \right] \quad (14)$$

Where $r_{plug} = \frac{2L.\tau_0}{\Delta P}$

$$Q_{plug} = \pi \left(r_{plug} \right)^2 . \left\{ \frac{\Delta P}{4L\, \mu_p} \left(R^2 - {r_{plug}}^2 \right) - \frac{\tau_0}{\mu_p} \left(R - r_{plug} \right) + V_{LL} \right\} \quad (15)$$

$$Q_{Total} = Q_{sheared} + Q_{plug} \quad (16)$$

CHAPTER 4: EXPERIMENTAL INVESTIGATIONS

4.1 Introduction

Experimental investigations had been carried out in two phases. In the first phase, experimental investigation on concrete pumping at the construction sites. In the second phase, laboratory scale investigation of rheological properties of fresh concrete. The followings are the objectives of the experimental investigations.

(1) Investigation of on Concrete pumping under field conditions in a high-rise building construction site to obtain the necessary data to validate the current model for pipe flow of concrete

(2) Laboratory experimental investigations to find the effect of mix design parameters on rheological properties and thixotropic behaviour of fresh concrete

4.2 Equipment

4.2.1 Rheological Measurements with ICAR plus Rheometer

ICAR plus, commercially available concrete rheometer has been used in several research projects and the rheometer had been able to produce reliable measurements on rheology of concrete and mortar (Feys, Khayat, Perez-Schell, & Khatib, 2015); (Kwon, Jang, Kim, & Shah, 2016). Hence, in this research study, ICAR plus rheometer was used to assess rheology of both concrete and mortar.

ICAR plus rheometer is a coaxial cylinder type rheometer, of which the inner cylinder is a set of four vanes connected to a servo motor. In addition, the rheometer consists of a data acquisition software.

The components and the arrangement of the ICAR plus concrete rheometer have been presented in Figure 4-1. Figure 4-2 is a picture of the rheometer taken while conducting a test.

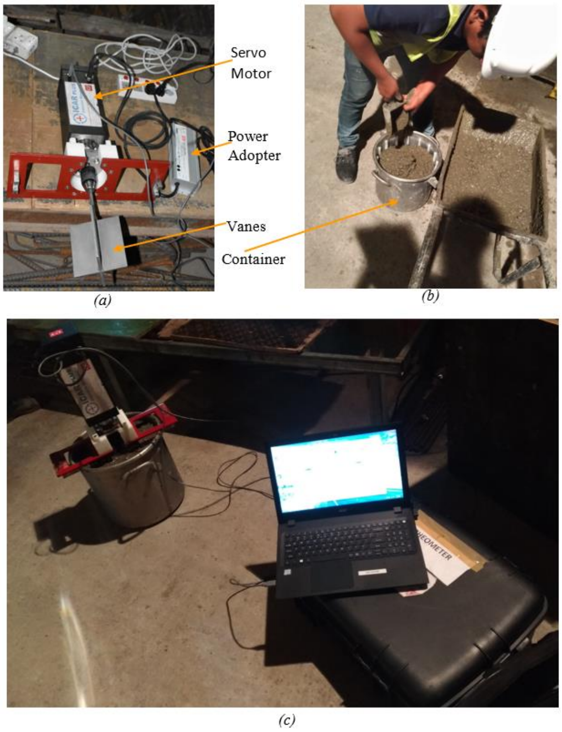

Figure 4-1: Assembly of the servo motor with vanes (a); Collecting a concrete sample to the container (b) & Arrangement of the ICAR plus Rheometer (c)

Figure 4-2: Conducting a test with ICAR plus Rheometer at the Luna Tower construction site- before concrete being pumped

A consistent concrete sample should be filled into the cylinder and the vanes should be exerted into the concrete, under the self-weight of vanes and motor. If the sample is too stiff that the vanes do not immerse under self-weight, extra pressure should not be applied and the test cannot be implemented. It has been recommended to use the rheometer for concrete samples of which the slump is greater than 75mm. However, practically there were some situations where the slump value is more than 150mm, but the concrete mix was too stiff to be measured in the rheometer.

The ICAR plus rheometer was used in both field and lab experiments;

1. To measure Yield Stress and Plastic Viscosity of pumped concrete at the construction sites.
2. To measure Yield Stress and Plastic Viscosity of Paste and Mortar phases of concrete in the Laboratory.

4.2.1.1 *Technical Information*

When the container is filled with a concrete sample and vanes are exerted into the fresh concrete sample, dynamic flow curve test can be started after calibrating the instrument. The vanes are connected to the servo motor which is capable of applying a maximum continuous torque of 32 Nm. When the flow curve test is started, the servo motor is programmed to increase the rotation speed of the vanes to the maximum value (0.500 rps by default) and maintain the speed for 20 s to allow breakdown of the flocculation. Then the rotation speed is reduced in 7 steps. At each constant rotation rate, the torque applied is recorded.

Since the rotation rate is corresponding to the shear rate of the concrete sample and the applied torque to the shear stress; shear stress versus shear rate data can be produced from the above test. The interception and the gradient of this relationship can be considered as the yield stress and the plastic viscosity of the sample.

As demonstrated in Figure 4-3, bulk concrete trapped to the vanes rotates in the same angular velocity with the vanes. When that cylindrical concrete volume starts to flow, a shearing is induced at the interface of the cylinder with the rest of the bulk concrete. That induces a shear stress on the next layer of bulk concrete. The shear stress will make this layer to flow following Bingham’s flow model. As the first layer starts to rotate it passes a certain amount of torque to the second next layer. Likewise, concrete between vanes and outer cylinder starts to flow circumferentially but with reduced angular velocities as the radius is increased. Similarly, the applied shear stress and shear rate also decrease as the radius increases. The last layer attached to the outer cylinder can be considered stationary since there are ribs inside the outer cylinder (see Figure 4-3) to resist relative moment at the interface.

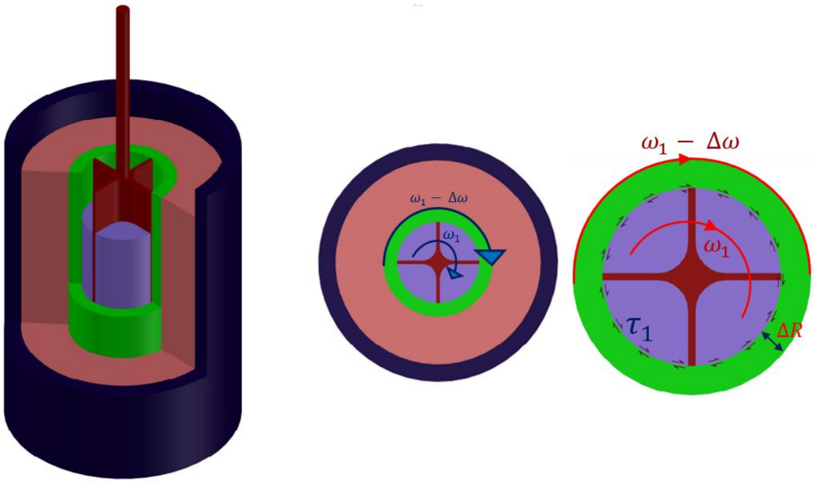

Figure 4-3: Mechanism of torque and angular velocity

However, the conversions of torque and rotation rate to the shear stress and shear rate are not simple linear relationships, because the flow condition in rheometer is not uniform. In addition, there can be situations that the whole concrete between vane and outer cylinder is not sheared. When the applied torque is insufficient to shear the whole volume between vanes and container, only a portion of concrete would be sheared. Figure 4-4 can be referred to understand on the two types of possible flow conditions in this rotational rheometer.

Inner radius shown in Figure 4-4 is referred to the radius of the vanes and outer radius to the radius of the container. As shown in Figure, only the portion between vanes and outer radius is able to flow, and depending on the applied torque (hence the shear stress), there can be a dead zone occurred near the outer radius. Therefore, in calculations, outer radius is also a variable.

Possible flow conditions in ICAR rheometer are shown in Figure 4-4.

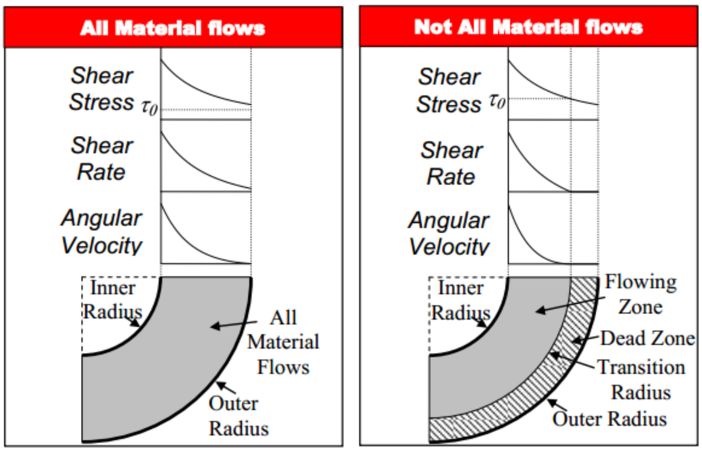

Figure 4-4: Flow condition in ICAR plus Rheometer

Equation (17) applies to the points where all the material between vanes and outer cylinder flows.

$$\Omega = \frac{\mathrm{T}}{4\pi h\mu}\left(\frac{1}{{R_1}^2} - \frac{1}{{R_2}^2}\right) - \frac{\tau_0}{\mu} ln\left(\frac{R_2}{R_1}\right) \quad (17)$$

Where Ω (rad/s) refers to the rotation speed, T (Nm) to the torque, h (m) to the height of the vanes, R_1(m) to the vane radius and R_2 (m) to the container radius. Here τ_0 and μ are referred to the dynamic yield stress (Pa) and plastic viscosity (Pa.s) respectively.

When dead flow occurs, outer radius has to be replaced with the radius from which onwards shearing is zero. Or in other words radius of the transition point which is given by Equation (18);

$$R_{2,eff} = \sqrt{\frac{\mathrm{T}}{2\pi h\tau_0}} \quad (18)$$

By substituting for effective outer radius in Equation (17), characteristic equation for the case of dead flow can be expressed as in Equation (19);

$$\Omega = \frac{\mathrm{T}}{4\pi h\mu}\left(\frac{1}{{R_1}^2} - \frac{2\pi h\tau_0}{T}\right) - \frac{\tau_0}{2\mu} ln\left(\frac{T}{2\pi h\tau_0 {R_1}^2}\right) \quad (19)$$

The calibration report and the general specifications of ICAR plus rheometer has been annexed to this report as Appendix – III.

4.2.2 Dynamic Data Logger – Kyowa Edx-100A

It was necessary to incorporate a dynamic data logger to monitor and record the pressure variation along the pipe line during concrete pumping. Kyowa dynamic data logger EDX-100A is capable of handling 32 channels simultaneously.

At the field tests, a pressure transducer and several strain gauges were applied along the concrete pumping pipe line. Edx-100A data logger has 4 input cables, each consisting of 8 NDIS female ports. Pressure transducer used also consisted of a NDIS plug (male port), hence was compatible with the data logger directly. However, it was not possible to connect the strain gauges directly, because the data logger doesn't have inbuilt bridge circuits. Figure 4-5 is a diagram from Kyowa Edx-100A manual that describes the connection of strain gauge transducer to the data logger.

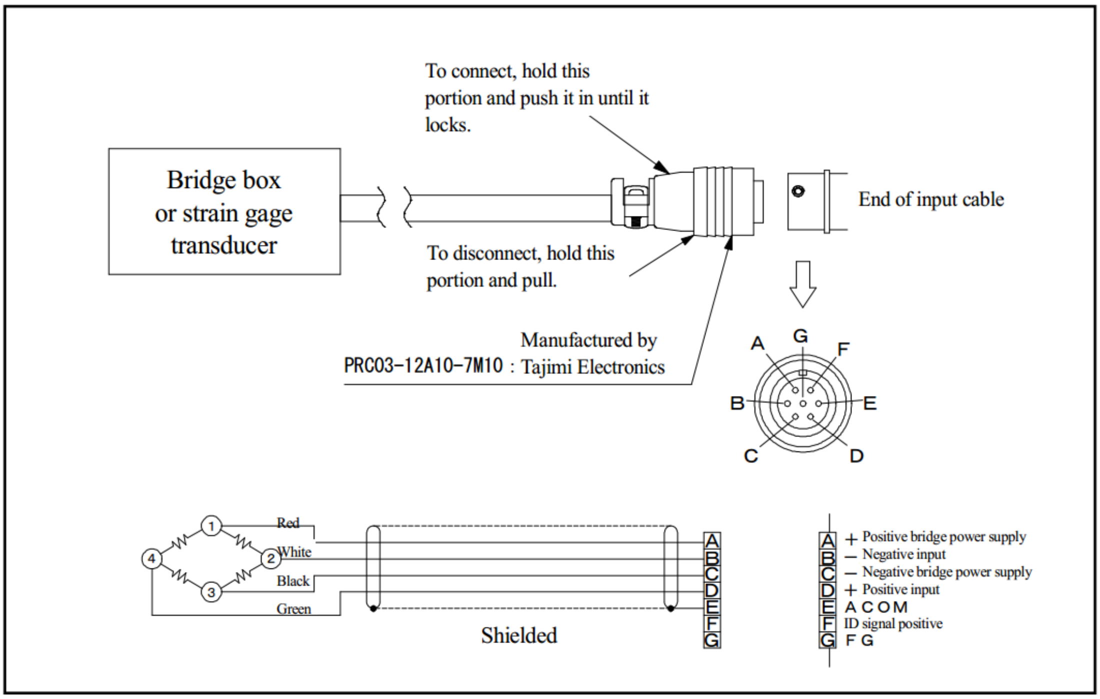

Figure 4-5: Strain gauge transducer to input to Edx-100A

4.2.3 Diaphragm type Pressure Transducer

A pressure transducer was used to monitor pipe line pressure at a section closer to the concrete pumping pump. A diaphragm type transducer was necessary, because fresh concrete is a rough slurry including large particles of coarse aggregates. Figure 4-6 shows a picture of the PWF-20MPB pressure transducer used in field experiments.

Figure 4-6: Pressure transducer attached to the pipe line

Specifications of the pressure transducer (PWF-20MPB 1-50 M Pa) can be found in Appendix – IV.

A section of the concrete pumping pipe line happened to be altered, allowing a G3/8 size groove connection (Figure 4-7) in order to fix the pressure transduce to the pipe line circuit. The connection was fabricated as per the specifications given by the TML Company.

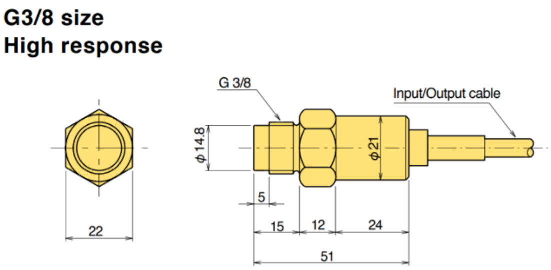

Figure 4-7: Pressure transducer connection to the pipe line

The pressure transducer is consisted of an inbuilt Wheatstone bridge circuit and the output cable has an NDIS male connection, hence this could be directly connected to the data logger input cable.

The whetstone bridge consists of 4 resisters of 352.2 Ω as shown in Figure 4-8.

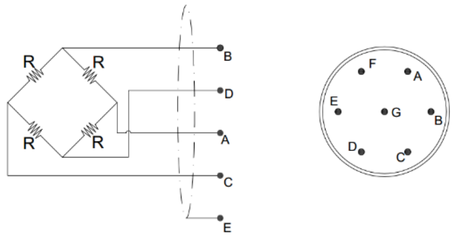

Figure 4-8: NDIS plug of the Pressure Transducer

4.2.4 3-wire Strain Gauges

It was decided to use 3 wire strain gauges to measure peripheral strains on pipe line at certain sections. FLA-5-11 type strain gauges from TML Company were used. Detail sheet of the strain gauges has been attached to the report as Appendix – V.

- Strain gauge resistance: 120 Ω
- Applicable Specimen: Metal, Glass, Ceramic
- Backing: Epoxy
- Operational Temperature: -20 ~+80^{o}C
- Strain Limit: 5% (50000×10^{-6} strain)
- Bonding adhesive: CN, P-2, EB-2

Bridge circuits and connections of the three wire strain gauges used in the experiments have been designed in accordance to the guidelines given by Kyowa technical team (Kyowa Electronic Instruments Co., n.d.). Appendix – VI on strain gauge connection bridges by Kyowa Electronic Instruments, has also been attached to the report.

The circuit details of the quarter bridge circuit for a 3 wire strain gauge is shown in Figure 4-9.

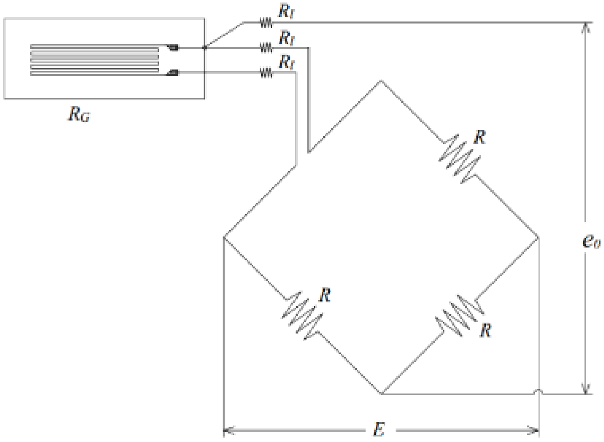

Figure 4-9: Quarter Whenston Bridge circuit for Strain Gauge

3 wire strain gauges were beneficial for the field experiment since it has a compensation mechanism for the resistance of the wire length. In that case the error due to temperature rise is also compensated in case of a 3 wire strain gauge. The compensation technique allowed in a three wire strain gauge can be explained with the simplified circuit in Figure 4-10.

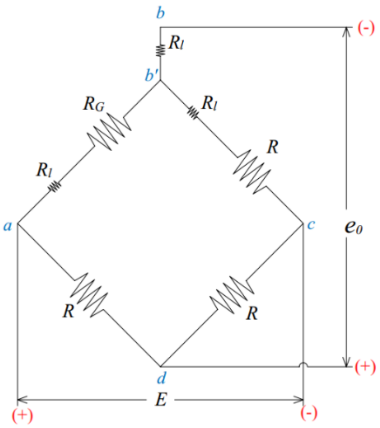

Figure 4-10: Compensation of lead wire length in 3 wire strain gauge

If the reference voltage at node ***c*** (which is the negative bridge power supply), is considered zero, reference voltage at ***a*** is E. When there is no strain in the strain gauge the resistance of the strain gauge is **R**. Hence, at equilibrium state, reference voltages at nodes $\boldsymbol{b'}$ and $\boldsymbol{d}$ are equal to **E/2**; the voltage drop between $\boldsymbol{b'}$ and $\boldsymbol{d}$ is zero. In addition voltage drop from $\boldsymbol{b'}$ to $\boldsymbol{b}$ is zero as well, because due to bridge excitation **E** there won't be a current flow in $\boldsymbol{b'}$ to $\boldsymbol{b}$ branch.

Therefore, irrespective of the resistance of the wire length and increase of lead wire resistance due to temperature at equilibrium state output voltage $\mathbf{e_0}$ remains to be zero. In that case $\mathbf{e_0}$ voltage only corresponds to the variation of strain gauge resistance due to strain.

Since the required bridge circuits are not available inside the data logger, it was necessary to fabricate bridge circuits separately and feed the signals from strain gauges through those bridge circuits to the input cables of the Edx-100A Kyowa dynamic data logger. Figure 4-11 is a picture of the strain gauge bridges fabricated for the field tests in this research project.

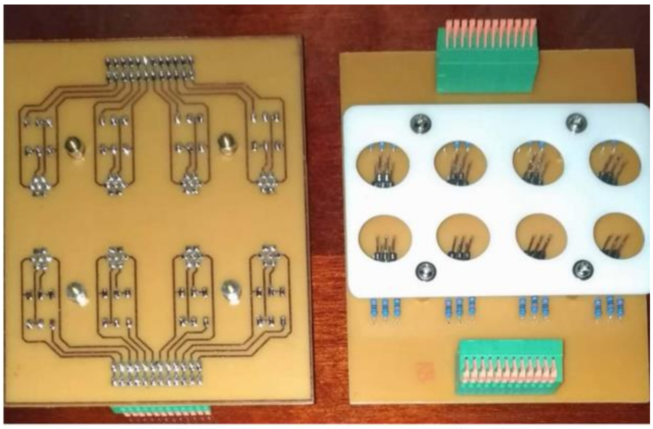

Figure 4-11: Bridge Circuits used to connect strain gauges to the data logger

4.3 Evaluation of Concrete Pumping in High-rise Building Constructions

Field experiments were implemented at two high rise building projects in parallel to the concrete pumping operations to investigate on concrete pumpability parameters under actual concrete pumping operation.

First set of field experiments were carried out at Colombo City Centre (CCC) construction project, which is located at 137, Sir James Pieris Mawatha, Colombo 02. Picture of the CCC is shown in Figure 4-12.

The tower consists of 47 stories. In this project, Grade 50 concrete had been used for the slab concretes. The mix proportion of grade 50 concrete used in the project is given in Appendix – VII. The design slump flow value is specified as 500$\pm$50 mm.

Secondly, field experiments were implemented at the Luna Tower construction site located at Union place, Colombo. Figure 4-13 shows a picture of the Lunar Tower building.

In this 44-story tower, slab concretes were done with a grade 30 concrete and the specified slump was 200$\pm$50 mm.The mix design details of the slab concrete is given in Appendix – VIII.

Figure 4-12: Colombo City Centre Tower

Figure 4-13: Construction site of 447 Luna

The following are the objectives of the investigations carried out in actual concrete pumping operations at high rise building construction sites.

(1) Investigation on variation of concrete rheology during pumping operation
(2) To study the influencing parameters for concrete rheology
(3) Investigate on the applicability of theoretical models on actual concrete pumping data
(4) To investigate the pressure drops at horizontal and vertical bends and horizontal and vertical straight pipes in actual concrete pumping operation at the site

4.3.1 Procedure

Procedure followed in the field investigation is as follows.

1. Rheology of Concrete

   Rheological properties of concrete (DYS and PV) were measured

   a. Batching plant
   b. At the site before being pumped
   c. At the pipe outlet after concrete being pumped

   Since transport of concrete and waiting time of the concrete trucks at the site may even take two to three hours it was necessary to obtain rheological measurements at the plant and just before pumping. On the other hand rheology of concrete might subjected to change due to pumping because large amount of shear stress is applied on concrete (Banfill, 2006). To understand if there's a tendency of degrading the rheological properties as being pumped and result blocking in the pipe line, rheological measurements were taken before and after concrete is being pumped. ICAR plus concrete rheometer was used to make these rheological measurements.

2. Rheology of Lubrication Layer

   A tribometer was not available to make rheological measurements of the lubrication layer directly. Hence, ICAR plus rheometer was used to evaluate lubrication layer parameters as well, by conducting a test on constituent mortar at the laboratory scale. In that case DYS and PV of lubrication layer could be derived. As found in previous studies, thickness of lubrication ayer was reasonably assumed to be 2 mm (Choi, Kim, & Kwon, 2013a) & (Kwon, Jang, Kim, & Shah, 2016).

3. Pressure applied on concrete pipe flow

   Obtaining the pressure applied by the concrete pump on the pipe flow was a challenging task at the beginning. First the applied pressure was tried to be noted from the pressure gauge attached to the pump. However, it doesn't indicate the pressure given on the concrete pipe flow, but only the pressure in the oil chambers of the pump. Applying a conversion factor was also not practical because the actual conversion factor may change due to wear of the components and the concrete mix. Hence, the only solution was to apply a pressure transducer to the pipe line and record the pressure in concrete pumping pipe line.

4. Flow rate

   Flow rate of the concrete pipe flow was taken by measuring the time to fill a container of known volume at the pipe outlet on top flow.

5. Pressure drops at bends

   ACI guidelines has proposed 15 psi pressure drop for a 90^0 bend while JSCE guidelines has proposed an equivalent horizontal length of 6m for a 90^0 bend. However, both of these guidelines have not considered horizontal and vertical bends separately. Therefore, it was decided to apply strain gauges at the bends (before and after the bend) and monitor the pressure drops.

Figure 4-14 illustrates the procedure adopted in the field investigation.

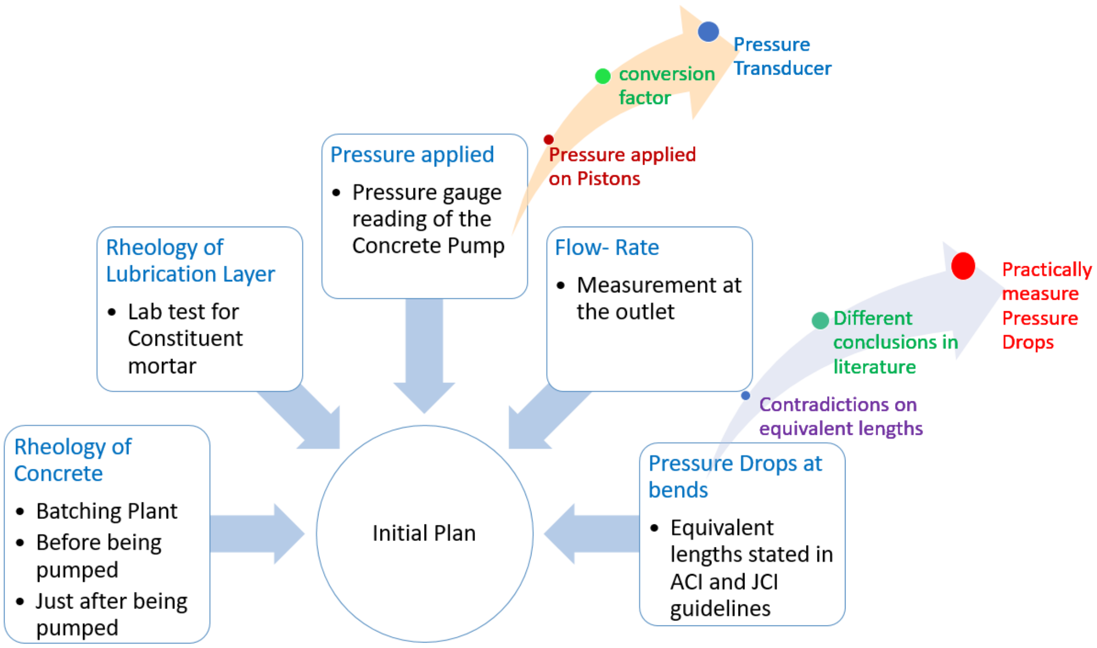

Figure 4-14: Field Experiment procedures

4.4 Laboratory Experiments

Paste phase and mortar phase of concrete were studied for the rheological properties in laboratory experiments. Several mix design parameters were changed systematically and the corresponding rheological property variations were observed. Furthermore, all the fresh concrete samples were studied for a 3 hour period to understand the thixotropic behaviour of fresh concrete. The following are the objectives of the laboratory experimental investigation.

(1) Study on rheological properties of paste and mortar phases of concrete
(2) Identify the effect of mix design parameters on rheology of paste and mortar
(3) Understand the thixotropic behaviour of concrete

4.4.1 Procedure of measurement of rheological properties

The mix design of the control sample was fixed based on the concrete mix design details of the Colombo City Centre project (see Table 4-1).

Table 4-1: Mix proportions of concrete phase control specimen

Strength Grade: Grade 50 Specified Slumpflow: 500±50 mm					
Quantities	Cement (OPC) *(kg)*	Water *(kg)*	Coarse Aggregate *(kg)*	Fine Aggregate *(kg)*	Hypercrete plus M *(ml)*
Per m^3	430	176	1000	817	4100

Table 4-2 shows the mix proportions of the control sample used for paste phase experiments.

Table 4-2: Paste phase control sample

Cement Type	**w/c ratio**	**PCE Admixture Dosage**
OPC	0.33	0.40 l/ 100 kg of Cement (ie: 0.40%)

Mix proportions of the mortar phase control sample are presented in Table 4-3.

Table 4-3: Control sample in mortar phase

Cement Type	**w/c ratio**	**PCE Admixture Dosage**	**Fine Aggregate Type**	**Fine Aggregate Concentration**
OPC	0.42	0.9 l/ 100 kg of Cement (ie: 0.90%)	Unwashed Manufactured Sand	Fine aggregates to mortar = 0.50 by volume

Rheology of paste and mortar phases were investigated against mix design parameters as presented in Table 4-4. The parameter values were selected based on common ranges of mix design parameters used for pumped concrete. A list of mix proportions used for pumped concrete in recently constructed major high-rise building projects are given in Appendix – IX.

Table 4-4: Mix design parameters studied in lab experiments

Phase	Tested Parameter	Selected parameter values
Paste Phase	Admixture (PCE) dosage	0.2%, 0.4% & 0.6%
	w/c ratio	0.33, 0.36, 0.39, 0.42 & 0.45
	Cement Type	Sanstha (PLC), Rapid Flow (OPC), Mahaweli Marine (OPC), Rapid Flow Plus (Fly Ash Blended) & Extra (Fly Ash Blended)
Mortar Phase	Admixture (PCE) dosage	0.6%, 0.7%, 0.8% & 0.9%
	w/c ratio	0.33, 0.36, 0.39, 0.42 & 0.45
	Fine Aggregate Type	0.50 Unwashed MS (Manufactured Sand) 0.50 Washed MS 0.25 Unwashed MS & 0.25 River Sand 0.50 River Sand
	Fine Aggregate concentration	0.45, 0.50 & 0.55

4.4.1.1 *Procedure followed for testing one sample*

Rheology of cement based mixtures depends on both time and shear stress applied to the sample. That is why the thixotropic behaviour of concrete and mortar cannot be neglected. And also, mixing and applying shear to the sample cause breaking of irreversible flocculation of the sample. Hence, mixing and time variable are two major concerns need to be controlled well in order to produce correct results.

Therefore, the procedure for testing of each sample was thoroughly controlled. Figure 4-15, shows the procedure followed in steps. The following tests were carried out to obtain the rheological properties of cement paste and mortar.

1. Rheometer test
2. V funnel test
3. Flow table test

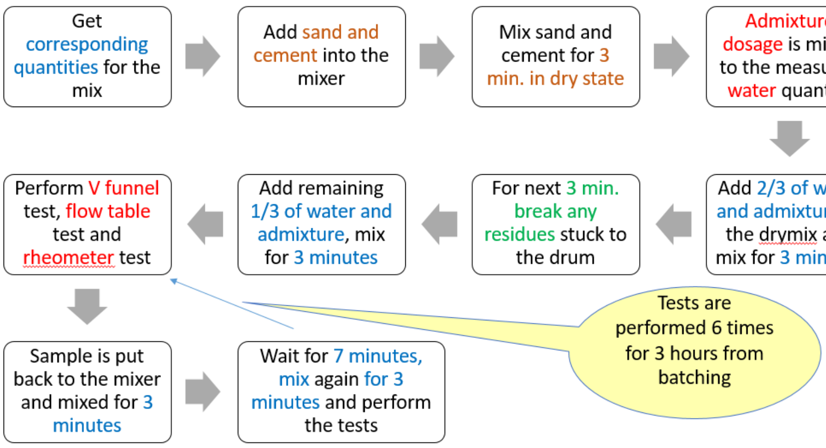

Figure 4-15: Procedure for lab tests

4.4.2 Rheometer Test

ICAR plus rheometer used to test on rheology of every chosen paste and mortar sample at the laboratory experiments, at half hour interval up-to three hours from batching the sample. Following two inbuilt tests were implemented at each time;

1. Stress Growth Test
   a. Static Yield Stress (SYS) value can be derived

Figure 4-16 shows a picture of the stress growth test application window. In this test while the vanes are rotated in the sample at a very low angular velocity (i.e.: 0.025 rps), the applied torque on the vanes are plotted against time. As the torque value have reach the maximum peak and started to decline the test has to be manually terminated. The static yield stress is calculated by the program from the maximum recorded torque value, since that was the torque capable of braking the inter particle bonds in the media and caused the dynamic flow. SYS is considerably greater than the DYS of the sample.

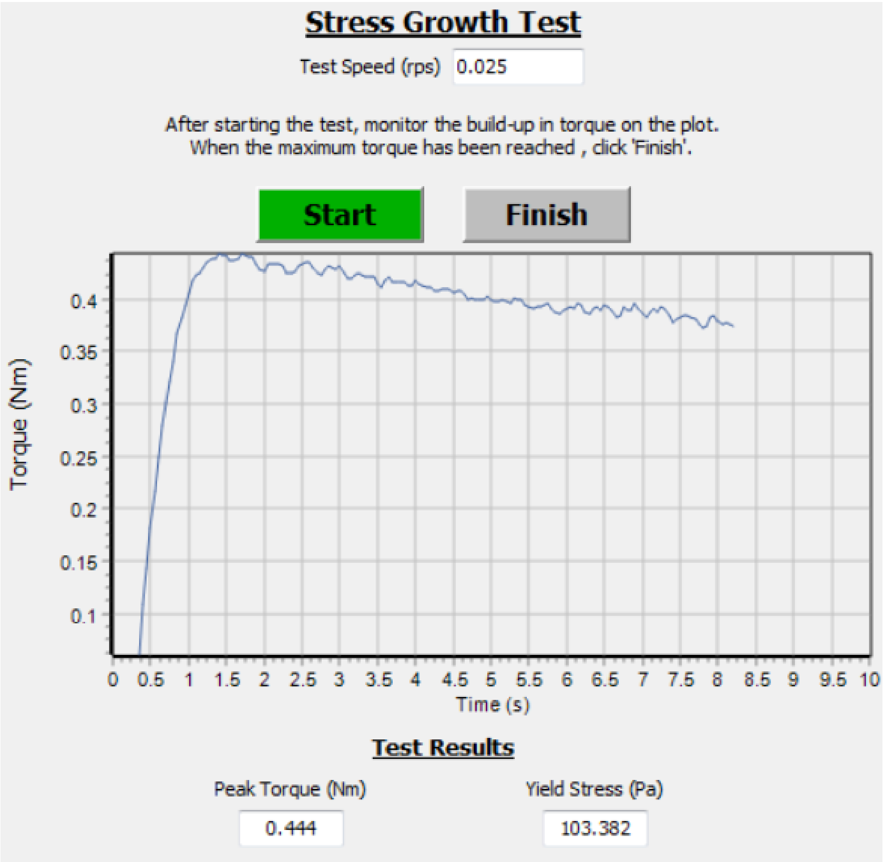

Figure 4-16: Stress Growth Test in ICAR plus rheometer

2. Flow Curve Test
    a. Dynamic Yield Stress (DYS) &
    b. Plastic Viscosity (PV) can be found

Flow curve test shown in Figure 4-17 has been designed to derive DYS and PV of the sample, which are the Bingham parameters. As the test is started, the application induce torque on the vanes so as to rotate in several constant angular velocities. The applied torque is recorded with respect to the time. The maximum rotation speed (0.5 rps) is maintained at the beginning and is reduced in several steps (7) allowing different angular velocities. 15s were spent at each angular velocity step, whereas, 20s were spent initially at the first (maximum) angular velocity to allow breakdown of inter particle bonds.

When the torque versus angular velocity relationship is known from the geometry of the instrument shear stress versus shear rate relationship can be built up. Hence, the Bingham parameters could be found. Technical information has been described in more details in the Section 4.2.1.

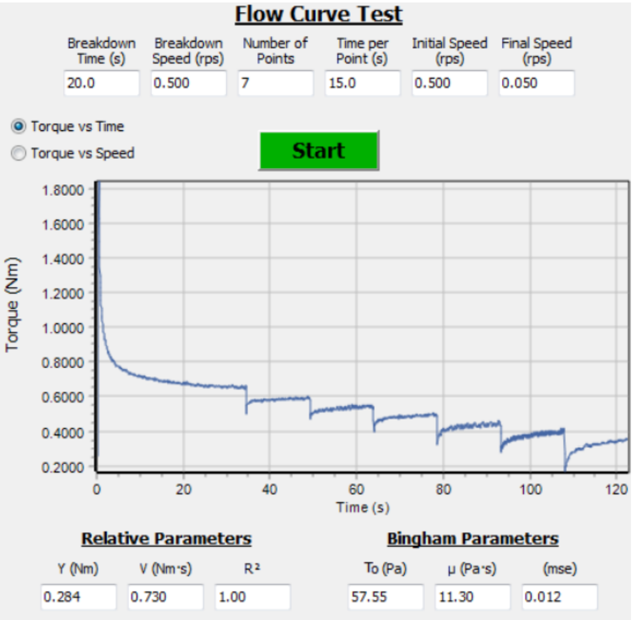

Figure 4-17: Flow Curve Test in ICAR plus rheometer

4.4.3 V funnel test

In literature, V funnel time has been correlated with plastic viscosity of concrete [Jodeh & Nassar (2009) according to (Roussel N. , 2016)]. In laboratory experiments V funnel times were measured for a set of mortar samples. Figure 4-18 shows a schematic diagram of the V funnel apparatus with dimensions. Some pictures taken at the laboratory tests have been presented in Figure 4-19.

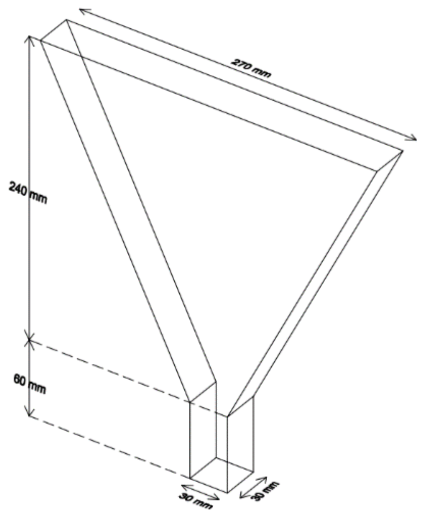

Figure 4-18: Schematic Diagram of the V funnel test apparatus

Figure 4-19: V funnel test

Test procedure:

1. V funnel is washed and let the water to be drained out from the apparatus
2. The apparatus is mounted on a firmed surface and levelled
3. Then gate at the bottom surface is closed and fresh mortar is poured into the chamber
4. Then the gate is released as the timer of the stop watch is started
5. Timer is pressed off at the first instance that a hole is created through mortar as it flows out
6. The time measured is the V funnel time T_0
7. Again the gate is closed and the chamber is filled with mortar
8. In the second turn mortar in the V funnel is let to be in the chamber for 5 minutes without disturbing
9. At the five minutes from filling the sample, the gate is released and the timer is started
10. At this time also the stop watch is stopped as an opening is created through the mortar sample
11. The time recorded at this instance is T_5 which greater than T_0

4.4.4 Flow Table Test

Flow table spread has found to be correlated to the yield stress of concrete (Mechtcherine, Nerella, & Kasten, 2014). Figure 4-20 show a diagram of the cone and hammer used for flow table test on mortar. Some pictures taken of the flow table test in the laboratory are shown in Figure 4-21.

Figure 4-20: Schematic diagram of cone and hammer - flow table test for mortar

Figure 4-21: Flow Table Test for mortar

Test Procedure:

1. The flow table, cone and the rod are washed ant let water be drained
2. The cone is placed on the table centred correctly
3. A mortar layer of half of the height is filled into the cone
4. 15 reps from tamping rod are applied on the sample
5. Secondly the cone is filled with another layer of mortar and the excess amount is cut with a straight edge of the trowel
6. 10 reps are applied on the sample
7. Then the mould is lifted up without exerting lateral forces
8. The flow table is given 25 drops in 15s by rotating the wheel in a constant speed
9. Maximum spread and the perpendicular spread to the maximum are measured with a straight ruler and recorded as the flow value.

CHAPTER 5: RESULTS AND ANALYSIS

The first two objectives of field experiments have been obtained from the field tests implemented at Colombo City Centre (CCC) site; while the other two objectives were covered during field tests at Luna Tower.

In field tests at CCC project, rheological properties of a concrete batch were studied at the batching plant and at the site. At the construction site, rheological measurements were taken before the concrete is being pumped and just after the concrete is being pumped. This procedure was followed for the field tests implemented in several days at the CCC construction site.

When field tests had been first planned to monitor the concrete pumping pressure and flow-rate in order to apply theoretical model, pumping pressure was planned to be monitored from the pressure gauge attached to the concrete pump. As described in previous chapter, reading the applied pressure on concrete, from pressure gauge on concrete pump was not successful. Incorporating a conversion factor was neither successful. Hence, the field tests happened to be conducted applying a pressure transducer directly to the concrete pumping pipe line. On the other hand, previous knowledge on pressure drops at horizontal and vertical bends, vertical straight sections and tapered sections was not clear so that practical measurements of pressure drop at those sections were necessary. For this purpose, strain gauges were used to monitor the peripheral strain and get the strains converted to the pressure, because use of several pressure transducers was not financially feasible in this research project.

5.1 Change of Fresh Concrete Properties and Influencing Factors

Properties of Fresh concrete (Bingham Parameters, Slump/ Slump flow and Temperature) were measured;

1. At the plant,
2. Before being pumped (at the site) &
3. Just after being pumped

Each time, the flow curve test (Inbuilt test in rheometer to produce DYS and PV) was performed three times in the ICAR plus rheometer and for the analysis, the average DYS and PV values of the second and third flow curve tests were considered.

Similarly, Stress growth test which measures the SYS was performed 3 times and second and third test results were averaged and used for the analysis. Table 5-1 contains average rheological measurements (SYS, DYS and PV), Slump Flow values and temperature readings obtained at CCC and Luna Tower project. Sheet number 29 to 33 of the Appendix – X contains the related observation sheets.

Table 5-1: Change of fresh concrete properties

Date	Parameter	At the Plant	Before Pumping	After Pumping
17/02/2018	Time (h)	0.2	1.5	2.5
	SYS (Pa)	442	254	193
	DYS (Pa)	221	127	157
	PV (Pa.s)	21	12	6
	Slump flow (mm,mm)	310,300		520,520
	Temperature (^{0}C)	31	31	29
20/02/2018	Time (h)	0.1	1.0	1.5
	SYS (Pa)	327	412	217
	DYS (Pa)	191	154	117
	PV (Pa.s)	16	38	7
	Slump flow (mm,mm)	470,450	420,410	600,580
	Temperature (^{0}C)	32	31	34
7/03/2018	Time (h)	0.1	2.2	2.8
	SYS (Pa)	394	306	236
	DYS (Pa)	171	170	201
	PV (Pa.s)	19	11	5
	Slump flow (mm,mm)	380,350	530,500	525,505
	Temperature (^{0}C)	33	34	31
22/03/2018	Time (h)	0.2	2.1	
	SYS (Pa)	331	188	
	DYS (Pa)	181	98	
	PV (Pa.s)	20	19	
	Slump flow (mm,mm)	520,510	480,470	
	Temperature (^{0}C)	29	31	
8/06/2018	Time (h)	0.2	1.3	2.0
	SYS (Pa)	480	456	513
	DYS (Pa)	199	209	161
	PV (Pa.s)	25	41	26
	Slump flow (mm,mm)	510,510	440,420	
	Temperature (^{0}C)	32	31	32

5.1.1 Discussion

Different behaviours of fresh concrete rheology as shown in Table 5-1 can be explained with thixotropy and the influence of agitation. The thixotropic (time depended) behaviour is caused by reversible and irreversible flocculation of cement based material and the effect of PCE (poly-carboxylic ether).

Among these factors, flocculation leads to increase of Bingham parameters resulting stiffening whereas effect of PCE and agitation or mixing influence the rheology (decrease of PV and DYS).

Strictly speaking, PCE admixture influence rheology of fresh concrete by dispersing the cement flocs in the media up to about ½ hour and the rate of improvement of properties degrade from 3 ½ to 4 hours from mixing and after that, PCE admixture is not capable of dispersing the particles. Hence, there will be a sudden increase of Bingham parameters after 3 ½ to 4 hour period.

5.1.1.1 *Change of Concrete Rheology from Batching plant to the Site*

When a concrete truck had been sent from the batching plant, generally it could take one or two hours in the queue before being pumped. Throughout this time the concrete is supplied agitation continuously at a very low rpm (i.e.: 15 to 20 rpm).

Incidents of decreasing PV and DYS from batching plant to the site (i.e.: row 1, 3 and 5 of Table 5-1), is due to the improvement of concrete rheology with time due to the effect of PCE (Poly Carboxylic Ether) and due to the shear (deformation) applied from agitation.

PV and DYS could even be increased with time irrespective of the admixture behaviour due to insufficient shear stress applied (i.e.: row 2 & 4). The driving factor for degradation of rheology (increase of PV and DYS) is the hydration process and the resulting flocculation in the media. Change of Concrete Rheology due to pumping

Significant change of values could be noted comparing the PV and DYS before and after concrete is being pumped. The average velocity of the concrete in the pipeline is between 0.75 to 0.9 m/s, which results the travel time in the pipe line is 1 ½ minutes maximum. However, due to practical situation rheological tests cannot be done at the ground level and move to top floor in few minutes to take sample for the rheological measurements at the end. To move on to the top level it would definitely take more than ½ hour. Therefore, between the rheological measurements before and after pumping there were considerable time durations (ie: ½ to 1 hour).

When comparing PV and DYS values corresponding to the before and after concrete being pumped, the PV values had been dramatically reduced while the DYS had been fluctuated slightly. Experimental observations and sensitivity analysis of the theoretical model proved that PV is the most influencing rheological property for deciding pressure loss. The reduction of PV is mainly due to the shear stress and deformation applied while it is being pumped through the pipe line. The mechanism of shear stress application on concrete has been described in detail in Chapter 3. Further agitation by the concrete truck and the effect of admixture might also have improved the PV since there were long time durations between measurements. However, comparing the values of PV, the reduction of PV of before and after being pumped, is much larger than from batching plant to site. That confirms the existence of a different factor for the decrease of PV and that should be the shear stress applied during pumping through pipe line.

5.1.1.2 *Variation of Slump Flow Value*

Slump flow measurements were taken at the batching plan, at the site before pumping concrete and just after being pumped. A considerable variation of slump flow value can be observed at the instances rheological properties had been changed significantly. For instance, slump flow value measured at the top flow (after concrete being pumped) are the highest values reported where plastic viscosities are minimum. In addition, on 20-02-2018 and 08-06-2018 PV has been increased from batching plant to the site. That can be due to insufficient agitation applied to the concrete. In those two cases Slump Flow has also decreased implying degradation of rheology.

Though slump flow seems to give some idea of the rheology of the concrete sample, yet it is insufficient to indicate DYS and PV since it is a one point test.

5.1.1.3 *Temperature of fresh concrete*

Temperature measurements show only slight fluctuations where the maximum temperature variation has been 2 ^{0}C. It should be noted that these observations were made at several night time concrete works. When the concrete was batched, normal temperature water was used and while transporting or pumping no cooling action was performed. Still throughout 1 ½ or 2 ½ hour period, the temperature of fresh concrete has not been increased as time elapsed or as being pumped through a pipeline that is longer than 100m.

The rheological behaviour of a material is directly related to the nature of inter particle bonds and inter particle bonds are reflected by the temperature of the material. However, in above concrete pumping incidents temperature of fresh concrete has not been changed significantly, but a significant variation can be observed with rheological properties. Hence, the incurred changes of rheology has not been influenced by the temperature but by the thixotropic behaviour and deformation applied on concrete due to mixing and pumping.

5.1.2 Summary

- ✓ Rheology of a PCE based concrete batch can be improved over time, as adequate agitation is provided while being transported and waiting in the queue. When sufficient agitation is not provided coagulation in the fresh concrete media would lead to significant increase of plastic viscosity.
- ✓ Rheology of the PCE based concrete has been dramatically improved as it is being transported through the pip-line. The reduction of plastic viscosity from before pumping case to after pumping case is much larger compared to the over-time reduction of plastic viscosity from batching plant to site. This implies shear stress applied on concrete and the resulting deformation cause large reduction of plastic viscosity.
- ✓ As the rheological properties improve over time, slump flow measurement has also been improved. However, slump flow value is not related to one particular parameter (i.e.: plastic viscosity or yield stress); being a single point test slump or slump flow alone cannot indicate the rheology of fresh concrete.
- ✓ Experiments had been carried out at night time concrete works. No significant variation of temperature has been observed, from batching plant to site or due to pumping. Hence, observed changes of fresh concrete rheology had not been influenced by temperature rise.

5.2 Investigation on Pressure drops at horizontal and vertical bends and horizontal and vertical straight sections

Second phase of field experiments have been implemented at Luna Tower project.

5.2.1 Instrumentation

A pressure transducer and strain gauges were used to study the pressure variation at bends and straight sections. Figure 5-1 shows a schematic diagram of the concrete pumping pipe line circuit used to pump the concrete to the 35th floor in Luna Tower building. The monitored sections of the pipe line with strain gauges (SG) and pressure transducer (PT) are also marked in Figure 5-1.

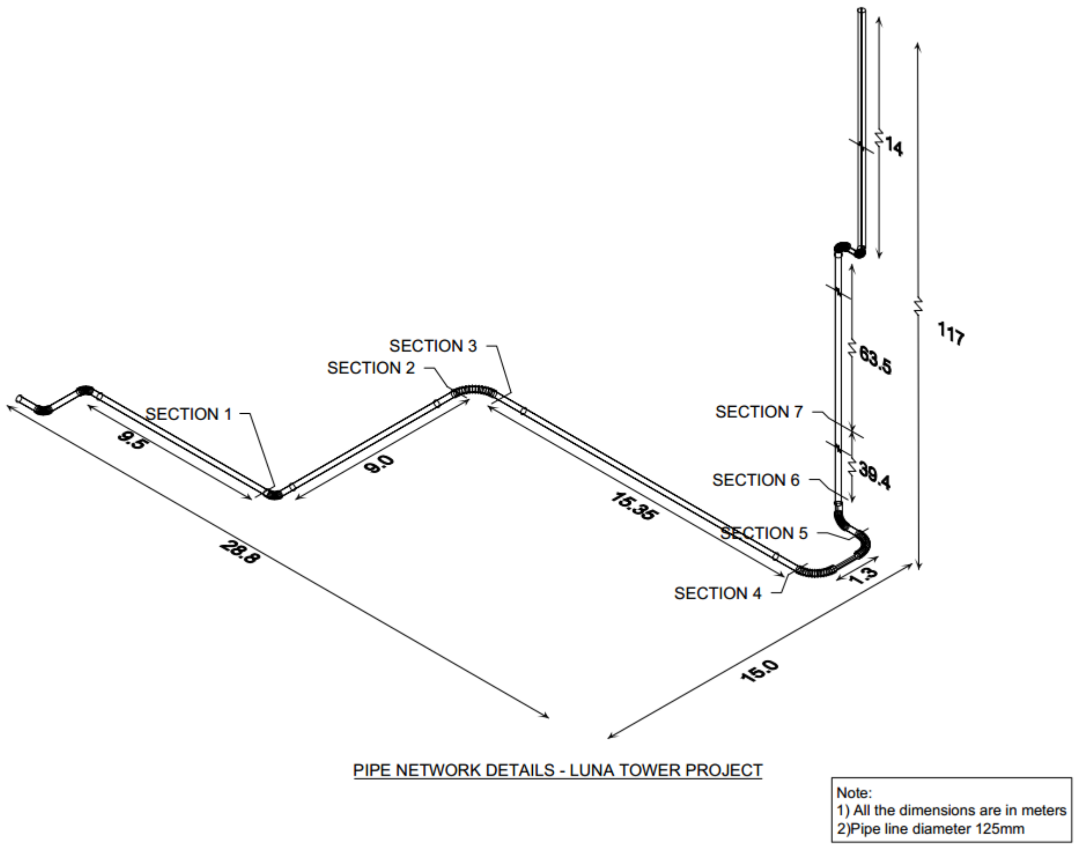

Figure 5-1: Pipe circuit details of Luna Tower construction site

Strain gauges were fixed on the pipe line surface after thoroughly cleaning the surface with a grinder and sand papers of two sizes. After removing the paint and polishing the surface, the surface was cleaned with acetone. Then the strain gauge was pasted on to the cleaned surface with additive specified by the manufactures (TML Company).

Figure 5-2, shows some photos of fixing strain gauges along the pipe line.

Figure 5-2: Photos of the strain gauges

To apply pressure transducer, it was necessary to alter a pipe section with the correct groove connection (G3/8). Figure 5-3 shows some pictures taken at the site, whiling doing modifications to the pipe line circuit.

Figure 5-3: Fixing the altered pipe section to apply pressure transducer

PWF-20 MPB pressure transducer was fixed to the pipe section as per the manufacturer's specifications. Figure 4-6 in chapter 4 that shows a photo of the pressure transducer.

Edx-100A Kyowa dynamic data logger was used to monitor and record the data from pressure transducer and strain gauges. As described in Chapter 4, pressure transducer could be connected to the input cable of the data logger directly while strain gauges were connected through bridge circuit that was fabricated especially for this field test.

The arrangement of data logger and bridge circuits is shown in Figure 5-4.

Figure 5-4: Data Logger and Bridge circuits

In addition to the pressure variation monitoring, rheological properties were measured at the site with ICAR plus rheometer.

5.2.2 Procedure

On 18th February 2019, a comprehensive experimental study was carried out at Luna Tower project. Pressure transducer and Strain gauges were installed in the pipe line used to pump concrete at the site. The data logger was available with a set of bridge circuits to monitor and record pressure and strain details. ICAR plus rheometer was used for the rheological measurements.

Rheological properties of fresh concrete samples taken from five concrete trucks were measured. From each truck a sample of concrete was taken and tested in the ICAR rheometer. For every sample, 3 flow curve tests were carried out and the average Bingham values of second and third was considered for the analysis.

Throughout the pumping time of a concrete truck, the pressure and strain variations were observed and recorded using the data logger. Data was captured at 1000 Hz sample frequency.

It was planned to measure the flow rate practically at the pipe outlet using a stop watch and a 30 l container. However, due to heavy flow, the container was damaged while taking the readings of the first concrete truck. Hence, flow rate measurement could not be continued. Nevertheless, the stroke period could be derived later on from the pressure transducer and strain gauge readings and found to be more or less the same value.

5.2.3 Analysis of field data

When the sensors were correctly connected to the data logger, the readings were balanced out using the application of the data logger, before concrete pumping was started. Then the strain gauge and pressure values were negligibly small.

Since the sample frequency was considerably large, all data was first filtered by averaging 100 values into one producing 10 Hz frequency data. 10 Hz frequency was more than enough for this data analysis because the stroke period of the signals varied from 5 to 8 minutes. Therefore 10 Hz frequency was enough to carry the waveform information with good accuracy. A sample of data acquired with data logger is shown in Figure 5-5.

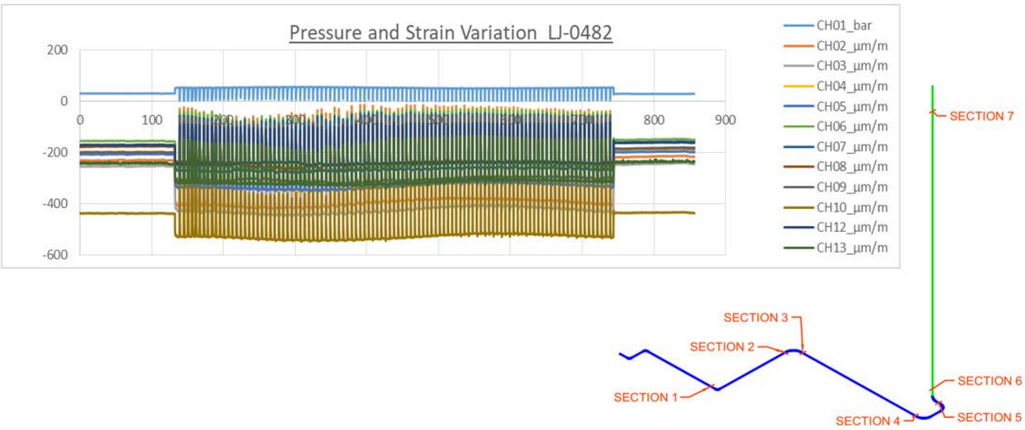

Figure 5-5: Pressure and strain variation with pumping of LJ-0482 concrete truck

If several strokes are enlarged, the graph is obtained as in Figure 5-6.

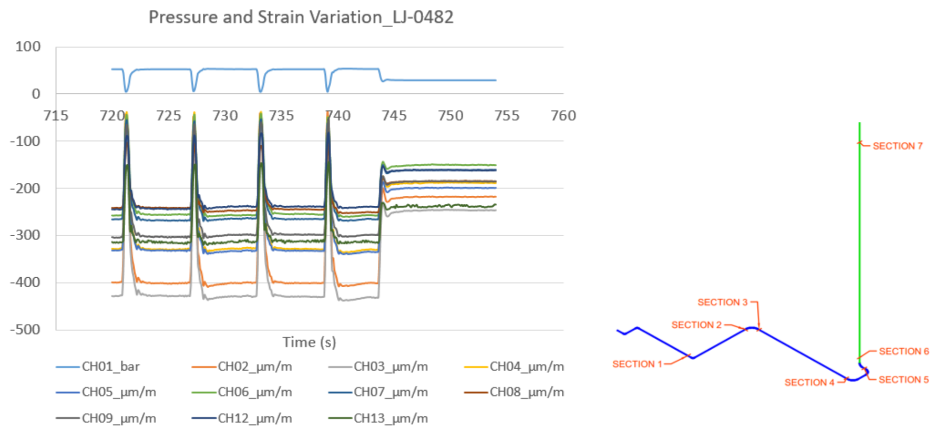

Figure 5-6: Readings corresponding to several strokes

CH01 wave is for the pressure transducer in bar while other channels showing negative values (micro) are for the strain gauges. Minus values in strain gauges are due to the swopping of $\boldsymbol{b}$ and $\boldsymbol{d}$ terminals (Refer to Figure 4-10 in chapter 4 for the bridge circuit).

Square wave form has been occurred at the dynamic part of the flow, where each square is corresponding to a piston stroke. From about 75 seconds onwards, the graphs remain almost constant. That is the static pressure head of the pipe flow. In other words, when the pipe line is filled with concrete from bottom to top, but there is no flow, pressure exerted on the pipe wall was due to the static pressure head of the concrete volume in the pipe line.

For each strain gauge, the initial strain value at no load condition is zero because the data logger was balanced before concrete pumping starts. In addition, the strain corresponding to the static pressure head and the constant pressure applied at dynamic strokes can also be derived from recorded data. On the other hand, at no load condition, pressure applied on pipe wall is also zero and the pressure applied on pipe wall at a certain location due to static pressure head can easily be calculated with Bernoulli's equation(ie: $h\rho g$).

Figure 5-7, shows the basis used in prediction of dynamic pressures from strain gauges measurements.

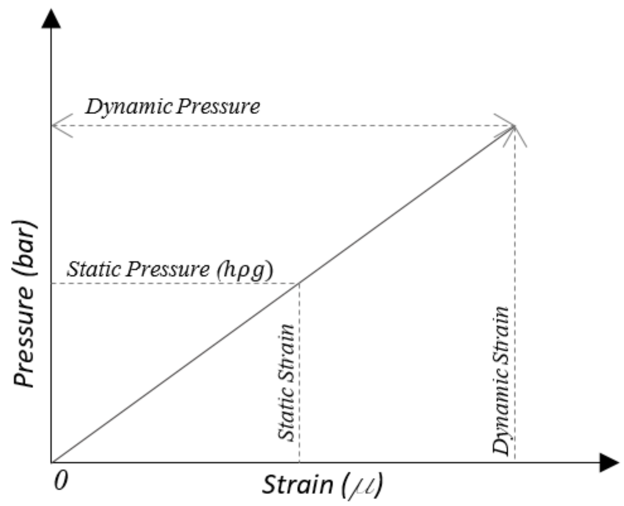

Figure 5-7: Prediction of dynamic pressure from strain gauge measurements

Here, the static strains were obtained by averaging the strain values at static condition, while the dynamic strains were produced by averaging the dynamic strains staring from 1s after the minimum point up-to 5s from the minimum. The graphical explanation for the dynamic strain and pressure consideration is given in Figure 5-8.

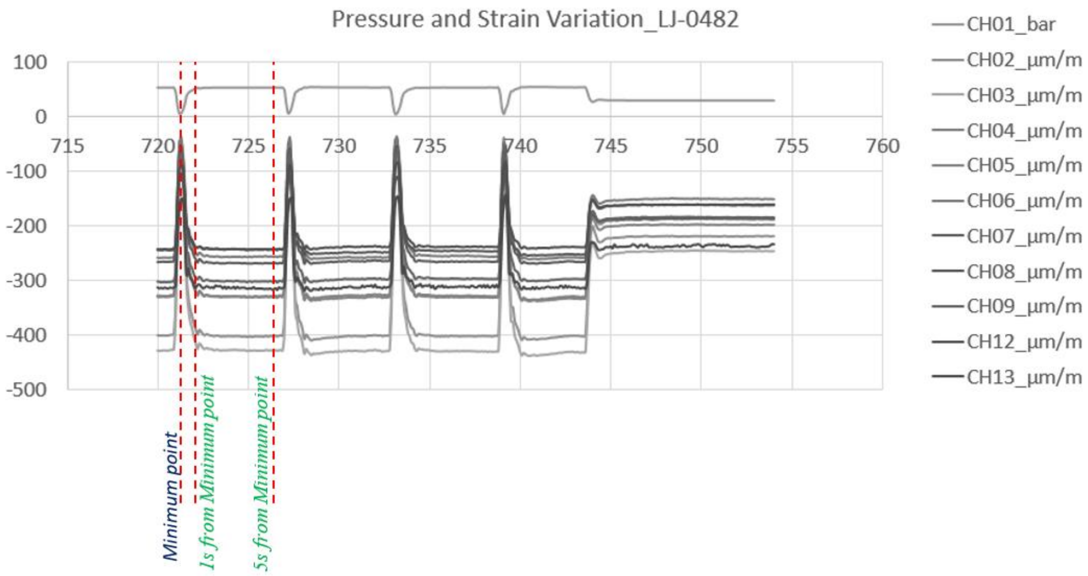

Figure 5-8: Averaging pressure and strain values in dynamic range

After calculating the dynamic pressure values corresponding to each strain gauge, dynamic pressure at selected sections were derived and given in Table 5-2. The corresponding raw data files with data at 1 k Hz and the filtered data at 10 Hz are too large to be annexed to this report. However, soft copies of those files are included in the electronic submission. Observation sheet of the measured rheological parameters can be found as sheet number 34 of Appendix – X.

Table 5-2: Average Dynamic pressure at each section

Truck No:	**Average Pressure (bar)**						
	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
ZA-8346	43.42	40.74	39.95	37.23	36.61	33.16	23.81
LL-2894	44.43	42.63	42.23	38.46	39.62	33.64	24.32
LL-5012	48.44	46.14	45.20	40.98	40.48	34.18	24.76
LL-8638	52.01	49.31	47.65	44.58	41.91	35.48	26.43
LJ-0482	50.56	48.16	46.69	42.16	41.07	35.05	25.97

When obtaining pressure values at sections, average of pressure calculated from two strain gauges attached the particular pipe section were used.

The seven selected sections of the pipe network cover;

- a location near to the pump (section 1)
- a horizontal bend of 370 mm radius (section 2 & 3)
- a horizontal length of 15.3m (section 3 & 4)
- a vertical bend of 400 mm radius (section 5 & 6)
- a vertical length of 39 m (section 6 & 7)

5.2.4 Pressure variation in Horizontal Straight pipe Section

Pressure drop in a 15.3 m long horizontal straight pipe section was obtained by strain measurements at pipe section 3 and 4. These actual pressure drops were compared against the theoretical pressure drop prediction from the theoretical model stated by Equation (14), (15) and (16) in Section 3.4;

$$Q_{sheared} = 2\pi\left[\frac{1}{2}.\left\{\frac{\Delta P.R^2}{4L\,\mu_p} - \frac{\tau_0 R}{\mu_p} + V_{LL}\right\}\left\{R^2 - {r_{plug}}^2\right\} + \frac{\tau_0}{3\mu_p}\left\{R^3 - {r_{plug}}^3\right\} - \frac{\Delta P}{16L\,\mu_p}\left\{R^4 - {r_{plug}}^4\right\}\right] \quad (14)$$

Where $r_{plug} = \frac{2L.\tau_0}{\Delta P}$ &

$$V_{LL} = \frac{1}{\eta_{LL}}.\left(\frac{\Delta P.R}{2L} - \tau_{0,LL}\right) + \frac{\tau_0}{\mu}\left(R - r_{plug}\right) - \frac{\Delta P}{4\mu_p L}\left(R^2 - \left(r_{plug}\right)^2\right)$$

$$Q_{plug} = \pi\left(r_{plug}\right)^2.\left\{\frac{\Delta P}{4L\,\mu_p}\left(R^2 - {r_{plug}}^2\right) - \frac{\tau_0}{\mu_p}\left(R - r_{plug}\right) + V_{LL}\right\} \quad (15)$$

$$Q_{Total} = Q_{sheared} + Q_{plug} \quad (16)$$

The values used for the theoretical pressure predictions are as follows;

$R = 0.0625\ m, \qquad L = 15.3\ m,$

$Q_{Total} = 0.0083\ m^3/s$ (Practically measured at the site by recording the time to fill a 30l container at the outlet.

$\tau_{0,ll} = 0\ Pa, \quad \eta_{ll} = \frac{2.5}{0.002} = 1250\ Pa.s$ (Lubrication layer properties were found, by testing a constituent mortar sample at the lab)

τ_0 & μ_p values obtained by testing concrete samples at the site.

Table 5-3 gives the actual and predicted values of the pressure drops including corresponding concrete rheological measurements. Figure 5-9 shows the pressure drop for the five concrete pumping operations that have been monitored at the field tests.

Table 5-3: Pressure Drop in 15.3 m Horizontal Straight Pipe section

Truck No:	Yield Stress (Pa)	Plastic Viscosity (Pa.s)	Theoretical Pressure drop in 15.3m pipe (bar)	Actual Pressure drop in Horizontal pipe (bar)
ZA-8346	292.1	13.84	2.80	2.72
LL-2894	251.2	24.775	3.02	3.77
LL-5012	195.5	37.59	3.16	4.22
LL-8638	202.8	51.48	3.36	3.07
LJ-0482	179.8	54.76	3.36	4.53

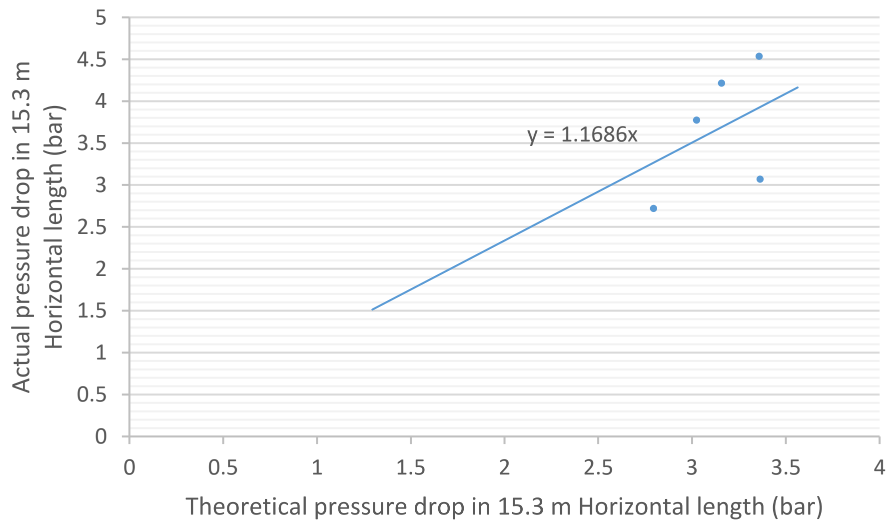

Figure 5-9: Pressure drop in horizontal length versus theoretical values

Actual pressure drop of horizontal section was compared against the plastic viscosity and it is shown in Figure 5-10.

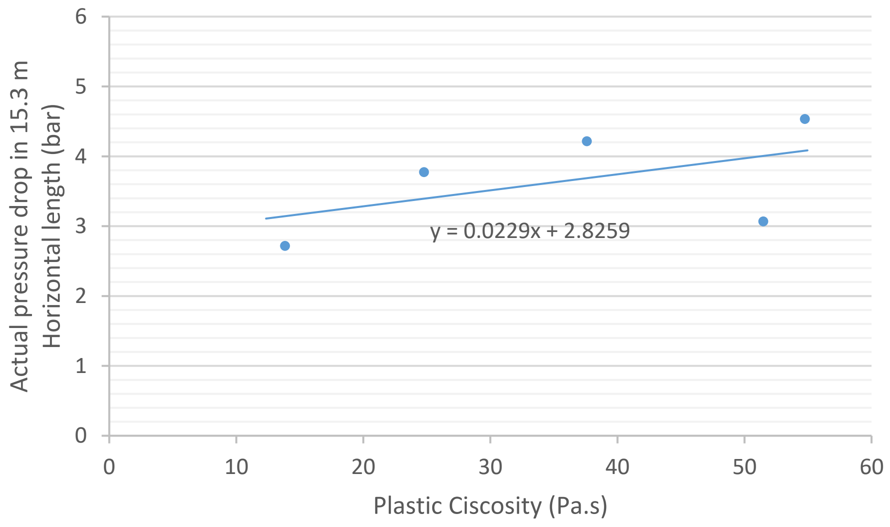

Figure 5-10: Pressure drop in horizontal section w.r.t. Plastic Viscosity

5.2.4.1 *Discussion*

Actual pressure drops occurred in the horizontal straight length are more or less in the range of theoretically predicted values. However, the variation of actual pressure drop from the predicted values is up to 25%.

On the other hand, pressure drop of horizontal straight section has been increased with increase of plastic viscosity of concrete as well.

The differences of actual and theoretically predicted values are due to the influencing factors that had not been considered for the theoretical derivations, such as;

- Relatively high coarse aggregate concentration and solid to solid friction between coarse aggregate particles and steel pipe wall due to imperfection of practical flow profile
- Possible asymmetric velocity profile in concrete pipe flow in horizontal pipes, influenced by gravity
- Effect of applied shear and mixing due to pipe flow, on the rheological properties of concrete
- Possible, Shear thinning or Shear thickening effect based on properties of cementitious material and PCE admixture

Existence and uniformity of lubrication layer is the basis of theoretical derivations on concrete pipe flow. However, when the volume fraction of paste media is inconsistent and when the cohesiveness of paste and mortar phases is comparatively low, concrete mix would not be consistent or uniform. This causes bleeding and segregation of concrete when it is being pumped; the lubrication layer would not be uniform either hence, solid – solid interactions and fiction cannot be neglected as assumed in idealised fresh concrete theory.

On the other hand, in theoretical models on concrete pipe flow, gravitational influence on flow profile has been completely neglected. As shown in Figure 5-11, particle concentration should be considerably larger toward the bottom layer resulting asymmetric flow profile.

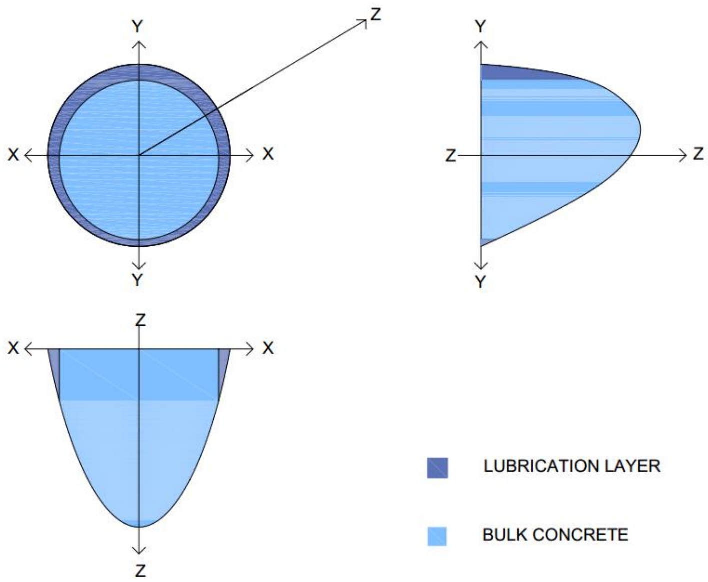

Figure 5-11: Asymmetric flow profile due to gravity

When concrete is being pumped, a significant stress is applied on material. Hence, the applied shear and mixing on concrete during its pipe flow influence the rheological properties. In fact, applied stresses cause breakage of irreversible flocks formed in fresh concrete and influence the flow properties.

In addition, possible shear thinning or shear thickening behaviours should be considered carefully, because the rheological properties are evaluated applying very low shear rates than actual shear rates experienced by concrete during concrete pumping. Hence, the Bingham values of fresh concrete during pipe flow can be far more different than the measured values in rheometer. However, for comparison purpose, evaluating rheology with a rheometer would be fine.

Effect of shear thinning or shear thickening can be explained more with flow curve properties. In theoretical models, Bingham's flow curve model was considered for practical reasons. However, different flow curve models have been proposed for fresh concrete as explained in the literature review. Moreover, Bingham model on fresh concrete had been found to be correct only for a small range of shear rates (Roussel N. , 2006).

Trends of Bingham model has been compared against the shear thinning and shear thickening behaviours as shown in Figure 5-12.

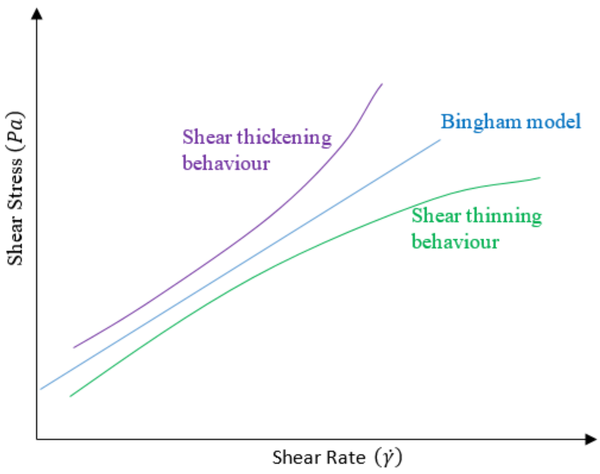

Figure 5-12: Possible flow curve patterns for fresh concrete

5.2.5 Pressure drop at Horizontal Bend

Pressure drop in a horizontal bend was evaluated using the strain measurements at section 3 and 4. The bend had a radius of 1050 mm. Corresponding pressure drop values of five concrete pumping cases at the horizontal bend are given in Table 5-4.

Table 5-4 also includes the relevant theoretical pressure gradients (pressure drop per unit length) calculated based on Equation (14), (15) and (16) in Chapter 3.

Table 5-4: Pressure Drop in Horizontal 90^0 Bend of 370 mm radius

Truck No:	Yield Stress (Pa)	Plastic Viscosity (Pa.s)	Pressure drop in 90^0 bend		Actual Pressure drop Horizontal Bend (bar)
			JSCE guidelines	ACI guidelines	
ZA-8346	292.1	13.84	1.1	1.0	0.79
LL-2894	251.2	24.775	1.5	1.0	0.4
LL-5012	195.5	37.59	1.7	1.0	0.94
LL-8638	202.8	51.48	1.2	1.0	1.66
LJ-0482	179.8	54.76	1.8	1.0	1.47

Figure 5-13 presents the pressure drop values corresponding to the horizontal bend with respect to the theoretical pressure gradient in a horizontal straight section.

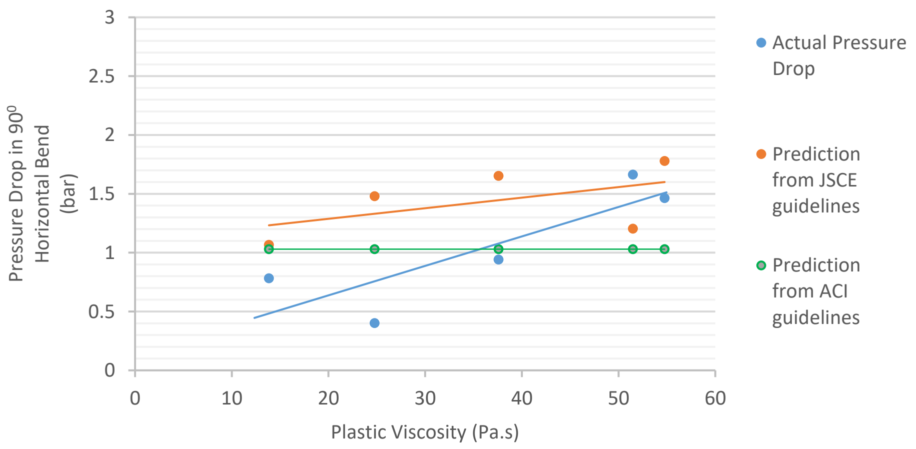

Figure 5-13: Pressure drop in 90^0 Horizontal bend w.r.t. guidelines predictions

5.2.5.1 *Discussion*

Pressure drops experienced at 90^0 horizontal bend with 1050 mm radius were in the range of 0.5 to 1.7 bars. JSCE guidelines (Tamon & Hiroshi, 2010) has stated the pressure drop in a 90^0 bend in concrete pumping pipe line as equivalent to the pressure drop in a horizontal straight length of 6m. Since the actual pressure drop over 15.3m horizontal run has been monitored, equivalent drops for a 6m length were derived. ACI guidelines (Akers, et al., 1996) recommends 15 psi (1.03 bar) pressure drop for every 90^0 bend. This pressure drop from bends is a considerably large pressure compared to the total pressure in the entire pipe line. In fact there were six 90^0 horizontal bends and three 90^0 vertical bends in the fixed pipe line circuit. Hence, the pressure drop due to horizontal bends were in the range of 10 bars where the total pressure drop in the entire line was between 40 to 50 bars. Hence, pressure drops at horizontal bends cannot be neglected.

Furthermore, Johansson (Johansson, Tuutti, & Petersons, 1976) has experimentally derived the pressure drop of a 90^0 horizontal bend to be 1 kgf/cm^2 (~0.98 bar). Therefore, the pressure drop for 90^0 bend in ACI guidelines is almost the same as this result. Pressure drop values measured in this research experiments prove that a 1 bar pressure drop in a horizontal 90^0 bend would be a reasonable estimation.

However, the actual pressure drop in the bend has been increased with increase of plastic viscosity of the concrete, which has not been addressed in ACI guidelines. In that case equivalent length concept in JSCE guidelines might be more suitable for the prediction of pressure drop in a horizontal bend.

5.2.6 Pumping pressure drop in Vertical pipe Length

Pressure drop in a vertical pipe length was obtained by measuring circumferential pipe strain at Section 6 and 7 which are at a distance of 39.0 m. Actual pressure drop of the vertical pipe length with Bingham parameters are given in Table 5-5.

Table 5-5: Pressure Drop in 39 m long Vertical Straight Pipe

Truck No:	Yield Stress (Pa)	Plastic Viscosity (Pa.s)	Actual Pressure drop Vertical Length (bar)
ZA-8346	292.1	13.84	9.35
LL-2894	251.2	24.78	9.32
LL-5012	195.5	37.59	9.42
LL-8638	202.8	51.48	9.05
LJ-0482	179.8	54.76	9.08

Figure 5-14, shows the pressure drops corresponding to the vertical straight length against plastic viscosity.

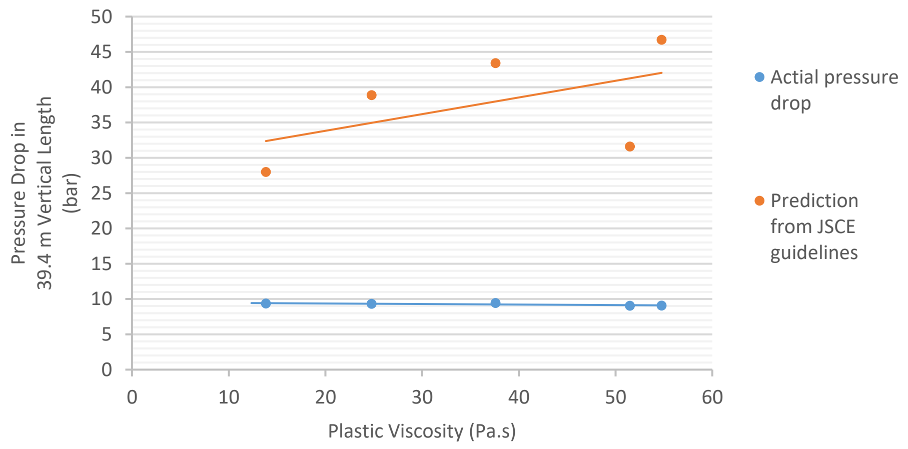

Figure 5-14: Pressure drop in Vertical length

5.2.6.1 *Discussion*

As shown in Table 5-5, pressure drop obtained for the 39 m long vertical pipe length has only slight variations for significant variation of plastic viscosity and yield stress. The pressure drop is in the range 9 to 9.5 bars irrespective of plastic viscosity and yield stress.

General belief on vertical pipe flow of concrete was that it consists of the pressure needed to overcome the pipe wall friction and the pressure needed to overcome the potential height difference [Lessard et al., 1996 & Chapdelaine, 2007 as cited in (Roussel N. , 2016)]. However, from the field test results this belief has been contradicted.

Pressure needed to overcome the potential height difference is equal to $h\rho g$; where h is the height difference, ρ is the density and g is the gravitational acceleration.

$$h\rho g = 39.0 \times 2400 \times 9.81\ Pa$$

$$= 9.18\ k\ Pa$$

Therefore, the pressure drop in a vertical straight pipe line is only due to the potential height difference. Pipe wall friction in vertical pipe flow has not been an influencing factor for the pressure gradient.

5.2.7 Radial and Line pressure in concrete pumping pipe-line

Pressure transducer and the strain gauges were used to monitor the pressure in concrete pumping pipe line and the calculations were done assuming radial pressure in the pipe line is equal to the line pressure. Almost all of the research studies in the stream of concrete pumpability has been based on this assumption, because pressure transducers and strain gauges had been used to monitor the line pressure and measured radial pressure values have been considered equal to the corresponding line pressure values (Kaplan, Lerrard, & Sedran, 2005); (Feys, Khayat, & Khatib, 2016) & (Choi, Kim, & Kwon, 2013a).

In the experimental investigations at the construction site, pressure drop in the considered 39m long vertical length remained same during static and dynamic time intervals for all the five cases when the total pressure changed. If the pressure applied on strain gauges (in the radial direction) is a factor of line pressure difference in the vertical section would change as the total pressure changes. This proves that the assumption of radial pressure is equal to the line pressure at concrete pumping pipeline is a realistic assumption.

5.2.8 Pumping pressure drop in Vertical Bend

Pressure variation at the vertical bend located between section 5 and 6 was obtained by using the strain gauges attached to those sections. This is the bend where horizontal flow is diverted to the vertical direction. It is a 400 mm radius bend. Measured pressure drops in the vertical bend are given in Table 5-6 with corresponding rheological properties and pressure prediction for a 90^0 bend w.r.t. JSCE and ACI guidelines.

Table 5-6: Pressure Drop in 90^0 Vertical Bend of 400 mm radius

Truck No:	Yield Stress (Pa)	Plastic Viscosity (Pa.s)	Pressure drop in 90^0 bend		Actual Pressure drop in Vertical Bend (bar)
			JSCE guidelines	JSCE guidelines	
ZA-8346	292.1	13.84	1.1	1.1	3.45
LL-2894	251.2	24.775	1.5	1.5	5.98
LL-5012	195.5	37.59	1.7	1.7	6.3
LL-8638	202.8	51.48	1.2	1.2	6.43
LJ-0482	179.8	54.76	1.8	1.8	6.02

Comparison of pressure drop in 400 mm radius vertical bend with respect to the predictions based on JSCE and ACI guidelines is shown in Figure 5-15.

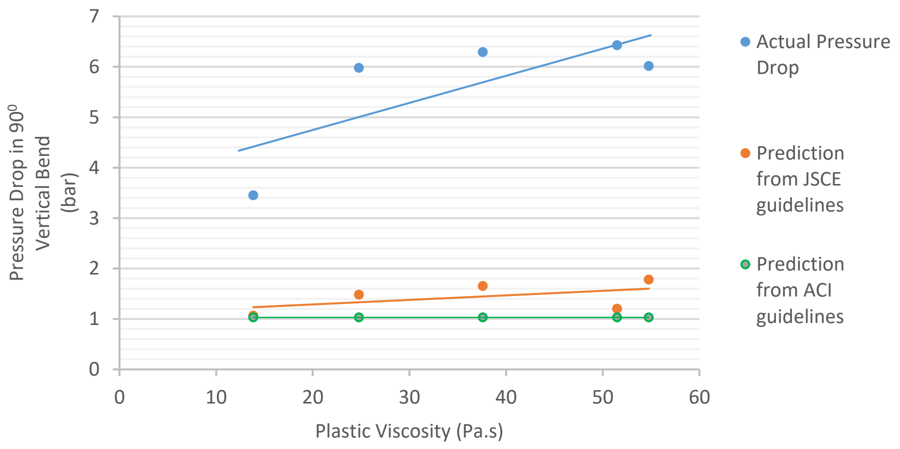

Figure 5-15: Pressure drop in Vertical 90^0 bend w.r.t. guideline predictions

5.2.8.1 *Discussion*

Even though, JSCE (Tamon & Hiroshi, 2010) and ACI (Akers, et al., 1996) guidelines have recommended values for pressure drops at 90^0 bends, neither of them have not addressed horizontal and vertical bends separately. On the other hand, referring to Figure 5-13, pressure drop in horizontal 90^0 bend was roughly 1 bar while pressure drop in vertical 90^0 bend was roughly 6 bars.

Since the horizontal flow is completely diverted to the vertical flow at this point, the applied pressure loss has been quite high. And it should also be considered that the velocity profiles before (at the horizontal flow) and after (vertical flow) the bend are completely different.

When the data corresponding to the horizontal straight flow was analysed, it was confirmed that the sheared plus plug flow was occurred. On the other hand, pressure drop corresponding to the vertical straight section was only due to the potential height difference, so that considerable frictional forces could not have been induced on pipe wall. This can only happen, when the properties of the lubrication layer are almost similar to water and it behaves as a simple Newtonian liquid and no shearing of concrete occurs during flow, which means it should be a plug flow.

Hence, at the vertical bend, the flow profile is changed from sheared plus plug flow to plug flow condition, and a large pressure drop is occurred at the bend.

5.2.9 Summary of the finding of the concrete pumping field test

- ✓ Pressure drop in horizontal straight length can be reasonably predicted with the model of sheared plus plug flow of concrete with a 20% margin.
- ✓ Pressure drop in a 90^0 horizontal bend was 0.5 to 1.7 bar, which roughly equals to the predictions by JSCE and ACI guideline recommendations.
- ✓ Pressure drop for a vertical straight length in a concrete pipe flow is equal to the pressure needed to overcome the potential height difference.
- ✓ Pressure drop in a 90^0 vertical bent was around 6 bars whereas, which is several times larger than a horizontal bend.
- ✓ Total pressure needed to be applied on concrete pipe flow in a 125mm diameter pipe circuit can be estimated based on rheological properties of concrete and mortar and pipe network details with a 20% margin.
- ✓ In fresh concrete pipe flow, radial pressure is equal to the line pressure of concrete.

  Irrespective of total applied pressure for the whole concrete pumping pipe line, the pressure difference corresponding to the 39 m long vertical section remained same at the static and dynamic time intervals. Hence, the radial and line pressures of concrete pumping pipe line are equal.

5.3 Influence of Mix-Design Parameters on rheological properties of cement paste and mortar phases of concrete

Details of the lab experiments have been described in section 4.4 of this report. Table 1 in the same section contains the list of mix design parameters tested in paste and mortar phases of concrete. Appendix – X contains the observation sheets of the laboratory experiments as sheet number 1 to 29.

5.3.1 Effect of PCE Dosage

PCE dosage of the constitute paste phase of selected mix design is 0.9%. PCE dosage is specified with respect to weight of cement which means theoretically PCE admixture combine with cement particles only. However, in concrete phase 0.9% dosage resulted a consistent and cohesive mix, where the behaviour of 0.9% dosage in paste phase was completely different. Bleeding and segregation were severe in paste phase sample with 0.9% PCE dosage. In mortar phase, 0.9% dosage was almost the upper bound for a consistent slurry. In that case, bleeding had been observed just after the mortar was mixed in the concrete mixer and until the sample was tested in rheometer for two cycles (1 hour). When the sample was tested in the third round, mortar mix was a consistent and cohesive slurry.

With above experience, compatible PCE dosages had been selected to study the rheology of paste and mortar phases of concrete against PCE admixture dosage.

Three samples of paste phase were tested with 0.2%, 0.4% and 0.6% PCE dosage. The samples were tested for 3 hours at ½ hour time interval. At each round, three rheometer tests had been conducted and the average Bingham values of second and third tests had been considered in the analysis. At 0.6% dosage in paste phase only the first round (at 1 ½ hours) produced realistic measurements; later, the paste sample had started to bleed and segregate. When the sample was filled into the rheometer cylinder and flow curve test was implemented the sample had been segregated; bleeding water had come to the top while cement particles moved to the bottom. Hence, the properties of the bleeding water had been measured as the paste sample was tested in the rheometer. Since the viscosity of the tested media was too low; rheometer software malfunctioned and produced very large viscosities.

Figure 5-16 and Figure 5-17, have compared the Dynamic Yield Stress (DYS) and Plastic Viscosity (PV) of the three paste phase samples respectively.

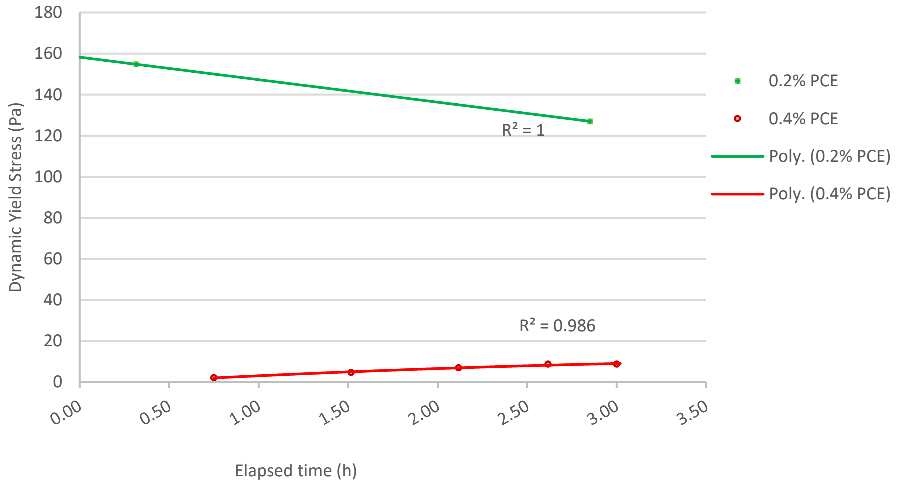

Figure 5-16: DYS over PCE dosage - Paste phase

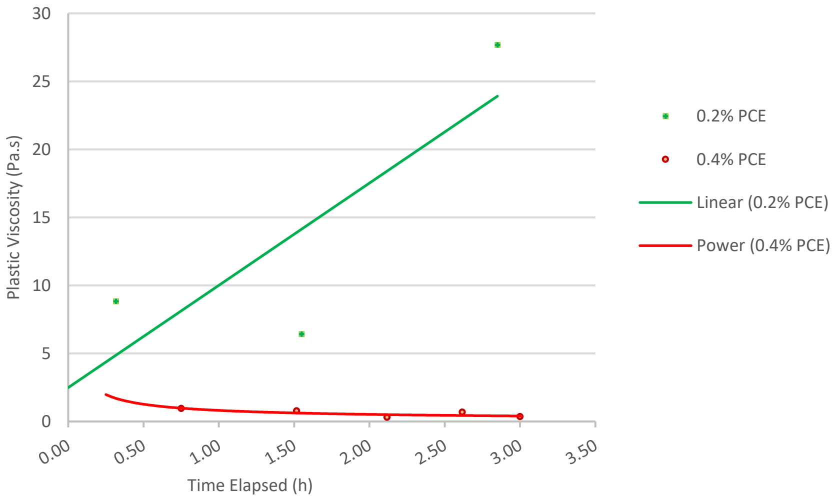

Figure 5-17: PV over PCE dosage - Paste phase

Rheological properties w.r.t. PCE dosage has been measured and analysed in mortar phase as well. Figure 5-18 and Figure 5-19 are the resulted DYS and PV variation for mortar samples at 0.6%, 0.7%, 0.8% and 0.9% PCE dosage.

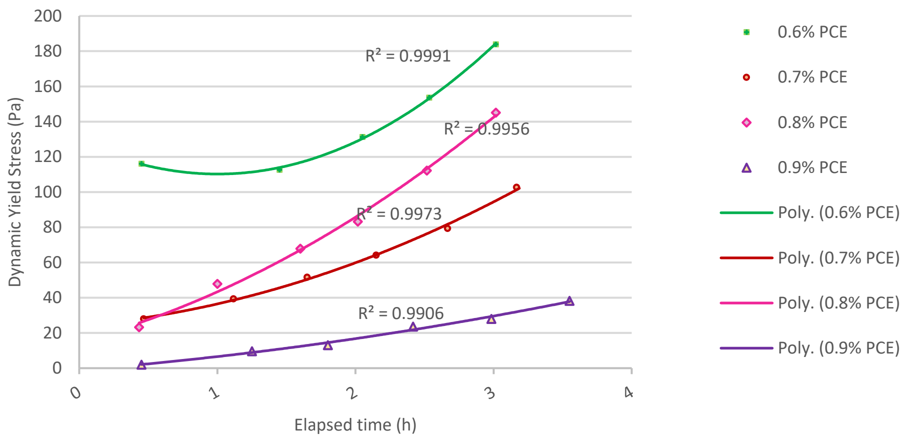

Figure 5-18: DYS over PCE dosage - Mortar phase

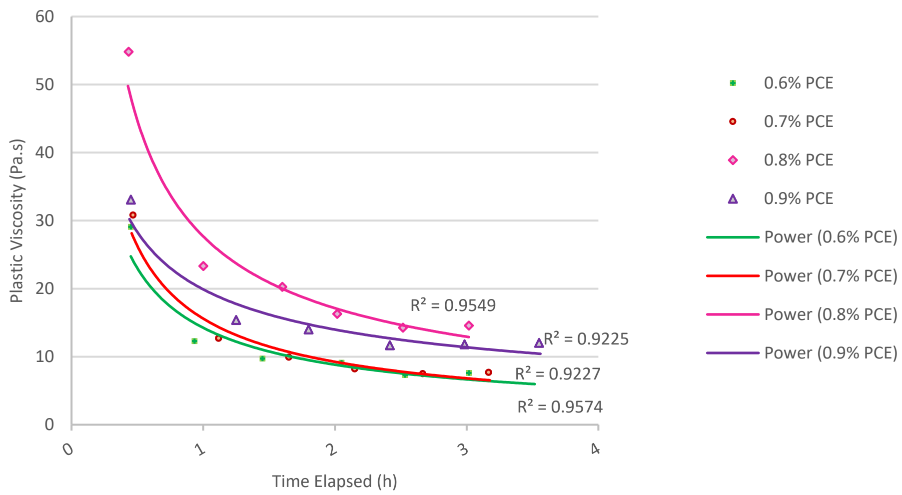

Figure 5-19: PV over PCE dosage - Mortar phase

According to Choi (Choi, Kim, & Kwon, 2013a), the rheological properties of lubrication layer of pumped concrete can be considered as similar to that of the constituent mortar. Hence, above DYS and PV of mortar samples had been considered as the corresponding lubrication layer properties and the theoretical model by Kaplan (Equation (13)) was used to predict flow rates at 28.5 k Pa/m pressure gradient in a horizontal pipe section. Rheological properties of concrete were adopted from field tests.

$$\Delta P = \frac{2L}{R}\left(\frac{\frac{Q}{3600\pi . R^2} - \frac{R}{4\mu_p}\tau_{0,LL} + \frac{R}{3\mu_p}\tau_0}{1 + \frac{R}{4\mu_p}\eta_{LL}}\eta_{LL} + \tau_{0,LL}\right) \tag{13}$$

The values of the parameters can be listed as;

$R = 0.0625\ m;$

$\Delta P = 25.5\ k\ Pa;$ $L = 1\ m;$ (Based on pumping pressure applied at actual concrete pumping)

$\tau_0 = 124\ Pa;\ \mu_P = 22\ Pa.s$ (Average rheological properties measured at the CCC site)

$e = 0.002\ mm$ (Reasonably assumed based on literature (Choi, Roussel, Kim, & Kim, 2013b) & (Kwon, Jang, Kim, & Shah, 2016).

$\tau_{0,ll}$ & $\mu_{p,ll}$ were substituted with rheological properties measured in lab experiments and calculated the corresponding flow-rates for each sample over 3 hour duration

The resulted variation of flow-rate predictions are shown in Figure 5-20.

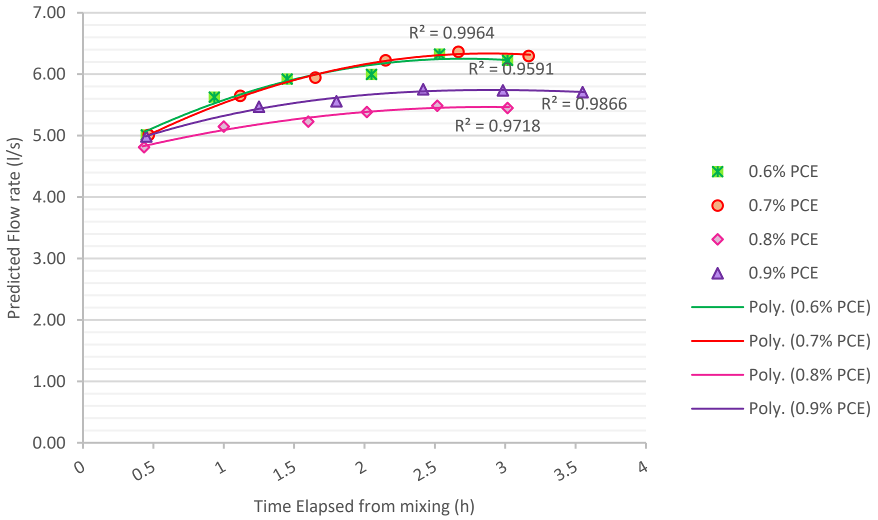

Figure 5-20: Flow-rate prediction over PCE dosage - Mortar phase

5.3.1.1 *Discussion*

Rheological properties at 0.4% dosage are much better compared to 0.2% dosage. At 0.6% dosage, bleeding and segregation issues have caused unrealistic parameter values due to instrument limitations. Anyway, paste sample at 0.6% was not a consistent and cohesive slurry. This behaviour explains that the PCE or admixture dosage can enhance the rheological properties and flow characteristics, but only up to a limited dosage of admixture may be used. Because there is an upper bound for the admixture dosage, beyond which a uniform slurry cannot be maintained. Hence, choosing the correct admixture dosage is very critical; it should be carefully selected and maintained at the batching plant.

DYS in mortar phase has been decreased with increase of PCE dosage whereas PV has been increased with increase of PCE dosage. The behaviour of PV values with respect to PCE dosage implies decline of rheology with increase of PCE dosage. Moreover, the flow-rate predictions also have reported same behaviour that the highest flow-rates had been obtained with lower PCE dosages that were used for samples. In addition, bleeding could be observed at 0.9% dosage, however from the third round of testing onwards the slurry was consistent and cohesive enough, so that no bleeding or segregation were observed.

Generally, it is expected to have improved rheological properties with increase of admixture dosage and the optimum dosage is to be chosen considering the additional cost incurred and the improvement of concrete rheology. However, as per the obtained test results, increase of PCE dosage does not always improve the rheology. Hence, PCE dosage should be carefully evaluated in order to get the optimum dosage. Otherwise, increase of PCE dosage can incur additional cost and degradation of rheological properties at the same time.

5.3.2 W/C Ratio

Five w/c ratios were selected to test the effect of w/c ratio on concrete rheology at both paste and mortar phases. Since the admixture dosages were selected for paste and mortar phases separately from previous set of lab experiments, w/c ratios were straight away selected considering the practical ranges of mix design parameters for pumpable concrete. The selected w/c ratios were 0.33, 0.36, 0.39, 0.42 and 0.45.

Figure 5-21 and 5-22 shows the DYS and PV measurements of the samples tested at paste phase.

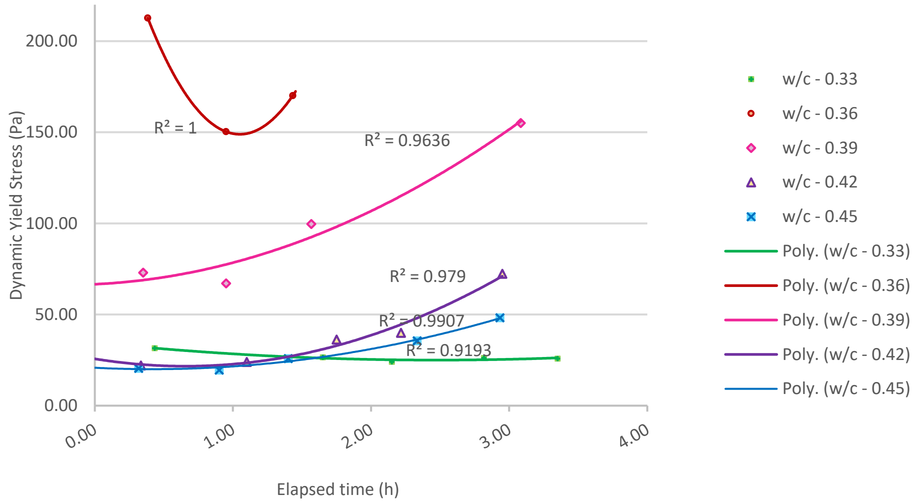

Figure 5-21: DYS over w/c ratio - Paste phase

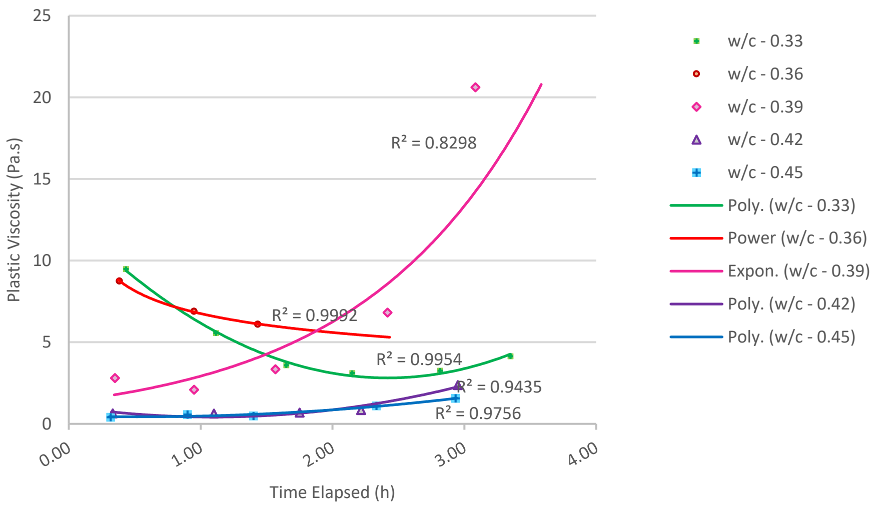

Figure 5-22: PV over w/c ratio - Paste phase

Figure 5-23 and 5-24 contains the results of DYS and PV over w/c ratio for the samples tested in mortar phase.

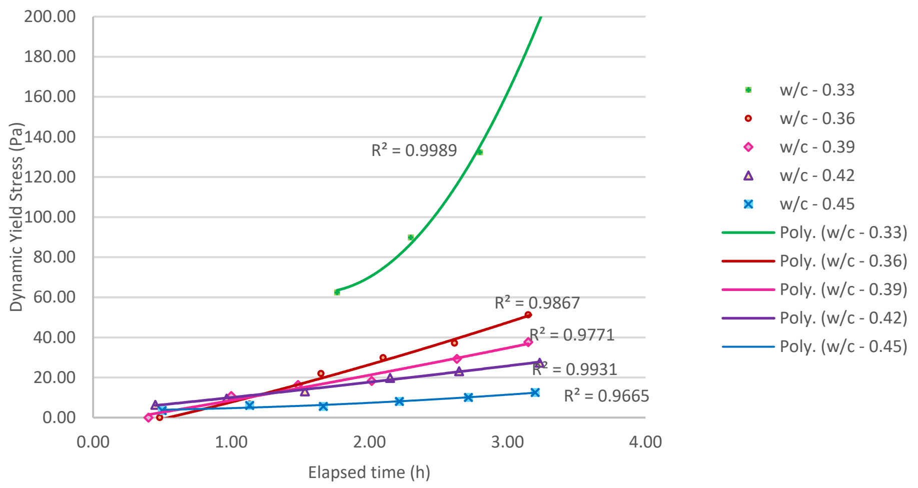

Figure 5-23: DYS over w/c ratio - Mortar phase

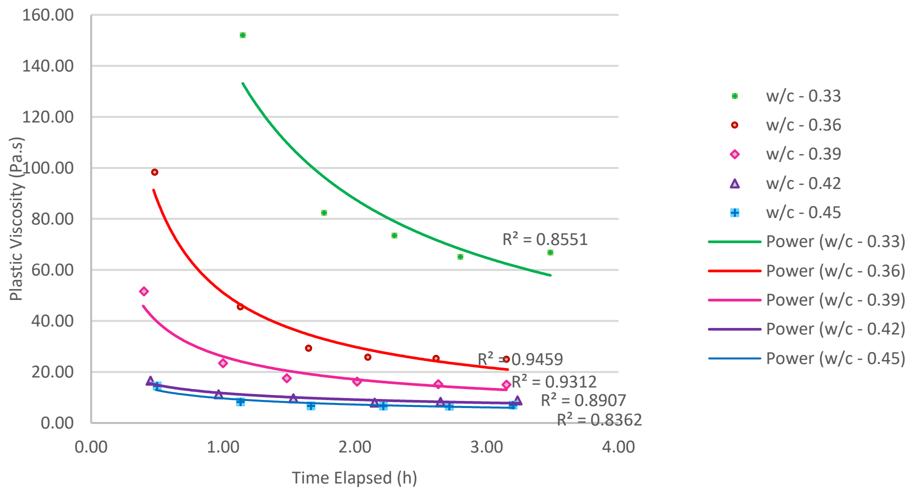

Figure 5-24: PV over w/c ratio - Mortar phase

Since, the combined effect of rheological properties has to be considered, flow-rate had been predicted assuming mortar phase rheology as the lubrication layer properties. Predicted flow-rates have been presented in Figure 5-25.

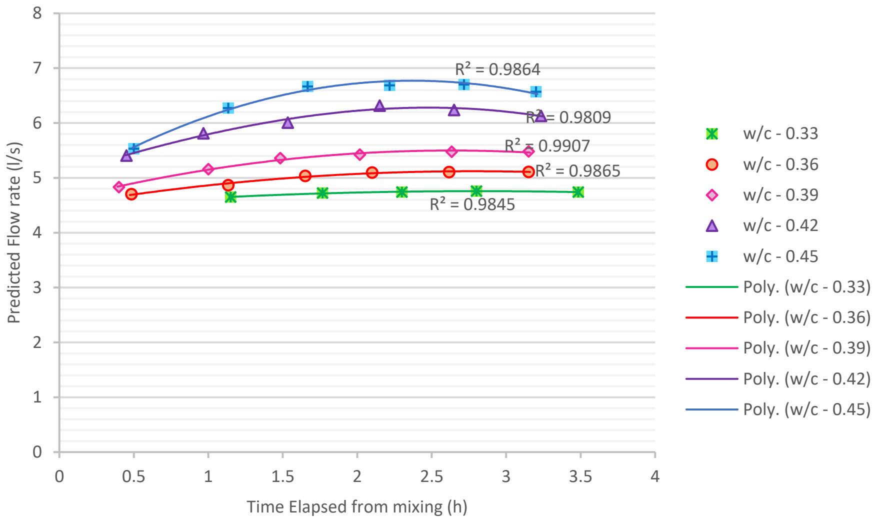

Figure 5-25: Flow-rate prediction over w/c ratio - Mortar phase

5.3.3 Cement Type

In order to study the influence of cement type on rheology of concrete, 5 commercially available cement products were used in paste phase experiments. Table 5-7 contains the list of cement products along with their type.

Table 5-7: Tested Cement Types

Cement Product	Cement Type
INSEE Sanstha	Portland Limestone Cement
INSEE Mahaweli Marine Plus	Portland Fly Ash Cement
INSEE Rapid Flow	Ordinary Portland Cement
INSEE Rapid Flow Plus	Portland Fly Ash Cement
INSEE Extra	Portland Fly Ash Cement

Figure 5-26 and 5-27 contain the DYS and PV results of the paste samples tested for five different cement products. Mix proportion parameters given in Table 4-2 for the control paste sample was used with each type of Cement in this lab tests series.

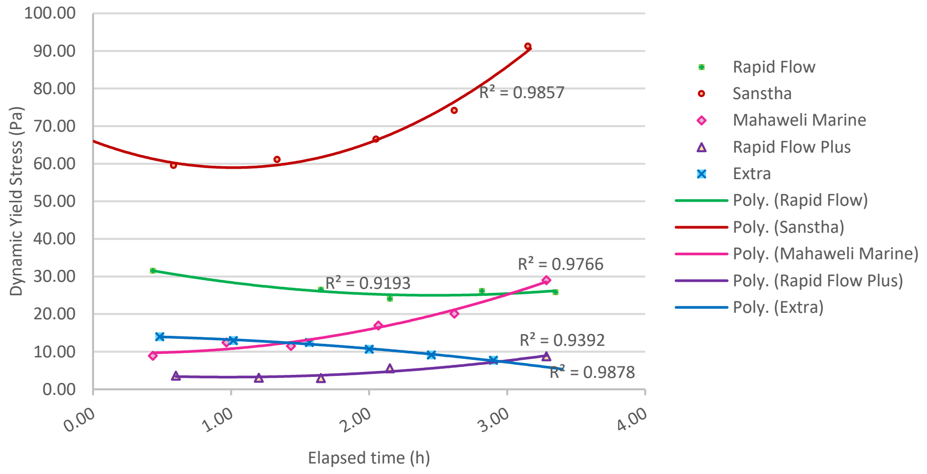

Figure 5-26: DYS over Cement type - Paste phase

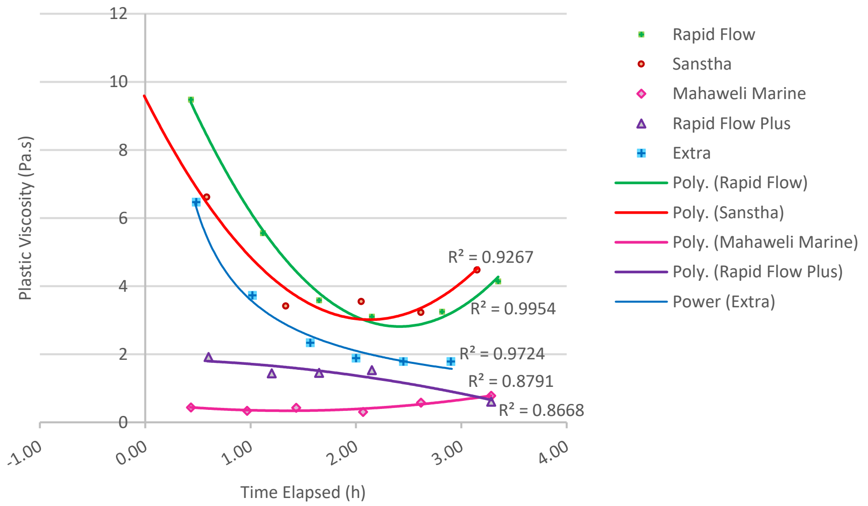

Figure 5-27: PV over Cement type - Paste phase

5.3.3.1 *Discussion*

The DYS of Sanstha, the PLC has been far higher than the rest of the cement types, while Portland Fly Ash Cement types (Mahawelli Marine, Rapid Flow Plus and Extra) have shown very low DYS values. Similar results have been reported for the PV values as well. The least values are corresponding to the Portland Fly Ash Blended Cement types, while PLC and OPC cement types have resulted higher PV values.

PV values have been generally decreased over 3 hour tested time duration while the variation of DYS is comparatively low.

When testing some of the fly ash blended cement samples, especially extra bleeding was observed during first three rounds.

The ingredients like fly ash seem to influence the rheology of concrete, hence the optimum w/c ratio and PCE dosage have to be altered with respect to the cement type used in the mix design to get the optimum rheological properties.

5.3.4 Fine Aggregate Concentration

When the mortar phase of concrete is concerned in terms of rheology, it can be considered as a slurry where the fine aggregate particles have dispersed in the paste media. As per Krienger (Krieger & Dougherty, 1959), volume fraction of solids is a governing factor that decides the properties of the slurry. In fact, volume fraction over maximum packing fraction is the critical parameter, which depends on shape, size and size distribution of fine aggregate particles.

Three mortar samples at different volume fractions of fine aggregates have been tested to study the effect of fine aggregate concentration on rheological properties. Unwashed manufactured sand was used for the three mortar phase samples.

Variation of DYS and PV with respect to fine aggregate concentrations is shown Figure 5-28 and 5-29 respectively.

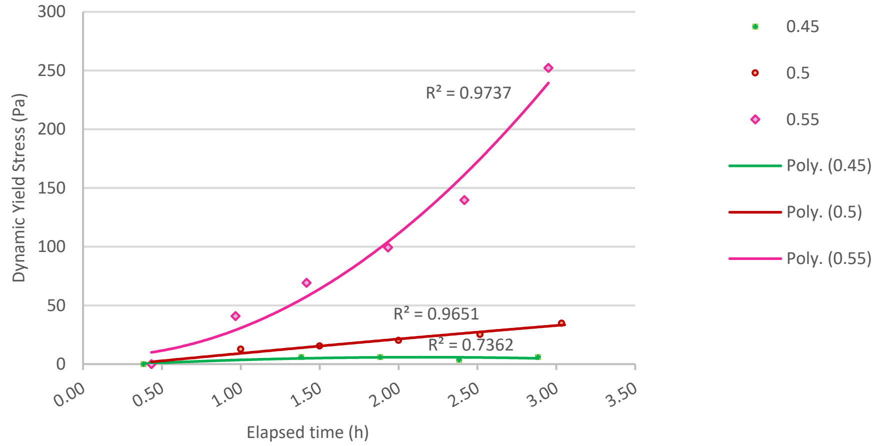

Figure 5-28: DYS over Fine Aggregate Concentration - Mortar Phase

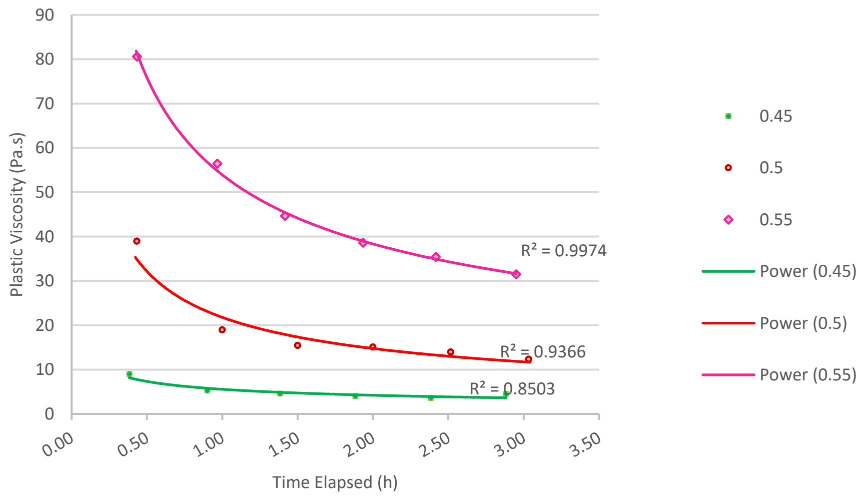

Figure 5-29: PV over Fine Aggregate Concentration - Mortar phase

Figure 5-30 presents the predictions for flow-rate at 28.5 k Pa/ m pressure gradient in horizontal line considering the rheology of mortar samples as the rheological properties of lubrication layer.

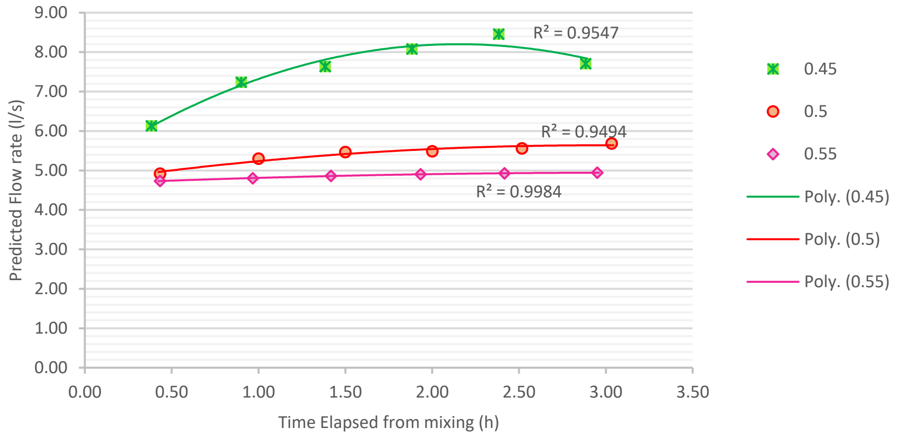

Figure 5-30: Flow-rate prediction over Fine Aggregate Concentration - Mortar phase

5.3.4.1 *Discussion*

A reasonable relationship was observed for rheological properties of mortar at different fine aggregate concentrations. Maximum DYS and PV values have been obtained for the maximum fine aggregate concentration which is 0.55. DYS and PV was decreased with decrease of fine aggregate concentration from 0.55 to 0.50 and 0.45. Hence the resulted flow-rate predictions are maximum for the least aggregate concentration implying better flow characteristics.

General trend of DYS is increasing with respect to the time elapsed from mixing, while PV has declined over time. In flow-rate prediction (see Figure 5-26) for fine aggregate concentration of 0.45 shows a decline in flow-rate toward the end of testing time after the incremental trend experienced initially. The decline of flow rate is due to the degradation of rheology with hydration of cement.

5.3.5 Fine Aggregate Type

Set of mortar samples were prepared maintaining same volume fraction of fine aggregates but the fine aggregate type was changed i.e. 100% Washed MS ,100% Unwashed MS , 50% of Unwashed MS with 50% River Sand and 100% River Sand.

Although the same volume fraction has been maintained;

- Particle Shape
- Particle Size &
- Size Distribution

were different at each sample, resulting different maximum packing fractions.

Figure 5-31 and 5-32 present the variation of DYS and PV of mortar samples with different types of fine aggregates (different maximum packing fractions).

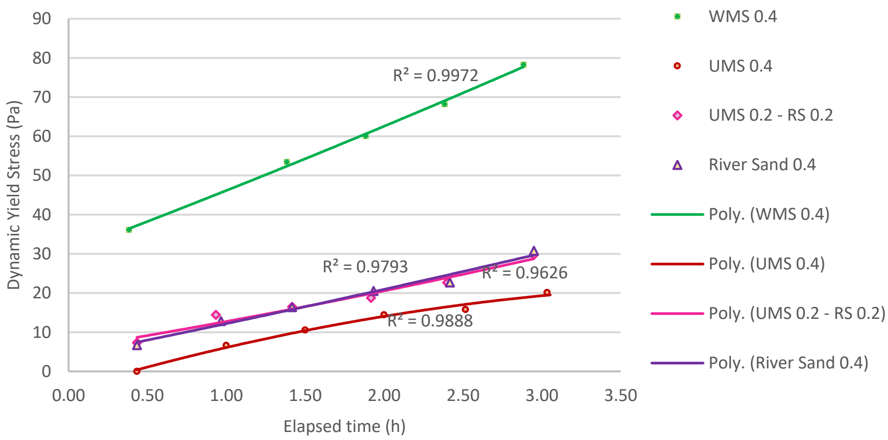

Figure 5-31: DYS over Fine Aggregate type - Mortar phase

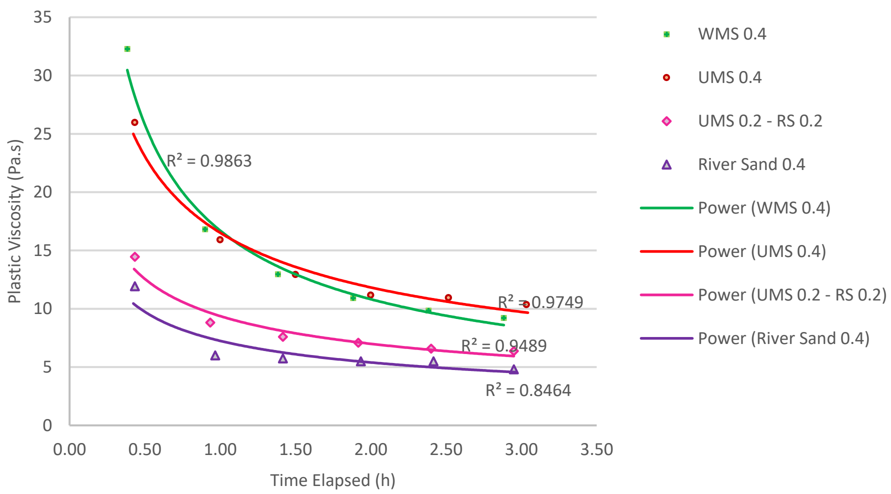

Figure 5-32: PV over Fine Aggregate type - Mortar phase

Predicted flow-rate for lubrication layer with different fine aggregate types have been presented in Figure 5-33.

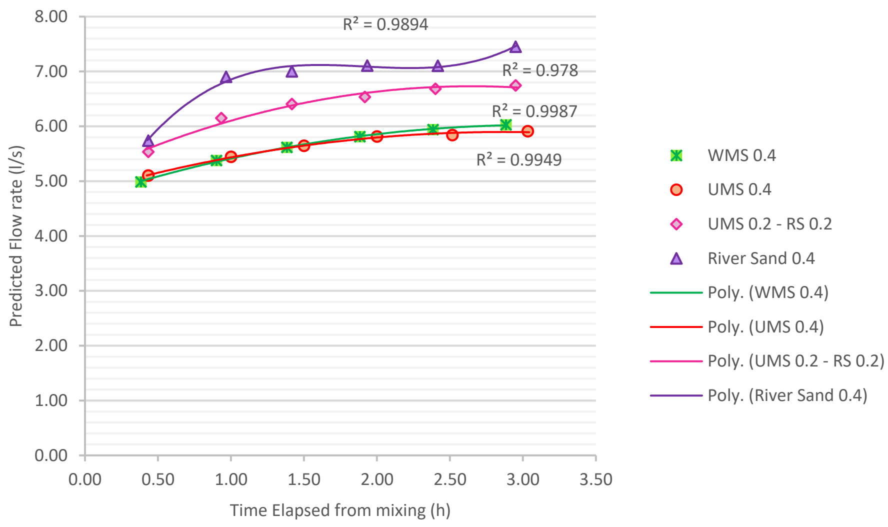

Figure 5-33: Flow-rate prediction over Fine Aggregate type - Mortar phase

5.3.5.1 *Discussion*

DYS of washed manufactured sand was the largest where minimum is with unwashed manufactured sand. In Figure 5-31, it can be seen that PV of both washed MS and unwashed MS was more or less in the same range while minimum PV was obtained for river sand.

However, if the predicted flow-rate values are considered, flow-rates corresponding to unwashed and washed MS were almost the same for entire time duration concerned. When 50% of the fine aggregate of unwashed MS sample had been replaced with same volume of river sand, the flow-rate has been considerably improved. With 100% replacement of M sand with river sand, the flow-rate has been even more improved.

Maximum DYS obtained for sample with washed manufactured sand is due to the lowest maximum packing fraction. Since washed MS is lack of fines, it leads to lesser maximum packing density. Influence in flow-rate when the MS had been replaced by 50% and 100% respectively is due to the improvement of particle shape and size.

Use of river sand over M sand increase the rheological properties of the concrete. However, due to scarcity of material, use of M sand cannot be avoided. Therefore, careful selection of admixture type and dosage is necessary to compensate the degradation of rheological properties caused by use of M sand.

5.3.6 Summary of the important finding of lab investigation

- ✓ It was observed that with time and agitation applied for mixes consisting PCE admixture;
  - DYS increases
  - PV decreases
- ✓ Increase of w/c ratio resulted decrease of both DYS and PV values in paste and mortar phases. Hence, the flow-rate of concrete pipe-flow, corresponding to a certain pressure gradient can be improved by increasing the w/c ratio, provided that segregation and bleeding is avoided.
- ✓ Reduction of fine aggregate concentration in mortar phase improves the rheology of media with lesser DYS and PV measurements. Therefore, flow-rate of concrete pipe flow can be risen when the fine aggregate volume concentration is reduced.
- ✓ Rather than using MS 100% as the fine aggregate, using MS and River sand 50% each can enhance the rheology of the mortar phase. When 100% river sand is used the rheology was even more enhanced. Hence the more MS is substituted from River sand, the greater the flow-rates.

CHAPTER 6: CONCLUSIONS

- ✓ Rheology of a PCE (poly carboxylic ether) based concrete can be improved over time, by providing adequate agitation while being transported and waiting in the queue.

  By supplying enough shear stress to the fresh concrete, resulting deformation would disturb the coagulation process and cause the flocs to disperse in the poly carboxylic ether based media. Hence, plastic viscosities observed at batching plant had even reduced to halves when observed at the construction site after one or two hours.

- ✓ Rheology of the poly carboxylic ether based concrete has been dramatically improved as it is being transported through the pip-line.

  The reduction of plastic viscosity from before pumping to after pumping is much larger compared to the reduction of plastic viscosity during transporting from batching plant to site.

- ✓ As the rheological properties improve over time, slump flow measurement has also been improved.

  However, slump flow value is not related to one particular parameter (i.e.: plastic viscosity or yield stress); being a single point test slump or slump flow alone cannot indicate the rheology of fresh concrete.

- ✓ Temperature of fresh concrete with poly carboxylic ether admixture did not change considerably at night time concreting.

  Even-though water at ambient temperature was used for concrete batching and no cooling action was performed while concrete is transported or pumped through pipe line, temperature of fresh concrete didn't vary noticeably.

- ✓ Pressure drop in horizontal straight length can be reasonably predicted with the model of sheared plus plug flow of concrete with a 20% margin.

  Theoretical model derived considering sheared plus plug flow of concrete can be found in Appendix – 2. This model gives the relationship between pressure gradient (i.e.: pressure loss per meter run) in horizontal concrete pipe flow and the flow rate, based on plastic viscosity and yield stress of concrete, viscous constant and yield stress of constituent mortar and pipe radius.

- ✓ Pressure drop in a 90^0 horizontal bend was 0.5 to 1.7 bar, which is roughly equal to the predictions by JSCE and ACI guideline recommendations.

- ✓ Pressure drop for a vertical straight length in a concrete pipe flow is equal to the pressure needed to overcome the potential height difference.

  While plastic viscosities of concrete and the total applied pressure were significantly different from one truck to the other, pressure drop in 39 m vertical length was around 9.3 bar which is the pressure difference corresponding to the potential height difference. This indicates that in vertical pipe flow, bulk concrete material cannot been sheared. Moreover, plug flow has been occurred in the vertical pipe flow and the lubrication layer is almost like water. Hence, pressure drop has not been incurred for shearing of mortar or concrete.

- ✓ Pressure drop in a 90^0 vertical bent was around 6 bars which is several times larger than that in a horizontal bend.

- ✓ Total pressure needed to be applied on concrete pipe flow in a 125mm diameter pipe circuit can be estimated based on rheological properties of concrete and mortar and pipe network details with a 20% margin using the following guidelines with respect to pressure drop

  Horizontal straight length – from sheared plus plug flow model
  Horizontal 90^0 bend – 1.7 bar
  Vertical 90^0 bend – 6 bar
  Vertical straight length – Pressure corresponding to potential height difference of a fresh concrete column

- ✓ In fresh concrete pipe flow, radial pressure is equal to the line pressure of concrete.

  Irrespective of total applied pressure for the whole concrete pumping pipe line, the pressure difference corresponding to the 39 m long vertical section remained same at the static and dynamic time intervals. Hence, the radial and line pressures of concrete pumping pipe line are equal.

- ✓ It was observed that with time and agitation applied for mixes consisting PCE admixture;

- DYS increases
- PV decreases

Generally, yield stress and plastic viscosity increase as rheology degrade over time. However, adequate agitation was applied by rotating the sample in the concrete mixing drum. So that PV value decreased over time improving the rheology of fresh concrete.

- ✓ Increase of w/c ratio resulted decrease of both DYS and PV values in paste and mortar phases. Hence, the flow-rate of concrete pipe-flow, corresponding to a certain pressure gradient can be improved by increasing the w/c ratio, provided that segregation and bleeding is avoided.

- ✓ Reduction of fine aggregate concentration in mortar phase improves the rheology of media with lesser DYS and PV measurements. Therefore, flow-rate of concrete pipe flow can be risen when the fine aggregate volume concentration is reduced.

- ✓ Rather than using MS (Manufactured Sand) 100% as the fine aggregate, using MS and River sand 50% each can enhance the rheology of the mortar phase. When 100% river sand is used the rheology was even more enhanced. Hence the more MS is substituted from River sand, the greater the flow-rates.

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APPENDIX-I: THEORETICAL DERIVATIONS FOR CONCRETE PIPE FLOW

Plug Flow of Fresh Concrete

Here only the lubrication layer is sheared.

$\tau = \tau_{0,LL} + \eta_{LL} V_{LL}$ $\qquad V_{LL} = \frac{\tau - \tau_{0,LL}}{\eta_{LL}}$

Since concrete is not sheared whole concrete bulk will move in V_{LL} velocity.

Also the thickness of the lubrication layer is negligible compared to the diameter.

$\frac{Q}{3600.\pi R^2} = \frac{\tau - \tau_{0,LL}}{\eta_{LL}}$ $\qquad \tau = \frac{Q}{3600\pi.R^2}\eta_{LL} + \tau_{0,LL}$

In this equation τ is referred to the shear stress of the lubrication layer; shear stress at the pipe wall.

$\tau = \tau_w = \frac{\Delta P}{L}.\frac{R}{2}$

$\frac{\Delta P}{L}.\frac{R}{2} = \frac{Q}{3600\pi.R^2}\eta_{LL} + \tau_{0,LL}$

$$\Delta P = \frac{2L}{R}\left(\frac{Q}{3600\pi.R^2}\eta_{LL} + \tau_{0,LL}\right)$$

Sheared Flow of Fresh Concrete

Equation of Bulk concrete flow

$\tau = \tau_0 + \mu_P \dot{\gamma}$

$\tau = \tau_0 - \mu_P.\frac{dV}{dr}$

$(\tau - \tau_0)dr = -\mu_p.dV,$ $\qquad \tau = \Delta P.\frac{r}{2L}$

$\int_0^r (\tau - \tau_0)dr = -\int_{U_o}^{U_r} \mu_p \, dV$

$\int_0^r \left(\Delta P.\frac{r}{2L} - \tau_0\right) dr = -\mu_p.\int_{U_o}^{U_r} 1 \, dV$

$$\Delta P.\frac{r^2}{4L} - \tau_0 r = -\mu_p.[U_r - U_0]$$

$$U_r = -\frac{\Delta P}{4L\,\mu_p} r^2 + \frac{\tau_0}{\mu_p} r + U_0$$

Boundary Conditions

At r = R, U_r = velocity of the lubrication layer

$$U_R = -\frac{\Delta P}{4L\,\mu_p} R^2 + \frac{\tau_0}{\mu_p} R + U_0 = \frac{1}{\eta_{LL}}\left\{\Delta P.\frac{R}{2L} - \tau_{0,LL}\right\} = V_{LL}$$

$$-\frac{\Delta P}{4L\,\mu_p} R^2 + \frac{\tau_0}{\mu_p} R + U_0 = \frac{1}{\eta_{LL}}\left\{\Delta P.\frac{R}{2L} - \tau_{0,LL}\right\}$$

$$U_0 = \frac{1}{\eta_{LL}}\left\{\Delta P.\frac{R}{2L} - \tau_{0,LL}\right\} + \frac{\Delta P}{4L\,\mu_p} R^2 - \frac{\tau_0}{\mu_p} R$$

$$U_0 = \frac{\Delta P.R}{2L}.\left(\frac{R}{2\,\mu_p} + \frac{1}{\eta_{LL}}\right) - \frac{\tau_0 R}{\mu_p} - \frac{\tau_{0,LL}}{\eta_{LL}}$$

General expression for flow velocity at r distance to the pipe centre,

$U_r = -\frac{\Delta P}{4L\,\mu_p} r^2 + \frac{\tau_0}{\mu_p} r + U_0$, where $U_0 = \frac{\Delta P.R}{2L}.\left(\frac{R}{2\,\mu_p} + \frac{1}{\eta_{LL}}\right) - \frac{\tau_0 R}{\mu_p} - \frac{\tau_{0,LL}}{\eta_{LL}}$

$$U_r = -\frac{\Delta P}{4\mu_p L}.r^2 + \frac{\tau_0}{\mu_p}.r + \frac{\Delta P.R}{2L}\left\{\frac{R}{2\mu_p} + \frac{1}{\eta_{LL}}\right\} - \frac{\tau_0.R}{\mu_p} - \frac{\tau_0}{\eta_{LL}}$$

Flow rate

$$\frac{Q}{3600} = \int_0^R U_r \times 2\pi r\,dr$$

$$\frac{Q}{3600} = \int_0^R \left\{-\frac{\Delta P}{4L\,\mu_p} r^2 + \frac{\tau_0}{\mu_p} r + U_0\right\} \times 2\pi r\,dr$$

$$\frac{Q}{3600} = 2\pi \int_0^R \left\{-\frac{\Delta P}{4L\,\mu_p} r^3 + \frac{\tau_0}{\mu_p} r^2 + U_0 r\right\} dr$$

$$\frac{Q}{3600} = 2\pi.\left[-\frac{\Delta P}{4L\,\mu_p}\frac{r^4}{4} + \frac{\tau_0}{\mu_p}\frac{r^3}{3} + U_0\frac{r^2}{2}\right]_0^R$$

$$\frac{Q}{3600} = 2\pi.\left\{-\frac{\Delta P}{4L\,\mu_p}\frac{R^4}{4} + \frac{\tau_0}{\mu_p}\frac{R^3}{3} + U_0\frac{R^2}{2}\right\}$$

$$\frac{Q}{3600.\pi R^2} = -\frac{\Delta P}{2L\,\mu_p}\frac{R^2}{4} + \frac{2\tau_0}{\mu_p}\frac{R}{3} + U_0$$

$$\frac{Q}{3600.\pi R^2} = -\frac{\Delta P}{2L\,\mu_p}\frac{R^2}{4} + \frac{2\tau_0}{\mu_p}\frac{R}{3} + \frac{\Delta P.R}{2L}.\left(\frac{R}{2\,\mu_p} + \frac{1}{\eta_{LL}}\right) - \frac{\tau_0 R}{\mu_p} - \frac{\tau_{0,LL}}{\eta_{LL}}$$

$$\frac{Q}{3600.\pi R^2} = \frac{\Delta P.R}{2L}.\left(-\frac{R}{4\,\mu_p} + \frac{R}{2\,\mu_p} + \frac{1}{\eta_{LL}}\right) + \frac{\tau_0 R}{3\,\mu_p}(2-3) - \frac{\tau_{0,LL}}{\eta_{LL}}$$

$$\frac{Q}{3600.\pi R^2} = \frac{\Delta P.R}{2L}.\left(\frac{R}{4\,\mu_p} + \frac{1}{\eta_{LL}}\right) - \frac{\tau_0 R}{3\,\mu_p} - \frac{\tau_{0,LL}}{\eta_{LL}}$$

$$\frac{Q}{3600.\pi R^2} = \frac{\Delta P.R}{2L}.\left(\frac{R}{4\,\mu_p} + \frac{1}{\eta_{LL}}\right) - \frac{\tau_0 R}{3\,\mu_p} - \frac{\tau_{0,LL}}{\eta_{LL}}$$

$$\frac{\Delta P.R}{2L}.\left(\frac{R}{4\,\mu_p} + \frac{1}{\eta_{LL}}\right) = \frac{Q}{3600.\pi R^2} + \frac{\tau_0 R}{3\,\mu_p} + \frac{\tau_{0,LL}}{\eta_{LL}}$$

$$\frac{\Delta P.R}{2L} = \frac{\frac{Q}{3600.\pi R^2} + \frac{\tau_0 R}{3\,\mu_p} + \frac{\tau_{0,LL}}{\eta_{LL}}}{\frac{R}{4\,\mu_p} + \frac{1}{\eta_{LL}}}$$

$$\frac{\Delta P.R}{2L} = \frac{\left(\frac{Q}{3600.\pi R^2} + \frac{\tau_0 R}{3\,\mu_p}\right)\eta_{LL} + \tau_{0,LL}\left(1 + \frac{R\,\eta_{LL}}{4\,\mu_p} - \frac{R\,\eta_{LL}}{4\,\mu_p}\right)}{1 + \frac{R\,\eta_{LL}}{4\,\mu_p}}$$

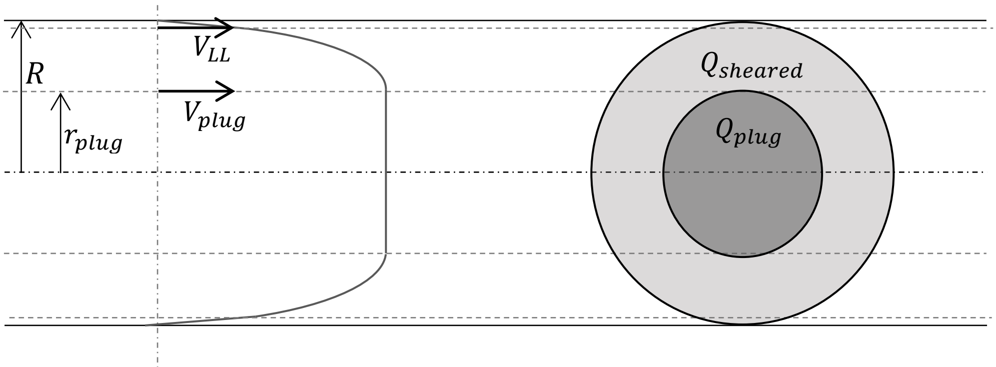
$$\frac{\Delta P.R}{2L} = \frac{\left(\frac{Q}{3600.\pi R^2} + \frac{\tau_0 R}{3\,\mu_p}\right)\eta_{LL} + \tau_{0,LL}\left(-\frac{R\,\eta_{LL}}{4\,\mu_p}\right)}{1 + \frac{R\,\eta_{LL}}{4\,\mu_p}} + \tau_{0,LL}$$

$$\frac{\Delta P.R}{2L} = \frac{\left(\frac{Q}{3600.\pi R^2} + \frac{\tau_0 R}{3\,\mu_p} - \tau_{0,LL}\frac{R}{4\,\mu_p}\right)\eta_{LL}}{1 + \frac{R\,\eta_{LL}}{4\,\mu_p}} + \tau_{0,LL}$$

$$\Delta P = \frac{2L}{R}\left(\frac{\frac{Q}{3600\pi.R^2} - \frac{R}{4\mu_p}\tau_{0,LL} + \frac{R}{3\mu_p}\tau_0}{1 + \frac{R}{4\mu_p}\eta_{LL}}\eta_{LL} + \tau_{0,LL}\right)$$

APPENDIX-II: THEORETICAL DERIVATIONS FOR SHEARED PLUS PLUG FLOW OF CONCRETE

When the applied shear stress on concrete exceed the yield stress of lubrication layer and bulk concrete the pipe flow will be a sheared plus plug flow condition. In this case lubrication layer will be sheared as usual while a part of bulk concrete material also be sheared. However, since the shear stress gets lower when it reaches toward the centre, a portion of bulk concrete will remain not sheared but moving as a plug as shown in the diagram.



(a) Side view – Velocity Profile *(b) Cross-Section*

Considering the shearing in lubrication layer,

$\tau_w = \tau_{0,LL} + \eta_{LL} V_{LL}$ $\quad V_{LL} = \frac{\tau_w - \tau_{0,LL}}{\eta_{LL}}$ Where $\tau_w = \frac{\Delta P}{L} . \frac{R}{2}$

Hence, $V_{LL} = \frac{\Delta P}{L} . \frac{R}{2} . \frac{1}{\eta_{LL}} - \frac{\tau_{0,LL}}{\eta_{LL}}$

From the characteristics of Bulk Concrete rheology,

$$\tau = \tau_0 + \mu_P \dot{\gamma}$$

$$\tau = \tau_0 - \mu_P . \frac{dV}{dr}$$

$$(\tau - \tau_0) dr = -\mu_P . dV, \qquad \left\{\tau = \Delta P . \frac{r}{2L}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{(8)}$$

$$\int_r^R (\tau - \tau_0) dr = -\int_{V_r}^{V_R} \mu_p \, dV$$

$$\int_r^R \left(\Delta P . \frac{r}{2L} - \tau_0\right) dr = -\mu_p . \int_{V_r}^{V_R} 1 \, dV$$

$$\frac{\Delta P}{4L}.(R^2 - r^2) - \tau_0(R - r) = -\mu_p.[V_R - V_r]$$

$$V_r = \frac{\Delta P}{4L\,\mu_p}(R^2 - r^2) - \frac{\tau_0}{\mu_p}(R - r) + V_R \; ; \qquad V_R = V_{LL} = \frac{\Delta P}{L}.\frac{R}{2}.\frac{1}{\eta_{LL}} - \frac{\tau_{0,LL}}{\eta_{LL}}$$

When $r = r_{plug}$; $\frac{d}{dr}(V_r) = 0$

$$\left[\frac{d}{dr}\left\{\frac{\Delta P}{4L\,\mu_p}(R^2 - r^2) - \frac{\tau_0}{\mu_p}(R - r) + V_R\right\}\right]_{r=r_{plug}} = 0$$

$$\left[\frac{\Delta P}{4L\,\mu_p}(0 - 2r) - \frac{\tau_0}{\mu_p}(0 - 1) + 0\right]_{r=r_{plug}} = 0$$

$$\left[-\frac{\Delta P.r}{2L\,\mu_p} + \frac{\tau_0}{\mu_p}\right]_{r=r_{plug}} = 0$$

$$-\frac{\Delta P}{2L\,\mu_p}.r_{plug} + \frac{\tau_0}{\mu_p} = 0$$

$$r_{plug} = \frac{2L.\tau_0}{\Delta P}$$

Sheared flow occurs in the region where the radius is greater than r_{plug} and less than R

$$Q_{sheared} = \int_{r_{plug}}^{R} V_r.2\pi r.dr$$

$$= 2\pi \int_{r_{plug}}^{R} V_r.r.dr$$

$$= 2\pi \int_{r_{plug}}^{R} \left\{\frac{\Delta P}{4L\,\mu_p}(R^2 - r^2) - \frac{\tau_0}{\mu_p}(R - r) + V_{LL}\right\}.r.dr$$

$$= 2\pi \int_{r_{plug}}^{R} \left\{\frac{\Delta P.R^2}{4L\,\mu_p} - \frac{\tau_0 R}{\mu_p} + V_{LL}\right\} r + \frac{\tau_0}{\mu_p} r^2 - \frac{\Delta P}{4L\,\mu_p}.r^3 dr$$

$$= 2\pi \left[\left\{\frac{\Delta P.R^2}{4L\,\mu_p} - \frac{\tau_0 R}{\mu_p} + V_{LL}\right\}\frac{r^2}{2} + \frac{\tau_0}{\mu_p}\frac{r^3}{3} - \frac{\Delta P}{4L\,\mu_p}.\frac{r^4}{4}\right]_{r_{plug}}^{R}$$

$$Q_{sheared} = 2\pi\left[\frac{1}{2}.\left\{\frac{\Delta P.R^2}{4L\,\mu_p} - \frac{\tau_0 R}{\mu_p} + V_{LL}\right\}\left\{R^2 - r_{plug}{}^2\right\} + \frac{\tau_0}{3\mu_p}\left\{R^3 - r_{plug}{}^3\right\} - \frac{\Delta P}{16L\,\mu_p}\left\{R^4 - r_{plug}{}^4\right\}\right]$$

Plug flow occurs in the region where the radius is less than r_{plug}

$$Q_{plug} = \int_0^{r_{plug}} V_r.\,2\pi r.\,dr$$

$$= \pi\left(r_{plug}\right)^2.V_{plug}$$

$$Q_{plug} = \pi\left(r_{plug}\right)^2.\left\{\frac{\Delta P}{4L\,\mu_p}\left(R^2 - r_{plug}{}^2\right) - \frac{\tau_0}{\mu_p}\left(R - r_{plug}\right)\right.$$

Then the total flow is the summation of sheared and plug flows;

$$Q_{Total} = Q_{sheared} + Q_{plug}$$

APPENDIX-III: SPECIFICATIONS AND CALIBRATION REPORT OF ICAR PLUS CONCRETE RHEOMETER

General Specifications (Source: ICAR plus rheometer manual)

Minimum slump:	The concrete has to have a slump greater than 75 mm, otherwise the concrete is too stiff for testing by the apparatus
Nominal maximum size of aggregate:	32 mm for largest available container
Vane rotation speed:	0.001 to 0.667 rev/s
Motor type:	Integrated Servo Motor
Minimum Torque:	0.01 Nm
Peak Torque:	90 Nm for not more than 2 seconds
Continuous Maximum Torque:	32 Nm
Power Supply:	Input of 100-240 VAC – 3.5A. Output of 48V - 6.7A. IP67
Computer requirements:	Windows 7 or higher. Processor I3 or higher
Motor drive dimensions:	11 x 11 x 43 cm
Motor drive weigh:	7.5 kg
Carrying Case dimensions:	67 x 52 x 28 cm
Carrying Case weight:	20 kg, including Motor Drive, Base Frame, Vane, Power Supply and Cables

Calibration Report (Scanned Picture of the original)

GERMANN INSTRUMENTS A/S

Emdrupvej 102 - DK-2400 – Copenhagen NV - Denmark
Phone: (+45) 39 67 71 17 - Fax: (+45) 39 67 31 67
E-mail: germann-eu@germann.org · Internet: www.germann.org

GI

Certificate of Compliance
RHM-5000 ICAR Plus Rheometer
SN 6784

For Quality Assurance a series of five test runs was performed on SN 6784 to confirm proper operation and parameter readings.

Relative Parameters

Run #	Y (Nm)	V (Nm.s)	R^2
1	0.004	1.611	1.00
2	0.003	1.603	1.00
3	0.001	1.613	1.00
4	0.002	1.607	1.00
5	0.002	1.612	1.00
AVG.	**0.002**	**1.609**	
STDEV	**0.0011**	**0.0041**	

Bingham Parameters

τ_0 (Pa)	μ_p (Pa.s)	mse
0.33	31.760	0.00
0.47	31.830	0.00
0.53	32.030	0.00
0.52	31.910	0.00
0.26	32.010	0.00
0.422	**31.908**	
0.1207	**0.1154**	

This is an in-house calibration performed with 30,000 centistokes silicone oil, which is not NIST traceable.

Date: October 26, 2017 Ambient Temperature: 20.7°C Technician: [signature]

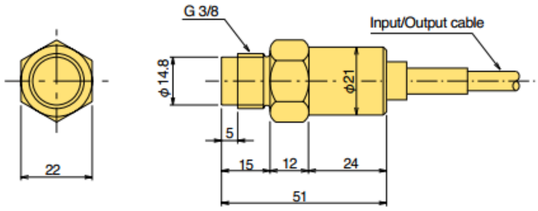
APPENDIX-IV: SPECIFICATIONS OF PWF-20MPB PRESSURE TRANSDUCER

Source: Tokyo Measuring Instruments Lab

PRESSURE TRANSDUCERS

PWF-PB Flush Diaphragm type Pressure Transducer 1~50MPa

G3/8 size
High response



Because this transducer has its pressure-receiving surface at the top of mounting screws, it is suitable for use in a situation where pressure changes dynamically. It is widely used to measure the pressure in pipelines, cylinder pressure, and so forth

Protection ratings: IP67 equivalent

■ SPECIFICATIONS

TYPE	PWF-1MPB	PWF-2MPB	PWF-5MPB	PWF-10MPB	PWF-20MPB	PWF-50MPB
Capacity	1MPa	2MPa	5MPa	10MPa	20MPa	50MPa
Rated Output	1.75mV/V(3500× 10^{-6} strain) ±25%					
Non-linearity	0.5%RO					
Hysteresis	0.5%RO					
Repeatability	0.5%RO					
Temperature effect on zero	0.06%RO/°C					
Temperature effect on span	0.03%/°C					
Compensated temperature range	-10 ~ +60°C					
Allowable temperature range	-20 ~ +70°C					
Over load	150%					
Input/Output resistance	350Ω					
Recommended exciting voltage	6V or less					
Allowable exciting voltage	10V					
Natural frequency	30kHz	40kHz	60kHz	80kHz	110kHz	170kHz
Mounting thread	G3/8 (PF3/8)					
Materials of pressure media	SUS630					
Weight	100g					

Input/Output cable :
φ6mm 0.35mm² 4-core shielded chloroprene cable 2m

Applicable fitting torque: 10~20N·m

APPENDIX-V: SPECIFICATIONS OF FLA-5 STRAIN GAUGE

Source: Tokyo Measuring Instruments Lab

FOIL STRAIN GAUGES series F

Operating temperature range: −196°C to +150°C

Temperature compensation range: +10°C to +100°C

Suffix code for temperature compensation materials
-11: Mild steel -17: Stainless steel -23: Aluminium

For ordering, the above suffix code should be added to the basic gauge type.

Applicable adhesives

CN	−196 ~ +120°C
P-2	−30 ~ +150°C
EB-2	−60 ~ +150°C

GENERAL USE

Gauge pattern

These gauges employ Cu-Ni alloy foils for the grid and special plastics for the backing. The plastics backing exhibits excellent electrical insulation performance, and is color-coded to identify the objective material for self-temperature-compensation. Various types of strain gauges such as "for residual stress measurenement" are available in addition to general use gauges.

M metal G general

Example of type number designation

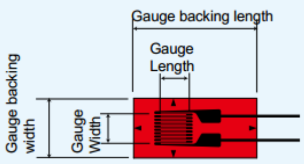
FLA-5 -350 -11 -3LJB/-3LJBT (2-wire/3-wire)

- Length in meter and type of integral leadwire(*1)
- Self-tempeatrure-compensation number(*2)
- Gauge resistance in ohm (Blank for 120Ω)
- Basic strain gauge type and gauge length

*1 : Not mentioned for gauges without leadwire
*2 : The following numbers are available for F series gauges
-11: Mild steel (11ppm/°C)
-17: Stainless steel, Copper alloy (17ppm/°C)
-23: Aluminium (23ppm/°C)

Single element : FLG/FLA/FLK

Each package contains 10 gauges.



Basic type	Gauge size L	Gauge size W	Backing L	Backing W	Resistance Ω
FLG-02	0.2	1.4	3.5	2.5	120
FLG-1	1	1.1	6.5	2.5	120
FLA-03	0.3	1.4	3	2	120
FLA-05	0.5	1.2	5	2.2	120
FLA-1	1	1.3	5	2.5	120
FLA-2	2	1.5	6.5	3	120
FLA-3	3	1.7	8.8	3.5	120
FLA-3-60	3	1.2	8	3	60
FLA-5	5	1.5	10	3	120
FLA-6	6	2.2	12.5	4.3	120
FLA-10	10	2.5	16.7	5	120
FLA-30	30	2	36.1	5.1	120
FLK-1	1	0.7	4.5	1.4	120
FLK-2	2	0.9	5.5	1.5	120
FLK-6	6	10	11.2	2.2	120
FLK-10	10	1.6	16.2	3.8	120
FLA-1-350	1	1.6	4.5	3	350
FLA-2-350	2	1.9	6.1	3.5	350
FLA-3-350	3	1.6	7.2	3	350
FLA-5-350	5	1.8	9.4	3.8	350
FLA-6-1000	6	4.6	13.5	7	1000

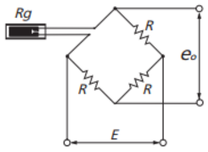
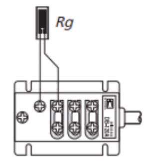
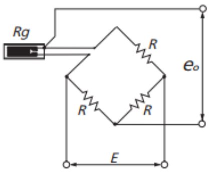
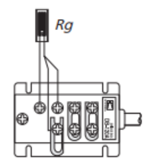
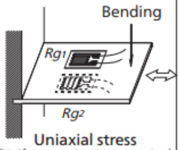
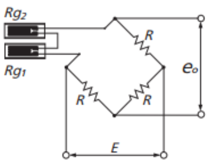
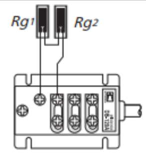
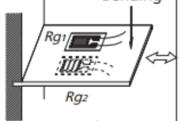
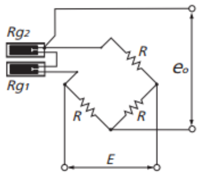
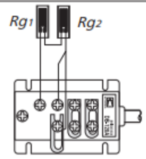
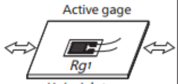
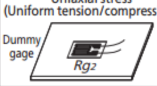
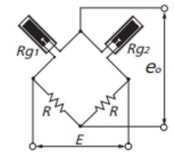
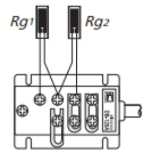
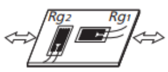
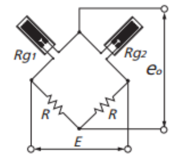
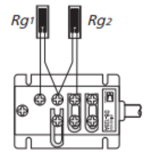
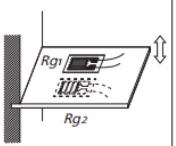
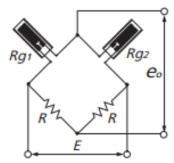
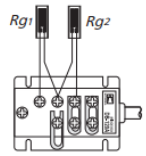
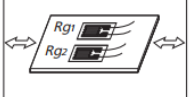
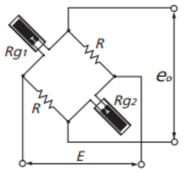
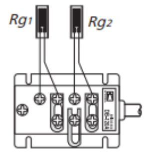
FLK type with narrow gauge width

High gauge resistance 350Ω and 1000Ω

APPENDIX-VI: BRIDGE CIRCUIT DETAILS FOR STRAIN GAUGES

Source: Kyowa Instrument Co., Ltd.

■How to Form Strain-gage Bridge Circuits

No.	Names	Sample Application	Circuits	Output	Remarks	Bridge Box DB-120A/350A
1	Active quarter-bridge 2-wire system Number of gages: 1	 Uniaxial stress (Uniform tension/compression)		$e_o = \frac{E}{4} K_s \cdot \varepsilon_o$ K_s: Gage factor ε_o: Strain E: Excitation voltage e_o: Output voltage Rg: Gage resistance R: Fixed resistance	Suitable for environments with little ambient temperature change; no temperature compensation. x 1 output	
2	Active quarter-bridge 3-wire system Number of gages: 1	 Uniaxial stress (Uniform tension/compression)		$e_o = \frac{E}{4} K_s \cdot \varepsilon_o$ K_s: Gage factor ε_o: Strain E: Excitation voltage e_o: Output voltage Rg: Gage resistance R: Fixed resistance	No temperature compensation; thermal effect of lead wires cancelled. x 1 output	
3	Active quarter-bridge (Dual series gages) 2-wire system (For cancelling bending strain) Number of gages: 2	Bending  Uniaxial stress (Uniform tension/compression)		$e_o = \frac{E}{4} K_s \cdot \varepsilon_o$ Rg_1 ……Strain: ε_1 Rg_2 ……Strain: ε_2 $\varepsilon_o = \frac{\varepsilon_1 + \varepsilon_2}{2}$ R: Fixed resistance $R = Rg_1 + Rg_2$ E.g. Rg_1 & Rg_2 are 60-ohm gages, if using a DB-120A.	No temperature compensation; bending strain cancelled. x 1 output	
4	Active quarter-bridge (Dual series gages) 3-wire system (For cancelling bending strain) Number of gages: 2	Bending  Uniaxial stress (Uniform tension/compression)		$e_o = \frac{E}{4} K_s \cdot \varepsilon_o$ Rg_1 ……Strain: ε_1 Rg_2 ……Strain: ε_2 $\varepsilon_o = \frac{\varepsilon_1 + \varepsilon_2}{2}$ R: Fixed resistance $R = Rg_1 + Rg_2$ E.g. Rg_1 & Rg_2 are 60-ohm gages, if using a DB-120A.	No temperature compensation; bending strain cancelled; thermal effect of lead wires cancelled. x 1 output	
5	Active-dummy half-bridge system Number of gages: 2	Active gage  Uniaxial stress (Uniform tension/compression) Dummy gage 		$e_o = \frac{E}{4} K_s \cdot \varepsilon_o$ K_s: Gage factor ε_o: Strain E: Excitation voltage e_o: Output voltage Rg_1 ……Strain: ε_o R: Fixed resistance Rg_2 ……Strain: 0	Temperature compensation; thermal effect of lead wires cancelled. x 1 output	
6	Orthogonal* active half-bridge system Number of gages: 2 * at a right angle	 Uniaxial stress (Uniform tension/compression)		$e_o = \frac{(1+\nu)E}{4} K_s \cdot \varepsilon_o$ ν: Poisson's ratio Rg_1, Rg_2: Gage resistance Rg_1 ……Strain: ε_o Rg_2 …Strain: $-\nu\varepsilon_o$ R: Fixed resistance	Temperature compensation; thermal effect of lead wires cancelled. x (1+ν) output	
7	Active half-bridge system (For bending strain measurement) Number of gages: 2	 Bending stress		$e_o = \frac{E}{2} K_s \cdot \varepsilon_o$ Rg_1 ……Strain: ε_o Rg_2 …Strain: $-\varepsilon_o$ R: Fixed resistance	Temperature compensation; thermal effect of lead wires cancelled; compressive/ tensile strain cancelled. x 2 output	
8	Opposite-leg active half-bridge 2-wire system Number of gages: 2	 Uniaxial stress (Uniform tension/compression)		$e_o = \frac{E}{2} K_s \cdot \varepsilon_o$ Rg_1 ……Strain: ε_o Rg_2 ……Strain: ε_o R: Fixed resistance	No temperature compensation; x 2 output bending strain cancelled by bonding to the front and rear.	

APPENDIX-VII: MIX DESIGN USED FOR SLAB CONCRETE AT CCC

Source: Sunken Construction (Pvt) Ltd.

Doc.No. 7/R/B-2
Revision. 01
Date. 31/12/2011.
Page. 01 of 01

Design No: 50N/50/20/SKCC/HR-01

CONCRETE MIX DESIGN DATA

(British Method Of Design Of Normal Concrete Mixes)

SANKEN CONSTRUCTION (PVT) LTD., NO. 295, MADAMPITIYA ROAD, COLOMBO 14. TEL. 522221 : FAX. 522942

BATCHING PLANT - TEL. / FAX. 2521834 - 5,2525728.

CONC. GRADE : 50 N/mm^2 DATE: 2017-03-20 DESIGN SLUMP: 500 ± 50 mm

Stage	Item	Reference or Calculation	Values
01	1.1 Characteristic strength	Specified	Compressive 50.0 N/mm^2 at 28 Days
			Proportion defective 5 percent
	1.2 Standard deviation		5.0 N/mm^2 or no data - N/mm^2
	1.3 Margin	C1	(k = 1.64) 1.64 x 5.0 = 8 N/mm^2
	1.4 Target mean strength	C2 & Para 8.1	50.0 + 8 = 58.2 N/mm^2
	1.5 Cement type	Specified	(OPC / SRPC / RHPC/PPC) OPC
	1.6 Aggregate type : Coarse		Crushed / Uncrushed
	Aggregate type : Fine		Manufactured Sand
	1.7 Free water / cement ratio	Table 2, Fig 4	0.42
	1.8 Maximum free water / cement ratio	Specified	0.45 Use the lower value 0.42
02	2.1 Slump or V-B	Specified	Slump 500 ± 50 mm or V-B - s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free water content	Table 3 & Para 8.2	176 kg/m^3
03	3.1 Cement content	C3	176/0.41 = 430 kg/m^3
	3.2 Maximum cement content	Specified	500 kg/m^3
	3.3 Minimum cement content	Specified	390 kg/m^3
			use 3.1 if ≤ 3.2
			use 3.3 if ≥ 3.1 430 kg/m^3
	3.4 Modified free water/cement ratio		0.41
04	4.1 Relative density of aggregate (SSD)		2.69 known / assumed
	4.2 Concrete density	Fig 5 & Para 8.3	= 2423 kg/m^3
	4.3 Total aggregate content	C4	2423 - 430 - 176 = 1817 kg/m^3
05	5.1 Grading of Fine aggregate	Percentage passing 600 µm sieve	Maximum 50 Minimum 30 percent
	5.2 Proportion of Fine aggregate		45 percent
	5.3 Fine aggregate content	C5	1817 x 0.45 = 817 kg/m^3
	5.4 Coarse aggregate content	C5	1817 - 817 = 1000 kg/m^3

Quantities	Cement (kg)	Silica fume (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Admixture 1 Hypercrete Plus M (ml)	Admixture 2 (ml)
Per m^3	430		176	817	1000	4100	
Per trial mix of 0.04 m^3	17.21		7.04	32.68	39.99	164.00	

Designed as per BS 5328

Sanken CONSTRUCTION (PVT) LTD sky's the limit

APPENDIX-VIII: MIX DESIGN USED FOR SLAB CONCRETE AT LUNA TOWER

<u>Source: Sunken Construction (Pvt) Ltd.</u>

Design : 30N/20/20/BS/SKUA/05

CONCRETE MIX DESIGN DATA

80

Doc No 7/R/B-2
Revision 01
Date . 31/12/2011.
Page. 01 of 01

(British Method Of Design Of Normal Concrete Mixes)

SANKEN CONSTRUCTION (PVT) LTD. , NO. 295 , MADAMPITIYA ROAD , COLOMBO 14. TEL. 522221 : FAX. 522942

BATCHING PLANT - TEL. / FAX. 2521834 - 5,2525728.

CONC. GRADE : 30 N / mm²

DESIGN SLUMP: 200 ± 25 mm

Stage	Item	Reference or Calculation	Values
01	1.1 Characteristic strength	Specified	Compressive 30 N/mm² at 28 Days
			Proportion defective 5 percent
	1.2 Standard deviation		6.0 N/mm² or no data - N/mm²
	1.3 Margin	C1	(k = 1.64) 1.64 x 6.0 = 10 N/mm²
	1.4 Target mean strength	C2 & Para 8.1	30 + 10 = 40 N/mm²
	1.5 Cement type	Specified	(OPC / SRPC / RHPC) OPC (Ultratech OPC)
	1.6 Aggregate type : Coarse		<u>Crushed</u> / Uncrushed
	Aggregate type : Fine		Manufacture Sand 75% & River Sand 25%
	1.7 Free water / cement ratio	Table 2 , Fig 4	0.42
	1.8 Maximum free water / cement ratio	Specified	Use the lower value 0.42
03	3.1 Cement content	C3	162/ 0.42 = 386 kg/m³
	3.2 Maximum cement content	Specified	400 kg/m³
	3.3 Minimum cement content	Specified	kg/m³
			use 3.1 if ≤ 3.2
			use 3.3 if > 3.1 — 386 kg/m³
	3.4 Modified free water/cement ratio		0.42
04	4.1 Relative density of aggregate (SSD)		2.69 <u>known</u> / assumed
	4.2 Concrete density	Fig 5 & Para 8.3	= 2465 kg/m³
	4.3 Total aggregate content	C4	2465 - 386 - 162 = 1917 kg/m³
05	5.1 Grading of Fine aggregate		Percentage passing 600 μm sieve Maximum 50 Minimum 30 percent
	5.2 Proportion of Fine aggregate		46 percent
	5.3 Fine aggregate content	C5	1917 x 0.46 = 882 kg/m³
	5.4 Coarse aggregate content	C5	1917 - 882 = 1035 kg/m³

Quantities	Cement (kg)	Silica fume (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Admixture 1 Hypercrete Plus M (ml)	Admixture 2 (ml)
per m³	386		162	882	1035	3857	
per trial mix of 0.04 m³	15.43		6.48	35.28	41.41	154.29	

APPENDIX-IX: CONCRETE PUMPING DATA FROM SEVERAL HIGH RISE CONSTRUCTIONS

Source: Eng. Shiromal Fernando

STRENGTH · SERVICEABILITY · SAFETY · SUSTAINABILITY

CONCRETE PUMPING DATA

14th of July 2017

Data obtained from,

Waterfront Project – Eng. Asoka Jayawardena

Avic Project – Eng. Shyanaka Dhananjaya

Lotus Tower Project – Eng. Ravindu Hettiarachchi

Colombo City Center Project – Eng. Bishar Haadi

Approved by,

....

Eng. Shiromal Fernando

Project	Concrete Grade	Pressure Applied (Psi)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water Content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (Vertical/Horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
WATER FRONT PROJECT	C 50/60	1800	0.067**	52	125	Iron Steel: 38 CrMoAl	14	833	River Sand	939	PPC	533	160	Hypercrete HS	5000	240	
	C 50/60 (L.C)	1800	0.1**	52	125	Iron Steel: 38 CrMoAl	20	1024	River Sand Manufactured Sand	450 387	PPC	450	139	Hypercrete Plus	6300	230	
	C 50/60 (L.C)	1800	0.227**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	625 208	OPC	400	146	Hypercrete Plus	5850	240	
	C 35/45	1800	0.2**	52	125	Iron Steel: 38 CrMoAl	20	973	River Sand Crushed sand	516 344	OPC	338	153	Optima 186	5400	230	
	C 35/45	1800	0.43*	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	230	
	C 35/45	1800	1	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	240	
	C 35/45	1800	0.46*	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	225	
	C 35/45	1800	0.133**	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	225	
	C 35/45	1800	0.133**	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	240	
	C 35/45	1800	0.43*	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	240	
	C 35/45	1800	0.136**	52	125	Iron Steel: 38 CrMoAl	20	993	River Sand Crushed Sand	516 344	OPC	338	153	Optima 186	5400	240	
	C 35/45	1800	0.47*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	220	
	C 35/45	1800	0.583*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	210	
	C 35/45	1800	0.35**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	456	Hypercrete R	5060	220	
	C 35/45	1800	0.082**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	210	
	C 35/45	1800	0.636*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	220	
	C 35/45	1800	0.583*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	220	
	C 35/45	1800	0.35**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	220	
	C 35/45	1800	0.5*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	220	
	C 35/45	1800	0.467*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	220	
	C 35/45	1800	0.14**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	230	
	C 35/45	1800	0.7*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	240	
	C 35/45	1800	0.875*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	235	

Project	Concrete Grade	Pressure Applied (Psi)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water Content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (Vertical/Horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
WATER FRONT PROJECT	C 35/45	1800	0.583*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	240	
	C 35/45	1800	0.7*	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	240	
	C 35/45	1800	0.259**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	250	
	C 35/45	1800	0.292**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	240	
	C 35/45	1800	0.368**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	240	
	C 35/45	1800	0.175**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	230	
	C 35/45	1800	0.056**	52	125	Iron Steel: 38 CrMoAl	20	1018	River Sand Manufactured Sand	480 320	PPC	459	156	Hypercrete R	5060	230	
	C 35/45	1800	0.316**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	1	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.462*	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	250	
	C 35/45	1800	0.3**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.3**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.3**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.109**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.133**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.6*	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.6*	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.4*	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.3**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.15**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.2**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.133**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.12**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	

Project	Concrete Grade	Pressure Applied (Psi)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water Content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (Vertical/Horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
WATER FRONT PROJECT	C 35/45	1800	0.33**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.545*	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.429*	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.33**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.075**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 35/45	1800	0.33**	52	125	Iron Steel: 38 CrMoAl	20	1075	River Sand Manufactured Sand	584 194	PPC	449	158	Hypercrete Plus	4500	225	
	C 30/37	1000	0.078**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	0.538*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	0.088**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	0.5*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	210	
	C 30/37	1000	0.35**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	240	
	C 30/37	1000	0.78*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	240	
	C 30/37	1000	0.2**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	0.5*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	1*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	0.32**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	240	
	C 30/37	1000	0.23**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	250	
	C 30/37	1000	1*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	230	
	C 30/37	1000	1*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	240	
	C 30/37	1000	0.538*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	240	
	C 30/37	1000	0.438**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	970	Washed Sand	900	OPC	410	160	Hypercrete	4500	250	
	C 30/37	1000	0.75*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1029	River Sand Manufactured Sand	421 421	OPC	430	159	Hypercrete	4700	230	
	C 30/37	1000	1.14*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1029	River Sand Manufactured Sand	421 421	OPC	430	159	Hypercrete	4700	240	

Project	Concrete Grade	Pressure Applied (Psi)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water Content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (Vertical/Horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
WATER FRONT PROJECT	C 30/37	1000	0.5*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1029	River Sand Manufactured Sand	421 421	OPC	430	159	Hypercrete	4700	230	
	C 30/37	1000	0.23*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1029	River Sand Manufactured Sand	421 421	OPC	430	159	Hypercrete	4700	230	
	C 50/60	1000	0.1**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1088	River Sand	756	PPC	485	146	Hypercrete	5335	250	
	C 50/60	1000	1	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1088	River Sand	756	PPC	485	146	Hypercrete	5335	230	
	C 50/60	1000	0.207**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	20	1088	River Sand	756	PPC	485	146	Hypercrete	5335	230	
	C 50/60	1000	0.2**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	14	833	River Sand	939	PPC	533	160	Hypercrete HS	5000	250	
	C 50/60	1000	0.316**	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	14	833	River Sand	939	PPC	533	160	Hypercrete HS	5000	250	
	C 50/60	1000	0.462*	Vertical: 61m Horizonal: 63m	125	Iron Steel: 38 CrMoAl	14	833	River Sand	939	PPC	533	160	Hypercrete HS	5000	240	
	C 40/50	1000	0.139**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1006	River Sand Manufactured Sand	494 330	OPC	345	147	Optima 186	5600	210	
	C 40/50	1000	0.5*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1006	River Sand Manufactured Sand	494 330	OPC	345	147	Optima 186	5600	240	
	C 40/50	1000	0.194**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1006	River Sand Manufactured Sand	494 330	OPC	345	147	Optima 186	5600	240	
	C 40/50	1000	0.194**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1006	River Sand Manufactured Sand	494 330	OPC	345	147	Optima 186	5600	240	
	C 40/50	1000	0.171**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1041	River Sand Manufactured Sand	472 314	PPC	469	150	Hypercrete R	5600	230	
	C 40/50	1000	0.167**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1041	River Sand Manufactured Sand	472 314	PPC	469	150	Hypercrete R	5600	250	
	C 40/50	1000	0.857*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1041	River Sand Manufactured Sand	472 314	PPC	469	150	Hypercrete R	5600	240	
	C 40/50	1000	0.133**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	20	1041	River Sand Manufactured Sand	472 314	PPC	469	150	Hypercrete R	5600	230	
	C 40/50 (SCC)	1000	0.6*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	610	
	C 40/50 (SCC)	1000	0.4*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	620	
	C 40/50 (SCC)	1000	0.375**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	600	
	C 40/50 (SCC)	1000	0.462*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	630	
	C 40/50 (SCC)	1000	0.375**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	600	
	C 40/50 (SCC)	1000	0.24**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	600	
	C 40/50 (SCC)	1000	0.667*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	610	

Project	Concrete Grade	Pressure Applied (Psi)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water Content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (Vertical/Horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
WATER FRONT PROJECT	C 40/50 (SCC)	1000	0.43*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	610	
	C 40/50 (SCC)	1000	0.6*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	680	
	C 40/50 (SCC)	1000	0.261**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	620	
	C 40/50 (SCC)	1000	0.5*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	660	
	C 40/50 (SCC)	1000	0.15**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	660	
	C 40/50 (SCC)	1000	0.3**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	680	
	C 40/50 (SCC)	1000	0.353**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	690	
	C 40/50 (SCC)	1000	0.4*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	680	
	C 40/50 (SCC)	1000	0.125**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	660	
	C 40/50 (SCC)	1000	0.75*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	650	
	C 40/50 (SCC)	1000	0.14**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	660	
	C 40/50 (SCC)	1000	1.2	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	630	
	C 40/50 (SCC)	1000	0.32**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	610	
	C 40/50 (SCC)	1000	0.43*	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	680	
	C 40/50 (SCC)	1000	0.3**	Horizonal: 68m Vertical: 31m	125	Iron Steel: 38 CrMoAl	14	827	River Sand	933	PPC	515	175	Hypercrete Plus	5500	680	

** Average time taken to pump a truck continuously is 5-6 mins. But results with a time duration less than 15 min can be considered on average

* These results cannot be considered since they have not undergone continuous pumping.

Project	Concrete Grade	Pressure Applied (Psi)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water Content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (Vertical/Horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
AVIC	30NC	40	23	Horizontal:71 Vertical: 138	150	Cast Iron	20	1075	River	845	PPC	385	146	Hypercerte R	3660	200±25	
	35SCC	40	26	Horizontal: 12.6 Vertical: 33.5	150	Cast Iron	20	1003	River	855	PPC	432	160	Hypercerte HS	4104	650±50	
	40NC	40	28	Pump Car	150	Cast Iron	20	997	River	849	PPC	444	160	Hypercerte R	5300	200±25	
	50SCC	40	15	Pump Car	150	Cast Iron	20	916	River	916	PPC	400	145	Hypercerte HS	4500	650±50	
	70SCC	40	8	Pump Car	150	Cast Iron	20	1186	River	592	OPC	450	126	Hypercerte HS	5400	600±50	

Project	Concrete Grade	Pressure Applied (MPa)	Flow rate (m^3/hr)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		water content kg/m3	Admixture		Measured Slump at the site (mm)	Remarks: Additive (Kg)/ Flyash
				Length (m) (vertical/ horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (kg)		
Lotus tower	C50	14-22	15-20	Horizontal: 41 Vertical: 265	130	Steel	20	637	River Sand	807	PPC	450	180	ART-JR2	7	250-270 (Flow: 550-650 mm)	68
	C40	14-22	15-20	Horizontal: 41 Vertical: 75	130	Steel	10	875	River Sand	875	PPC	441	177	ART-JR2	7.4	250-270 (Flow: 650-750 mm)	49
	C35	14-22	15-20	Horizontal: 41m Vertical: 15	130	Steel	10	887	River Sand	887	PPC	414	183	ART-JR2	6	250-270 (Flow: 550-650 mm)	46

Project	Concrete Grade	Pressure Applied (MPa)	Flow rate (m^3/min)	Pipe			Coarse Aggregate		Fine Aggregate		Cement		Water content (kg/m^3)	Admixture		Measured Slump at the site (mm)	Remarks
				Length (m) (vertical/horizontal)	Diameter (mm)	Material	Max. Size (mm)	Content (kg/m^3)	Type (River/M sand)	Content (kg/m^3)	Type (OPC/PPC)	Content (kg/m^3)		Type	Amount (ml)		
Colombo City Centre	C50	26-30	1	Horizontal: 15m Vertical: 57m	125 (Diameter varies from 200mm to 150mm to 125mm)	Cast iron	20	1049	Manufactured sand	791	OPC	410	176	Hypercrete Plus	3690	200	

APPENDIX-X: OBSERVATION SHEETS

Sheet Number: 1

Specimen: Paste phase – 0.2% PCE dosage

Test Date: 18-05-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
46.73 kg	15.42 l (w/c - 0.33)	93 ml (0.2% - 0.2l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	12:43:00	
Mixing	12:43:00	12:46:00
Adding 1/3 of (water and admix)	12:48:00	
Mixing	12:48:00	12:53:00
Sample Testing	12:57:00	13:05:00
Mixing	13:07:00	13:11:00
Mixing	13:24:00	13:32:00
Mixing	13:57:00	14:02:00
Sample Testing	14:03:00	14:20:00
Mixing	14:30:00	14:34:00
Mixing	15:06:00	15:10:00
Sample Testing	15:31:00	15:36:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
12:57:00	153.4	12:58:00	157.59	9.81
13:04:00	163.18	13:01:00	156.48	9.02
		13:04:00	153.06	8.64
14:03:00	254.78	14:04:00	148.37	5.05
14:15:00	191.94	14:16:00	127.7	6.61
14:18:00	146.6	14:17:00	133.71	6.24
		14:20:00	133.9	6.65
15:31:00	1438	15:32:00	864	53.8
15:34:00	835	15:33:00	763	22.51
15:37:00	371	15:36:00	127	32.83

Sheet Number: 2

Specimen: Paste phase – 0.4% PCE dosage

Test Date: 18-05-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
46.73 kg	15.42 l (w/c - 0.33)	187 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of water	10:12:00	
Mixing	10:12:00	10:15:00
Adding 1/3 of water	10:18:00	
Mixing	10:19:00	10:23:00
Adding 0.4% PCE admix.	10:33:00	
Mixing	10:34:00	10:37:00
Mixing	10:42:00	10:45:00
Sample Testing	10:53:00	11:01:00
Mixing	11:02:00	11:05:00
Mixing	11:23:00	11:26:00
Sample Testing	11:39:00	11:44:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
10:53:00	13.5	10:54:00	1.98	1.04
10:55:00	10.5	10:55:00	1.9	0.93
11:00:00	20.26	10:59:00	2.39	0.98
		11:01:00	1.86	1.13
11:39:00	13.19	11:40:00	6.61	0.55
11:41:00	13.93	11:42:00	5.53	0.61
11:43:00	13.32	11:44:00	3.87	0.94
12:14:00	11.41	12:16:00	8.06	0.32
12:17:00	15.3	12:18:00	6.91	0.51
12:19:00	22.05	12:20:00	6.96	0.103
12:22:00	19.2	12:23:00	6.03	0.91
12:45:00	11.34	12:46:00	10.87	0.43
12:47:00	14.91	12:48:00	7.73	0.73
12:50:00	25.33	12:51:00	9.69	0.62
12:52:00	17.35	12:53:00	10.45	0.62
13:09:00	11.61	13:10:00	7.91	0.49
13:13:00	11.97	13:12:00	8.97	0.39
		13:13:00	8.49	0.32
14:37:00	29.33	14:36:00	15.08	0.96

Sheet Number: 3

Specimen: Paste phase – 0.6% PCE dosage

Test Date: 18-05-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
46.73 kg	15.42 l (w/c - 0.33)	280 ml (0.6% - 0.6l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	15:14:00	
Mixing	15:14:00	15:17:00
Adding 1/3 of (water and admix)	15:20:00	
Mixing	15:21:00	15:27:00
Mixing	15:50:00	15:52:00
Sample Testing	15:54:00	16:00:00
Mixing	16:01:00	16:04:00
Mixing	16:28:00	16:32:00
Sample Testing	16:40:00	16:48:00
Mixing	16:54:00	16:57:00
Mixing	17:11:00	17:14:00
Sample Testing	17:17:00	17:24:00
Mixing	17:24:00	17:32:00
Mixing	17:40:00	17:43:00
Sample Testing	17:49:00	17:56:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
15:54:00	6.96	15:53:00	3	0.71
15:57:00	11.72	15:55:00	1.51	0.99
16:00:00	6.254	15:59:00	1.59	1.07
16:40:00	8.041	16:41:00	456	500
16:42:00	8.263	16:43:00	459	500
16:45:00	5.484	16:45:00	475	500
16:48:00	8.47	16:47:00	493	500
17:17:00	6.348	17:18:00	425	500
17:19:00	6.168	17:20:00	463	500
17:21:00	7.318	17:22:00	459	500
17:23:00	5.256	17:24:00	440	500
17:49:00	3.54	17:49:00	436	500
17:52:00	6.109	17:52:00	431	500
17:58:00	7.246	17:54:00	438	500
		17:56:00	445	500

Sheet Number: 4

Specimen: Paste phase – 0.36 w/c ratio

Test Date: 06-06-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
59.1 kg	21.3 l (w/c - 0.36)	188 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	11:41:00	
Mixing	11:41:00	11:44:00
Breaking the stagnated clogs	11:44:00	11:45:00
Adding 1/3 of (water and admix)	11:45:00	
Mixing	11:45:00	11:48:00
Breaking the stagnated clogs	11:48:00	11:52:00
Mixing	11:52:00	11:53:00
Sample Testing	11:59:00	12:07:00
Mixing	12:15:00	12:18:00
Mixing	12:27:00	12:30:00
Sample Testing	12:35:00	12:41:00
Mixing	12:48:00	12:51:00
Mixing	12:57:00	13:00:00
Sample Testing	13:03:00	13:10:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
11:59:00	222.78	12:00:00	222.53	10.59
12:02:00	289.04	12:03:00	217.55	9.14
12:04:00	255.3	12:05:00	207.79	8.35
12:06:00	198.81	12:07:00	140.24	9.5
12:35:00	186.29	12:36:00	196.39	6.7
12:37:00	200.26	12:38:00	150.5	6.77
12:39:00	171.07	12:39:00	150.16	7.01
12:40:00	191.71	12:41:00	156.85	6.86
13:03:00	176.75	13:04:00	210.67	5.07
13:06:00	220.45	13:07:00	167.31	5.95
13:08:00	227.82	13:08:00	172.94	6.25
13:09:00	222.31	13:10:00	174.09	6.98

Sheet Number: 5

Specimen: Paste phase – 0.39 w/c ratio

Test Date: 06-06-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
56.6 kg	22.1 l (w/c - 0.39)	113 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	14:52:00	
Mixing	14:52:00	14:55:00
Breaking the stagnated clogs	14:55:00	14:57:00
Adding 1/3 of (water and admix)	14:57:00	
Mixing	14:57:00	15:00:00
Breaking the stagnated clogs	15:00:00	15:02:00
Mixing	15:02:00	15:04:00
Sample Testing	15:09:00	15:16:00
Mixing	15:23:00	15:26:00
Mixing	15:38:00	15:41:00
Sample Testing	15:45:00	15:52:00
Mixing	15:58:00	16:01:00
Mixing	16:08:00	16:11:00
Sample Testing	16:22:00	16:31:00
Mixing	16:36:00	16:39:00
Mixing	17:04:00	17:07:00
Sample Testing	17:12:00	17:22:00
Mixing	17:26:00	17:29:00
Mixing	17:38:00	17:41:00
Sample Testing	17:52:00	18:00:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
15:09:00	82.04	15:10:00	94.15	2.3
15:11:00	93.53	15:12:00	72.31	2.75
15:13:00	90.85	15:14:00	73.66	2.86
15:16:00	97.55	15:16:00	106.06	2.88
15:45:00	70.36	15:46:00	81.25	1.7
15:48:00	59.16	15:48:00	66.64	2.01
15:49:00	81.96	15:50:00	67.6	2.17
15:51:00	79.9	15:52:00	90.93	2.23
16:22:00	119.84	16:23:00	115.46	2.98
16:24:00	111.9	16:25:00	92.93	3.21
16:28:00	154.95	16:28:00	106.37	3.48
16:31:00	138.68	16:31:00	107.26	3.64
17:12:00	248.17	17:13:00	257.21	5.67
17:15:00	313.4	17:16:00	187.6	6.76
17:19:00	191.86	17:19:00	194.75	6.86
17:21:00	280.78	17:22:00	178.26	7.24
17:52:00	1834.81	17:53:00	532.19	21.54
17:55:00	489.53	17:56:00	135.27	24.15
17:57:00	440.37	17:58:00	174.96	17.07
17:59:00	417.23	18:00:00	107.68	19.01

Sheet Number: 6

Specimen: Paste phase – 0.42 w/c ratio

Test Date: 07-06-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
54.25 kg	22.80 l (w/c - 0.42)	108 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	9:45:00	
Mixing	9:45:00	9:48:00
Breaking the stagnated clogs	9:48:00	9:52:00
Adding 1/3 of (water and admix)	9:52:00	
Mixing	9:52:00	9:55:00
Sample Testing	9:59:00	10:10:00
Mixing	10:15:00	10:18:00
Mixing	10:40:00	10:43:00
Sample Testing	10:47:00	10:55:00
Mixing	11:02:00	11:05:00
Mixing	11:18:00	11:21:00
Sample Testing	11:26:00	11:33:00
Mixing	11:36:00	11:39:00
Mixing	11:49:00	11:52:00
Sample Testing	11:56:00	12:02:00
Mixing	12:09:00	12:12:00
Mixing	12:20:00	12:23:00
Mixing	12:31:00	12:34:00
Sample Testing	12:40:00	12:47:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
9:59:00	26.4	10:01:00	34.62	0.25
10:03:00	41.61	10:04:00	20.47	0.61
10:06:00	34.92	10:07:00	23.66	0.66
10:09:00	37	10:10:00	24.4	0.63
10:47:00	26.69	10:48:00	30.64	0.43
10:49:00	30.04	10:50:00	23.91	0.59
10:52:00	34.52	10:53:00	24.02	0.66
10:54:00	33.23	10:55:00	25.81	0.73
11:26:00	33.35	11:27:00	38.06	0.56
11:29:00	27.44	11:29:00	31.84	0.65
11:30:00	36.42	11:31:00	40.65	0.72
11:32:00	39.21	11:35:00	32.64	0.86
11:56:00	44.76	11:56:00	47.96	0.8
11:57:00	35.72	11:57:00	39.06	0.88
11:59:00	36.65	11:59:00	40.84	0.8
12:02:00	52.45	12:02:00	58.02	0.92
12:40:00	87.59	12:40:00	94.49	1.96
12:41:00	83.75	12:41:00	67.43	2.28
12:43:00	72.25	12:44:00	77.33	2.46
12:45:00	100.41	12:47:00	112.24	2.34

Sheet Number: 7

Specimen: Paste phase – 0.45 w/c ratio

Test Date: 07-06-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
54.25 kg	22.80 l (w/c - 0.45)	108 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	14:13:00	
Mixing	14:13:00	14:16:00
Breaking the stagnated clogs	14:16:00	14:17:00
Adding 1/3 of (water and admix)	17:17:00	
Mixing	14:17:00	14:20:00
Breaking the stagnated clogs	14:20:00	14:22:00
Mixing	14:22:00	14:24:00
Sample Testing	14:29:00	14:36:00
Mixing	14:41:00	14:44:00
Mixing	14:57:00	15:00:00
Sample Testing	15:03:00	15:11:00
Mixing	15:14:00	15:17:00
Mixing	15:27:00	15:30:00
Sample Testing	15:33:00	15:50:00
Mixing	15:53:00	15:56:00
Mixing	16:21:00	16:24:00
Sample Testing	16:26:00	16:41:00
Mixing	16:46:00	16:49:00
Mixing	16:58:00	17:01:00
Sample Testing	17:06:00	17:09:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
14:29:00	18.97	14:30:00	20.37	0.51
14:30:00	22.45	14:31:00	21.11	0.37
14:33:00	18.42	14:33:00	19.83	0.44
14:36:00	23.22	14:36:00	25.67	0.64
15:03:00	19.04	15:03:00	19.97	0.49
15:05:00	19.48	15:06:00	20.94	0.51
15:09:00	20.85	15:08:00	18.17	0.63
15:11:00	20.55	15:11:00	23.74	0.49
15:33:00	19.97	15:34:00	23.39	0.41
15:36:00	23.13	15:36:00	24.59	0.42
15:38:00	25.05	15:38:00	27.13	0.55
15:50:00	21.11	15:50:00	18.63	0.85
16:26:00	35.72	16:28:00	41.58	0.84
16:31:00	43.37	16:32:00	34.92	0.97
16:34:00	48.21	16:34:00	36.19	1.22
16:41:00	31.67	16:41:00	33.42	1.49
17:06:00	58.31	17:06:00	64.79	1.37
17:06:00	44.81	17:09:00	48.19	1.74

Sheet Number: 8

Specimen: Paste phase – PLC Cement type

Test Date: 23-06-2018

Sample Quantities:

Portland Limestone Cement (INSEE Sanstha)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
49.5 kg	16.35 l (w/c - 0.33)	198 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of (water and admix)	9:13:00	9:18:00
Mixing	9:18:00	9:21:00
Breaking the stagnated clogs	9:21:00	9:23:00
Adding 1/3 of (water and admix)	9:23:00	
Mixing	9:23:00	9:27:00
Breaking the stagnated clogs	9:27:00	9:30:00
Mixing	9:30:00	9:33:00
Sample Testing	9:41:00	9:54:00
Mixing	9:58:00	10:02:00
Mixing	10:18:00	10:21:00
Sample Testing	10:25:00	10:34:00
Mixing	10:41:00	10:44:00
Mixing	11:01:00	11:04:00
Sample Testing	11:09:00	11:17:00
Mixing	11:26:00	11:29:00
Mixing	11:35:00	11:38:00
Sample Testing	11:42:00	11:52:00
Mixing	11:56:00	11:59:00
Mixing	12:06:00	12:09:00
Sample Testing	12:14:00	12:25:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
9:41:00	101.1	9:43:00	87.27	5.43
9:44:00	133	9:46:00	61.68	6.55
9:49:00	131.03	9:51:00	57.42	6.68
10:25:00	66.36	10:28:00	72.01	2.66
10:29:00	104.36	10:32:00	60.29	3.42
10:35:00	64.06	10:34:00	61.99	3.41
11:09:00	75.97	11:11:00	77.74	2.86
11:12:00	106.18	11:15:00	63.76	3.67
11:16:00	100.37	11:17:00	69.32	3.42
11:42:00	78.5	11:44:00	84.25	3.69
11:46:00	117.37	11:48:00	73.76	2.88
11:49:00	117.46	11:52:00	74.52	3.57
12:14:00	103.45	12:17:00	111.59	2.68
12:18:00	154.82	12:20:00	81.89	4.73
12:22:00	180.07	12:25:00	100.61	4.21

Sheet Number: 9

Specimen: Paste phase –Cement type

Test Date: 23-06-2018

Sample Quantities:

Portland Limestone Cement (INSEE Mahaweli Marine)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
49.5 kg	16.35 l (w/c - 0.33)	198 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of water	10:47:00	
Mixing	13:39:00	13:42:00
Breaking the residue	13:42:00	13:45:00
Adding 1/3 of water	13:45:00	13:48:00
Mixing	13:49:00	13:52:00
Sample Testing	13:58:00	14:07:00
Mixing	14:12:00	14:15:00
Mixing	14:22:00	14:25:00
Sample Testing	14:29:00	14:40:00
Mixing	14:43:00	14:46:00
Mixing	14:52:00	14:55:00
Sample Testing	14:58:00	15:07:00
Mixing	15:22:00	15:25:00
Mixing	15:30:00	15:33:00
Sample Testing	15:37:00	15:45:00
Mixing	15:54:00	15:57:00
Mixing	16:02:00	16:05:00
Sample Testing	16:08:00	16:19:00
Mixing	16:21:00	16:24:00
Mixing	16:32:00	16:35:00
Mixing	16:46:00	16:47:00
Sample Testing	16:49:00	16:58:00

Observations

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
13:58:00	11.89	14:00:00	10.54	0.15
14:01:00	23.75	14:03:00	8.29	0.49
14:05:00	20.81	14:07:00	9.53	0.38
14:29:00	13.62	14:32:00	11.48	0.18
14:33:00	24.98	14:35:00	14.12	0.31
14:38:00	24.45	14:40:00	10.8	0.36
14:58:00	13.83	15:00:00	12.47	0.42
15:01:00	24.04	15:03:00	11.67	0.25
15:05:00	24.74	15:07:00	11.4	0.6
15:37:00	17.41	15:39:00	19.01	0.12
15:42:00	17.87	15:42:00	16.83	0.24
15:43:00	31.36	15:45:00	17.13	0.37
16:08:00	19.75	16:11:00	16.48	0.75
16:12:00	37.38	16:14:00	17.6	0.49
16:15:00	36.57	16:19:00	22.66	0.66
16:49:00	31.52	16:52:00	33.51	0.59
16:55:00	35.78	16:55:00	30.31	0.66
16:55:00	57.26	16:58:00	27.78	0.9

Sheet Number: 10

Specimen: Paste phase – OPC Cement type

Test Date: 22-06-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
49.5 kg	16.35 l (w/c - 0.33)	198 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of water	10:47:00	
Mixing	10:47:00	10:50:00
Breaking the residue	10:50:00	10:54:00
Adding 1/3 of water	10:54:00	10:56:00
Mixing	10:56:00	10:59:00
Sample Testing	11:07:00	11:15:00
Mixing	11:25:00	11:28:00
Mixing	11:35:00	11:38:00
Sample Testing	11:48:00	11:55:00
Mixing	12:04:00	12:07:00
Mixing	12:12:00	12:15:00
Sample Testing	12:20:00	12:28:00
Mixing	12:32:00	12:35:00
Mixing	12:43:00	12:46:00
Sample Testing	12:49:00	13:01:00
Mixing	13:11:00	13:14:00
Mixing	13:29:00	13:23:00
Sample Testing	13:27:00	13:38:00
Mixing	13:40:00	13:43:00
Mixing	13:50:00	13:53:00
Sample Testing	13:59:00	14:10:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
11:07:00	85.73	11:09:00	31.36	12.29
11:09:00	100.96	11:12:00	30.64	9.92
11:13:00	95.31	11:15:00	32.46	9.04
11:48:00	60.27	11:49:00	37.3	5.58
11:51:00	72.57	11:53:00	31.85	5.25
11:54:00	73.2	11:55:00	30.68	5.86
12:20:00	34.63	12:21:00	27.96	3.42
12:22:00	47.83	12:24:00	25.86	3.36
12:25:00	55.65	12:28:00	27.2	3.81
12:49:00	28.01	12:51:00	23.75	2.74
12:58:00	46.16	12:54:00	23.05	2.88
12:59:00	77.15	12:58:00	25.13	3.33
13:27:00	29.59	13:30:00	22.49	3.13
13:31:00	63.58	13:34:00	23.41	3.21
13:36:00	67.63	13:38:00	28.98	3.29
13:59:00	36.55	14:02:00	30.1	3.14
14:06:00	32.66	14:06:00	29.33	3.31
14:08:00	85.48	14:10:00	22.36	4.97

Sheet Number: 11

Specimen: Paste phase – FA Cement type

Test Date: 24-06-2018

Sample Quantities:

Fly Ash Blended Cement (INSEE Rapid Flow Plus)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
49.5 kg	16.35 l (w/c - 0.33)	198 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of water	13:16:00	13:21:00
Mixing	13:21:00	13:24:00
Breaking the residue	13:24:00	13:28:00
Adding 1/3 of water	13:28:00	13:30:00
Breaking the residue	13:30:00	13:32:00
Mixing	13:32:00	13:33:00
Breaking the residue	13:33:00	13:36:00
Mixing	13:36:00	13:39:00
Sample Testing	13:44:00	13:54:00
Mixing	14:01:00	14:04:00
Mixing	14:10:00	14:13:00
Sample Testing	14:16:00	14:31:00
Mixing	14:34:00	14:37:00
Mixing	14:42:00	14:45:00
Sample Testing	14:48:00	14:57:00
Mixing	15:01:00	15:04:00
Mixing	15:10:00	15:13:00
Sample Testing	15:17:00	15:29:00
Mixing	15:32:00	15:35:00
Mixing	15:42:00	15:45:00
Sample Testing	15:49:00	15:56:00
Mixing	16:00:00	16:03:00
Mixing	16:10:00	16:13:00
Sample Testing	16:16:00	16:35:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
13:44:00	10.37	13:46:00	3.16	2.06
13:47:00	1958	13:50:00	4.51	2.01
13:51:00	23.55	13:54:00	2.8	1.82
14:16:00	6.97	14:19:00	1.18	1.3
14:20:00	11.97	14:25:00	2.76	1.69
14:27:00	18.11	14:31:00	3.37	1.18
14:48:00	5.79	14:50:00	1.02	1.31
14:51:00	10.63	14:53:00	2.53	1.51
14:55:00	16.65	14:57:00	3.47	1.39
15:17:00	7.33	15:20:00	1.36	1.39
15:20:00	9	15:23:00	3.18	1.26
15:24:00	11.39	15:27:00	8.02	1.8
15:49:00	7.1	15:51:00	error	error
15:52:00	12.06	15:55:00	error	error
15:56:00	12.8	15:58:00	error	error
		16:19:00	error	error
16:30:00	9.83	16:32:00	7.57	0.64
16:35:00	10.76	16:35:00	9.98	0.57

Sheet Number: 12

Specimen: Paste phase – FA Cement type

Test Date: 25-06-2018

Sample Quantities:

Fly Ash Blended Cement (INSEE Extra)	Water	Poly Carboxylic Ether (PCE) Hypercrete plus M
49.5 kg	16.35 l (w/c - 0.33)	198 ml (0.4% - 0.4l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Cement plus 2/3 of water	9:10:00	
Mixing	9:12:00	9:15:00
Breaking the residue	9:15:00	9:19:00
Adding 1/3 of water	9:20:00	9:23:00
Mixing	9:25:00	9:27:00
Sample Testing	9:31:00	9:41:00
Mixing	9:46:00	9:49:00
Mixing	9:56:00	9:59:00
Sample Testing	10:04:00	10:12:00
Mixing	10:17:00	10:20:00
Mixing	10:31:00	10:34:00
Sample Testing	10:37:00	10:46:00
Mixing	10:49:00	10:52:00
Mixing	10:58:00	11:01:00
Sample Testing	11:03:00	11:12:00
Mixing	11:15:00	11:18:00
Mixing	11:25:00	11:28:00
Sample Testing	11:31:00	11:39:00
Mixing	11:42:00	11:45:00
Mixing	11:52:00	11:55:00
Sample Testing	11:57:00	12:06:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
9:31:00	36.36	9:33:00	19.25	5.21
9:34:00	54.15	9:37:00	15.51	5.79
9:38:00	65.21	9:41:00	12.45	7.14
10:04:00	24.7	10:06:00	16.02	2.74
10:07:00	39.58	10:10:00	11.95	3.75
10:12:00	19.99	10:12:00	13.96	3.71
10:37:00	18.43	10:39:00	13.32	1.81
10:40:00	22.99	10:42:00	12.1	2.21
10:44:00	34.94	10:46:00	12.84	2.46
11:03:00	15.9	11:05:00	14.01	1.25
11:06:00	21.73	11:09:00	10.74	1.81
11:09:00	23.19	11:12:00	10.56	1.96
11:31:00	15.05	11:34:00	15.05	1.51
11:34:00	19.55	11:36:00	8.91	1.72
11:37:00	20.23	11:39:00	9.34	1.85
11:57:00	12.04	12:00:00	7.52	1.46
12:00:00	16.51	12:02:00	7.8	1.65
12:03:00	18.09	12:06:00	7.66	1.92

Sheet Number: 13

Specimen: Mortar phase – 0.6% PCE

Test Date: 10-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.70 kg	8.65 l (w/c - 0.42)	39.35 kg	125 ml (0.6% - 0.6l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	10:09:00	
Dry mix	10:09:00	10:12:00
Adding 2/3 of water	10:12:00	10:13:00
Mixing	10:13:00	10:16:00
Breaking Residue	10:16:00	10:19:00
Adding 1/3 of water and mixing	10:19:00	10:22:00
Sample Testing	10:28:00	10:38:00
Mixing	10:44:00	10:47:00
Mixing	10:54:00	10:57:00
Sample Testing	10:59:00	11:07:00
Mixing	11:12:00	11:15:00
Mixing	11:25:00	11:28:00
Sample Testing	11:29:00	11:38:00
Mixing	11:41:00	11:44:00
Mixing	11:55:00	11:58:00
Sample Testing	12:05:00	12:14:00
Mixing	12:18:00	12:21:00
Mixing	12:28:00	12:31:00
Sample Testing	12:33:00	12:43:00
Mixing	12:46:00	12:49:00
Mixing	12:56:00	12:59:00
Sample Testing	13:02:00	13:12:00

Observations:

Test Results

Stress Growth Test		Flow Table Test			Flow Table Test		V Funnel Test	
Time	SYS	Time	DYS	PV	Time	Flow	Time	T_0
10:28:00	563	10:31:00	118	45	10:30	180	10:35	17.88
10:31:00	509	10:34:00	120	30				
10:36:00	594	10:38:00	113	29				
10:59:00	208	11:01:00	135	13	10:59	195	11:03	8
11:01:00	203	11:04:00	127	12				
11:05:00	296	11:07:00	170	13				
11:29:00	175	11:32:00	143	8	11:31	200	11:36	6.44
11:32:00	254	11:35:00	115	9				
11:36:00	297	11:38:00	110	10				
12:05:00	184	12:07:00	165	6	12:06	190	12:10	8
12:08:00	284	12:11:00	130	9				
12:12:00	336	12:14:00	133	10				
12:33:00	200	12:36:00	196	5	12:35	190	12:39	8.09
12:36:00	257	12:39:00	148	7				
12:40:00	355	12:43:00	159	7				
13:02:00	254	13:04:00	245	5	13:03	175	13:08	8
13:05:00	302	13:08:00	177	7				
13:10:00	446	13:12:00	191	8				

Sheet Number: 14

Specimen: Mortar phase – 0.7% PCE

Test Date: 07-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.70 kg	8.7 l (w/c - 0.42)	39.35 kg	145 ml (0.7% - 0.7 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:41:00	
Dry mix	9:41:00	9:44:00
Adding 2/3 of water	9:44:00	9:47:00
Mixing	9:47:00	9:50:00
Breaking Residue	9:50:00	9:52:00
Adding 1/3 of water and mixing	9:52:00	9:55:00
Sample Testing	10:01:00	10:11:00
Mixing	10:16:00	10:19:00
Mixing	10:28:00	10:31:00
Sample Testing	10:40:00	10:50:00
Mixing	10:53:00	10:56:00
Mixing	11:03:00	11:06:00
Sample Testing	11:12:00	11:22:00
Mixing	11:29:00	11:32:00
Mixing	11:38:00	11:41:00
Sample Testing	11:44:00	11:52:00
Mixing	11:55:00	11:58:00
Mixing	12:07:00	12:10:00
Sample Testing	12:14:00	12:23:00
Mixing	12:25:00	12:28:00
Mixing	12:37:00	12:40:00
Sample Testing	12:44:00	12:53:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test	
Time	SYS	Time	DYS	PV	Time	Flow
10:01:00	247	10:04:00	28	35		
10:05:00	217	10:08:00	29	31	10:05	200
10:08:00	240	10:11:00	27	30		
10:40:00	130	10:43:00	51	9		
10:43:00	155	10:47:00	39	12	10:45	210
10:47:00	139	10:50:00	40	13		
11:12:00	94	11:15:00	63	6		
11:16:00	167	11:19:00	51	9	11:16	210
11:19:00	205	11:22:00	53	11		
11:44:00	82	11:46:00	81	4		
11:47:00	169	11:49:00	63	8	11:45	195
11:50:00	153	11:52:00	65	9		
12:14:00	114	12:16:00	97	5		
12:17:00	173	12:19:00	78	7	12:18	190
12:20:00	192	12:23:00	80	8		
12:44:00	134	12:47:00	118	6		
12:47:00	248	12:50:00	102	7	12:49	185
12:50:00	202	12:53:00	103	8		

Sheet Number: 15

Specimen: Mortar phase – 0.8% PCE

Test Date: 04-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.70 kg	8.7 l (w/c - 0.42)	39.35 kg	166 ml (0.8% - 0.8 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:10:00	
Dry mix	9:10:00	9:13:00
Adding 2/3 of water	9:13:00	9:16:00
Mixing	9:16:00	9:19:00
Adding 1/3 of water and mixing	9:19:00	9:22:00
Sample Testing	9:28:00	9:38:00
Mixing	9:44:00	9:47:00
Mixing	9:57:00	10:00:00
Sample Testing	10:03:00	10:12:00
Mixing	10:14:00	10:17:00
Mixing	10:27:00	10:30:00
Sample Testing	10:39:00	10:48:00
Mixing	10:51:00	10:54:00
Mixing	10:59:00	11:02:00
Sample Testing	11:04:00	11:13:00
Mixing	11:16:00	11:19:00
Mixing	11:29:00	11:32:00
Sample Testing	11:35:00	11:43:00
Mixing	11:45:00	11:48:00
Mixing	11:59:00	12:02:00
Sample Testing	12:04:00	12:12:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test		
Time	SYS	Time	DYS	PV
9:28:00	592	9:31:00	20	69
9:31:00	326	9:34:00	23	57
9:35:00	466	9:38:00	23	53
10:03:00	142	10:05:00	60	19
10:06:00	290	10:08:00	49	24
10:09:00	238	10:12:00	47	23
10:39:00	410	10:41:00	82	18
10:42:00	288	10:45:00	67	20
10:45:00	267	10:48:00	68	21
11:04:00	155	11:07:00	95	12
11:07:00	266	11:10:00	81	16
11:10:00	282	11:13:00	86	17
11:35:00	275	11:38:00	143	9
11:38:00	274	11:40:00	110	14
11:40:00	302	11:43:00	115	15
12:04:00	233	12:07:00	179	11
12:08:00	361	12:10:00	146	14
12:10:00	342	12:12:00	145	15

Sheet Number: 16

Specimen: Mortar phase – 0.9% PCE

Test Date: 09-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.70 kg	8.7 l (w/c - 0.42)	39.35 kg	186 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:08:00	
Dry mix	9:08:00	9:11:00
Adding 2/3 of water	9:11:00	9:13:00
Mixing	9:13:00	9:16:00
Breaking Residue	9:16:00	9:17:00
Adding 1/3 of water and mixing	9:17:00	9:20:00
Mixing	9:21:00	9:23:00
Sample Testing	9:28:00	9:37:00
Mixing	9:40:00	9:43:00
Mixing	9:53:00	9:55:00
Mixing	10:07:00	10:10:00
Sample Testing	10:12:00	10:25:00
Mixing	10:28:00	10:31:00
Mixing	10:38:00	10:41:00
Sample Testing	10:46:00	10:58:00
Mixing	11:06:00	11:09:00
Mixing	11:20:00	11:23:00
Sample Testing	11:25:00	11:34:00
Mixing	11:40:00	11:43:00
Mixing	11:53:00	11:56:00
Sample Testing	12:00:00	12:09:00
Mixing	12:15:00	12:18:00
Mixing	12:18:00	12:21:00
Sample Testing	12:33:00	12:43:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test	
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0
9:28:00	170	9:30:00	5	32	9:32	220	9:57	5.5
9:31:00	105	9:33:00	2	34				
9:34:00	93	9:37:00	2	33				
10:12:00	46	10:15:00	15	11				
10:20:00	127	10:22:00	9	15				
10:22:00	127	10:25:00	11	16				
10:46:00	45	10:48:00	18	10				
10:49:00	119	10:54:00	12	14				
10:55:00	100	10:58:00	14	14				
11:25:00	47	11:28:00	29	7	11:27	215	11:47	5.22
11:28:00	133	11:32:00	28	10				
11:32:00	117	11:34:00	20	13				
12:00:00	62	12:03:00	39	7	11:45	215		
12:03:00	116	12:05:00	29	11				
12:06:00	144	12:09:00	27	13				
12:33:00	73	12:36:00	52	7	12:35	200	12:52	5
12:36:00	205	12:39:00	36	12				
12:40:00		12:43:00	40	12				

Sheet Number: 17

Specimen: Mortar phase – 0.33 w/c ratio

Test Date: 27-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
23.65 kg	7.80 l (w/c - 0.33)	39.35 kg	213 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:27:00	
Dry mix	9:27:00	9:30:00
Adding 2/3 of water	9:30:00	9:31:00
Mixing	9:31:00	9:34:00
Breaking Residue	9:34:00	9:37:00
Adding 1/3 of water and mixing	9:37:00	9:40:00
Further Mixing	9:40:00	9:43:00
Sample Testing _too sticky	9:48:00	9:55:00
Mixing	10:00:00	10:03:00
Mixing	10:20:00	10:25:00
Sample Testing	10:29:00	10:42:00
Mixing	10:47:00	10:50:00
Mixing	11:00:00	11:03:00
Sample Testing	11:06:00	11:15:00
Mixing	11:18:00	11:21:00
Mixing	11:31:00	11:34:00
Sample Testing	11:38:00	11:47:00
Mixing	11:52:00	11:55:00
Mixing	12:02:00	12:05:00
Sample Testing	12:08:00	12:17:00
Mixing	12:25:00	12:28:00
Mixing	12:38:00	12:41:00
Sample Testing	12:46:00	12:49:00

Observations:

Tests Results

Stress Growth Test		Flow Curve Test			Flow Table Test	
Time	SYS	Time	DYS	PV	Time	Flow
10:29:00	920	10:32:00	0	188		
10:32:00	1120	10:35:00	10	162	10:35	155
10:35:00	835	10:38:00	18	142		
11:06:00	645	11:09:00	63	84		
11:09:00	875	11:12:00	65	81	11:09	150
11:12:00	956	11:15:00	60	84		
11:38:00	596	11:41:00	93	73		
11:41:00	906	11:44:00	91	72	11:45	145
11:44:00	832	11:47:00	89	75		
12:08:00	582	12:11:00	131	63		
12:11:00	1045	12:14:00	132	64	12:13	130
12:14:00	864	12:17:00	132	66		
12:46:00	961	12:51:00	219	70		
12:51:00	1682	12:54:00	239	66		
12:58:00	1206	12:59:00	250	67		

Sheet Number: 18

Specimen: Mortar phase – 0.36 w/c ratio

Test Date: 28-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
22.60 kg	8.14 l (w/c - 0.42)	39.35 kg	203 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:11:00	
Dry mix	9:11:00	9:14:00
Adding 2/3 of water	9:14:00	9:16:00
Mixing	9:16:00	9:19:00
Breaking Residue	9:19:00	9:20:00
Adding 1/3 of water and mixing	9:20:00	9:25:00
Sample Testing	9:32:00	9:45:00
Mixing	9:53:00	9:56:00
Mixing	10:06:00	10:09:00
Sample Testing	10:12:00	10:20:00
Mixing	10:23:00	10:26:00
Mixing	10:36:00	10:39:00
Sample Testing	10:43:00	10:51:00
Mixing	10:53:00	10:56:00
Mixing	11:03:00	11:06:00
Sample Testing	11:10:00	11:19:00
Mixing	11:23:00	11:26:00
Mixing	11:36:00	11:39:00
Sample Testing	11:42:00	11:50:00
Mixing	11:55:00	11:58:00
Mixing	12:06:00	12:09:00
Sample Testing	12:12:00	12:21:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:32:00	647	9:35:00	0	153	9:36:00	165			
9:36:00	372	9:39:00	0	106					
9:39:00	179	9:42:00	0	90					
10:12:00	119	10:15:00	15	38	10:12:00	175			
10:15:00	330	10:18:00	8	44					
10:18:00	182	10:20:00	5	47					
10:43:00	116	10:46:00	25	23	10:45:00	185	11:00:00	7.87	13.03
10:46:00	252	10:49:00	24	27					
10:48:00	204	10:51:00	20	31					
11:10:00	126	11:13:00	33	19	11:13:00	170	11:30:00	10.0	14.53
11:13:00	345	11:16:00	30	25					
11:16:00	227	11:19:00	30	27					
11:42:00	109	11:45:00	48	18	11:44:00	170	12:02:00	10.84	15.94
11:45:00	264	11:47:00	37	24					
11:47:00	257	11:50:00	37	26					
12:12:00	148	12:15:00	61	17	12:13:00	170	12:31:00	8.69	11.0
12:16:00	316	12:19:00	52	23					
12:19:00	337	12:21:00	51	27					

Sheet Number: 19

Specimen: Mortar phase – 0.39 w/c ratio

Test Date: 29-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
21.65 kg	8.45 l (w/c - 0.42)	39.35 kg	195 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:03:00	
Dry mix	9:03:00	9:06:00
Adding 2/3 of water	9:06:00	9:08:00
Mixing	9:08:00	9:11:00
Adding 1/3 of water and mixing	9:12:00	9:15:00
Sample Testing	9:20:00	9:28:00
Mixing	9:37:00	9:40:00
Mixing	9:50:00	9:53:00
Sample Testing	9:56:00	10:05:00
Mixing	10:07:00	10:10:00
Mixing	10:20:00	10:23:00
Sample Testing	10:25:00	10:34:00
Mixing	10:37:00	10:40:00
Mixing	10:50:00	10:53:00
Sample Testing	10:55:00	11:06:00
Mixing	11:10:00	11:13:00
Mixing	11:23:00	11:26:00
Sample Testing	11:33:00	11:43:00
Mixing	11:46:00	11:49:00
Mixing	11:59:00	12:02:00
Sample Testing	12:05:00	12:14:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:20:00	85	9:23:00	0	42	9:25:00	180	9:42:00	7.56	11
9:23:00	188	9:26:00	0	51					
9:26:00	150	9:28:00	0	52					
9:56:00	79	9:59:00	13	19	9:56:00	190	10:13:00	5.97	7.6
9:59:00	167	10:02:00	11	22					
10:02:00	122	10:05:00	10	24					
10:25:00	52	10:28:00	17	13	10:29:00	190	10:28:00	5.69	6.75
10:29:00	179	10:31:00	17	17					
10:31:00	114	10:34:00	16	18					
10:55:00	56	10:58:00	25	10	10:57:00	195	10:58:00	6	6.93
10:59:00	214	11:02:00	19	15					
11:02:00	111	11:06:00	18	17					
11:33:00	74	11:36:00	35	9	11:37:00	180	11:35:00	5.69	
11:36:00	202	11:39:00	31	14					
11:40:00	202	11:43:00	28	17					
12:05:00	90	12:08:00	46	9	12:06:00	180	12:07:00	6.59	8.09
12:09:00	204	12:11:00	39	14					
12:11:00	178	12:14:00	37	16					

Sheet Number: 20

Specimen: Mortar phase – 0.42 w/c ratio

Test Date: 30-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.70 kg	8.70 l (w/c - 0.42)	39.35 kg	186 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:09:00	
Dry mix	9:09:00	9:12:00
Adding 2/3 of water	9:12:00	9:14:00
Mixing	9:14:00	9:17:00
Breaking Residue	9:17:00	9:20:00
Adding 1/3 of water and mixing	9:20:00	9:23:00
Sample Testing	9:27:00	9:37:00
Mixing	9:41:00	9:44:00
Mixing	9:54:00	9:57:00
Sample Testing	10:00:00	10:07:00
Mixing	10:11:00	10:14:00
Mixing	10:24:00	10:27:00
Sample Testing	10:33:00	10:42:00
Mixing	10:45:00	10:48:00
Mixing	10:58:00	11:01:00
Sample Testing	11:08:00	11:19:00
Mixing	11:21:00	11:24:00
Mixing	11:34:00	11:37:00
Sample Testing	11:40:00	11:50:00
Mixing	11:53:00	11:56:00
Mixing	12:06:00	12:09:00
Sample Testing	12:14:00	12:24:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:27:00	60	9:30:00	7	12	9:34:00	185	9:29:00	3.66	4.78
9:31:00	152	9:34:00	6	16					
9:34:00	72	9:37:00	7	17					
10:00:00	76	10:02:00	15	7	10:03:00	195	10:00:00	3.82	4.31
10:03:00	79	10:05:00	13	10					
10:06:00	80	10:07:00	6	13					
10:33:00	48	10:36:00	16	6	10:34:00	215	10:33:00	3.66	3.81
10:37:00	120	10:39:00	13	9					
10:40:00	90	10:42:00	14	10					
11:08:00	44	11:11:00	22	4	11:16:00	205	11:10:00	3.37	3.72
11:12:00	112	11:15:00	21	7					
11:16:00	101	11:19:00	19	9					
11:40:00	55	11:43:00	26	5	11:42:00	195	11:40:00	3.68	4.4
11:44:00	111	11:44:00	23	8					
11:47:00	101	11:50:00	24	9					
12:14:00	69	12:17:00	32	5	12:15:00	190	12:14:00	3.82	4.19
12:18:00	158	12:21:00	28	8					
12:21:00	124	12:24:00	27	10					

Sheet Number: 21

Specimen: Mortar phase – 0.45 w/c ratio

Test Date: 31-08-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
19.95 kg	8.98 l (w/c - 0.42)	39.35 kg	180 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:15:00	
Dry mix	9:15:00	9:18:00
Adding 2/3 of water	9:18:00	9:21:00
Mixing	9:21:00	9:24:00
Breaking Residue	9:24:00	9:26:00
Adding 1/3 of water and mixing	9:26:00	9:29:00
Sample Testing	9:36:00	9:48:00
Mixing	9:53:00	9:56:00
Mixing	10:06:00	10:09:00
Sample Testing	10:14:00	10:24:00
Mixing	10:28:00	10:31:00
Mixing	10:41:00	10:44:00
Sample Testing	10:48:00	10:57:00
Mixing	11:02:00	11:05:00
Mixing	11:13:00	11:16:00
Sample Testing	11:21:00	11:30:00
Mixing	11:32:00	11:35:00
Mixing	11:43:00	11:46:00
Sample Testing	11:51:00	12:00:00
Mixing	12:01:00	12:04:00
Mixing	12:14:00	12:17:00
Sample Testing	12:20:00	12:28:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:36:00	24	9:39:00	4	9					
9:40:00	58	9:42:00	3	13			9:38:00	3.15	4.35
9:43:00	27	9:48:00	4	16					
10:14:00	29	10:18:00	6	6					
10:19:00	30	10:22:00	6	8	10:17:00	210	10:13:00	2.78	3
10:22:00	45	10:24:00	7	9					
10:48:00	-	10:48:00	-	-					
10:51:00	23	10:54:00	5	6	10:52:00	200	10:49:00	2.5	2.69
10:54:00	30	10:57:00	6	7					
11:21:00	26	11:24:00	8	5					
11:24:00	39	11:27:00	7	6	11:23:00	200	11:20:00	2.43	2.38
11:27:00	32	11:30:00	9	7					
11:51:00	30	11:54:00	11	4					
11:55:00	41	11:57:00	9	6	11:53:00	205	11:49:00	2.37	2.78
11:57:00	41	12:00:00	11	7					
12:20:00	29	12:23:00	15	4					
12:23:00	49	12:26:00	12	6	12:22:00	200	12:19:00	2.91	3.15
12:26:00	49	12:28:00	13	7					

Sheet Number: 22

Specimen: Mortar phase – 0.45 FA/Mortar by volume

Test Date: 07-09-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
22.30 kg	9.37 l (w/c - 0.42)	36.32 kg	201 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:40:00	
Dry mix	9:40:00	9:43:00
Adding 2/3 of water	9:43:00	9:46:00
Mixing	9:46:00	9:49:00
Breaking Residue	9:49:00	9:50:00
Adding 1/3 of water and mixing	9:50:00	9:53:00
Further Mixing	9:55:00	9:57:00
Sample Testing	10:08:00	10:15:00
Mixing	10:20:00	10:23:00
Mixing	10:38:00	10:41:00
Sample Testing	10:45:00	10:55:00
Mixing	10:59:00	11:02:00
Mixing	11:12:00	11:15:00
Sample Testing	11:17:00	11:27:00
Mixing	11:30:00	11:33:00
Mixing	11:40:00	11:43:00
Sample Testing	11:45:00	11:54:00
Mixing	11:59:00	12:02:00
Mixing	12:12:00	12:15:00
Sample Testing	12:18:00	12:28:00
Mixing	12:31:00	12:34:00
Mixing	12:44:00	12:47:00
Sample Testing	12:50:00	12:59:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
10:08:00	13	10:11:00	6						
10:11:00	12	10:13:00	8		10:12:00	240	10:09:00	3.31	3.53
10:13:00	11	10:15:00	10						
10:45:00	11	10:48:00	3						
10:49:00	22	10:52:00	5		10:47:00	255	10:48:00	2.75	2.87
10:52:00	20	10:55:00	6						
11:17:00	6	11:20:00	1						
11:21:00	21	11:23:00	4		11:20:00	255	11:19:00	2.06	2.22
11:24:00	29	11:27:00	5						
11:45:00	9	11:48:00	2						
11:49:00	17	11:52:00	3		11:51:00	220	11:48:00	3.5	4
11:52:00	18	11:54:00	5						
12:18:00	13	12:21:00	2						
12:22:00	21	12:25:00	3		12:24:00	255	12:19:00	2.1	2.56
12:25:00	20	12:28:00	4						
12:50:00	9	12:53:00	2						
12:53:00	25	12:56:00	4		12:55:00	250	12:51:00	2.31	2.5
12:56:00	24	12:59:00	5						

Sheet Number: 23

Specimen: Mortar phase – 0.50 FA/Mortar by volume

Test Date: 12-09-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.35 kg	8.55 l (w/c - 0.42)	40.25 kg	183 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:36:00	
Dry mix	9:36:00	9:39:00
Adding 2/3 of water	9:39:00	9:42:00
Mixing	9:42:00	9:45:00
Adding 1/3 of water and mixing	9:45:00	9:48:00
Sample Testing	9:57:00	10:05:00
Mixing	10:12:00	10:15:00
Mixing	10:25:00	10:28:00
Sample Testing	10:30:00	10:38:00
Mixing	10:40:00	10:43:00
Mixing	10:53:00	10:56:00
Sample Testing	10:59:00	11:07:00
Mixing	11:09:00	11:12:00
Mixing	11:23:00	11:26:00
Sample Testing	11:32:00	11:40:00
Mixing	11:42:00	11:45:00
Mixing	11:55:00	11:58:00
Sample Testing	12:02:00	12:10:00
Mixing	12:12:00	12:15:00
Mixing	12:25:00	12:28:00
Sample Testing	12:30:00	12:37:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:57:00	58	10:00:00	0	35	9:23:00	190	9:22:00	33.93	96.56
10:00:00	81	10:03:00	0	39					
10:03:00	66	10:05:00	0	39					
10:30:00	49	10:33:00	15	15	9:57:00	165	9:56:00	27.878	52.1
10:33:00	95	10:35:00	13	18					
10:35:00	83	10:38:00	13	20					
10:59:00	66	11:02:00	18	12	10:33:00	160	10:30:00	26.72	45
11:02:00	114	11:04:00	16	15					
11:04:00	85	11:07:00	15	16					
11:32:00	87	11:34:00	23	12	11:03:00	160	11:00:00	21.75	32.5
11:34:00	126	11:37:00	21	14					
11:37:00	140	11:40:00	20	16					
12:02:00	62	12:04:00	31	9	11:32:00	160	11:31:00	24.07	38
12:04:00	120	12:07:00	25	13					
12:07:00	128	12:10:00	25	15					
12:30:00	69	12:32:00	40	8	12:01:00	155	12:00:00	36	
12:32:00	133	12:35:00	35	12					
12:35:00	133	12:37:00	35	13					

Sheet Number: 24

Specimen: Mortar phase – 0.55 FA/Mortar by volume

Test Date: 11-09-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
18.20 kg	7.64 l (w/c - 0.42)	44.40 kg	164 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:03:00	
Dry mix	9:03:00	9:06:00
Adding 2/3 of water	9:06:00	9:07:00
Mixing	9:07:00	9:10:00
Breaking Residue	9:10:00	9:11:00
Adding 1/3 of water and mixing	9:11:00	9:14:00
Breaking Residue	9:14:00	9:15:00
Further mixing	9:15:00	9:17:00
Sample Testing	9:21:00	9:30:00
Mixing	9:36:00	9:39:00
Mixing	9:49:00	9:52:00
Sample Testing	9:54:00	10:04:00
Mixing	10:10:00	10:13:00
Mixing	10:21:00	10:24:00
Sample Testing	10:29:00	10:37:00
Mixing	10:42:00	10:45:00
Mixing	10:54:00	10:57:00
Sample Testing	10:59:00	11:07:00
Mixing	11:10:00	11:13:00
Mixing	11:23:00	11:26:00
Sample Testing	11:29:00	11:37:00
Mixing	11:41:00	11:44:00
Mixing	11:54:00	11:57:00
Sample Testing	11:59:00	12:08:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:21:00	133	9:23:00	0	94	9:56:00	215	9:57:00	9.75	11.69
9:24:00	145	9:26:00	0	82					
9:27:00	104	9:30:00	0	79					
9:54:00	223	9:57:00	47	60	10:31:00	200	10:30:00	5.09	6.72
9:58:00	530	10:00:00	42	58					
10:01:00	326	10:04:00	40	55					
10:29:00	267	10:32:00	67	47	11:00:00	200	10:59:00	5.13	5.5
10:32:00	359	10:34:00	69	44					
10:34:00	312	10:37:00	69	46					
10:59:00	265	11:02:00	103	36	11:33:00	190	11:32:00	5.34	5.97
11:02:00	405	11:04:00	99	37					
11:04:00	376	11:07:00	99	40					
11:29:00	329	11:32:00	144	31	12:05:00	190	12:02:00	4.9	4.97
11:32:00	460	11:34:00	139	34					
11:35:00	551	11:37:00	140	37					
11:59:00	417	12:02:00	231	30	12:33:00	180	12:31:00	5.22	6.12
12:02:00	657	12:05:00	250	29					
12:07:00	961	12:08:00	255	34					

Sheet Number: 25

Specimen: Mortar phase –Washed MS

Test Date: 21-09-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Washed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.35 kg	8.55 l (w/c - 0.42)	40.25 kg	183 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:24:00	
Dry mix	9:24:00	9:27:00
Adding 2/3 of water	9:27:00	9:28:00
Mixing	9:28:00	9:31:00
Breaking Residue	9:31:00	9:35:00
Adding 1/3 of water and mixing	9:35:00	9:38:00
Sample Testing _too sticky	9:40:00	9:48:00
Mixing	9:53:00	9:56:00
Mixing	10:06:00	10:09:00
Sample Testing	10:11:00	10:19:00
Mixing	10:23:00	10:26:00
Mixing	10:36:00	10:39:00
Sample Testing	10:41:00	10:49:00
Mixing	10:52:00	10:55:00
Mixing	11:06:00	11:09:00
Sample Testing	11:11:00	11:19:00
Mixing	11:12:00	11:15:00
Mixing	11:26:00	11:29:00
Sample Testing	11:41:00	11:49:00
Mixing	11:50:00	11:53:00
Mixing	12:06:00	12:09:00
Sample Testing	12:11:00	12:19:00

Observations:

Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:40:00	211	9:43:00	37	33					
9:43:00	361	9:46:00	37	32	9:44:00	175	9:42:00	8.91	15.79
9:46:00	229	9:48:00	35	32					
10:11:00	103	10:14:00	58	11					
10:14:00	227	10:17:00	51	16	10:15:00	175	10:12:00	6.13	7.84
10:17:00	202	10:19:00	47	18					
10:41:00	98	10:44:00	57	9					
10:44:00	175	10:46:00	55	12	10;44	180	10:43:00	5.31	6.14
10:47:00	170	10:49:00	52	14					
11:11:00	94	11:13:00	64	8					
11:14:00	173	11:16:00	61	10	11:13:00	180	11:12:00	5.16	6.13
11:17:00	184	11:19:00	60	12					
11:41:00	86	11:43:00	68	7					
11:43:00	170	11:46:00	67	9	11:42:00	180	11:41:00	5.03	5.81
11:46:00	172	11:49:00	70	10					
12:11:00	90	12:13:00	81	6					
12:14:00	197	12:16:00	77	9	12:13:00	175	12:12:00	5.22	6.25
12:17:00	186	12:19:00	80	10					

Sheet Number: 26

Specimen: Mortar Unwashed MS
Test Date: 26-09-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate Unwashed Manufactured Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.35 kg	8.55 l (w/c - 0.42)	40.25 kg	183 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	9:47:00	
Dry mix	9:47:00	9:50:00
Adding 2/3 of water	9:50:00	9:53:00
Mixing	9:53:00	9:56:00
Breaking Residue	9:56:00	10:00:00
Adding 1/3 of water and mixing	10:00:00	10:03:00
Sample Testing	10:06:00	10:14:00
Mixing	10:21:00	10:24:00
Mixing	10:34:00	10:37:00
Sample Testing	10:41:00	10:48:00
Mixing	10:52:00	10:55:00
Mixing	11:05:00	11:08:00
Sample Testing	11:11:00	11:18:00
Mixing	11:21:00	11:24:00
Mixing	11:34:00	11:37:00
Sample Testing	11:41:00	11:49:00
Mixing	11:53:00	11:56:00
Mixing	12:06:00	12:09:00
Sample Testing	12:12:00	12:20:00
Mixing	12:25:00	12:28:00
Mixing	12:38:00	12:41:00
Sample Testing	12:43:00	12:51:00

Observations:
Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
10:06:00	41	10:08:00	1	18					
10:09:00	43	10:12:00	0	24	10:07:00	230	10:07:00	4.34	5.97
10:12:00	30	10:14:00	0	27					
10:41:00	49	10:43:00	8	13					
10:44:00	53	10:46:00	7	15	10:40:00	220	10:40:00	4.63	5.43
10:46:00	49	10:48:00	6	16					
11:11:00	31	11:13:00	13	9					
11:13:00	60	11:16:00	10	12	11:15:00	210	11:11:00	4.16	5.03
11:16:00	62	11:18:00	11	14					
11:41:00	43	11:44:00	17	8					
11:44:00	81	11:46:00	14	11	11:43:00	200	11:42:00	3.94	
11:47:00	67	11:49:00	14	12					
12:12:00	42	12:14:00	21	7					
12:15:00	76	12:17:00	16	10	12:14:00	215	12:13:00	4.19	4.4
12:17:00	69	12:20:00	16	12					
12:43:00	39	12:45:00	24	6					
12:46:00	94	12:48:00	20	10	12:44:00	210	12:43:00	4.32	4.81
12:48:00	99	12:51:00	20	11					

Sheet Number: 27

Specimen: Mortar phase – 50% Unwashed MS, 50% River Sand by Volume
Test Date: 29-09-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate		Poly Carboxylic Ether (PCE) Hypercrete plus M
		Unwashed Manufactured Sand	River Sand	
20.35 kg	8.55 l (w/c - 0.42)	20.10 kg	20.15 kg	183 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mix MS and River Sand	9:00:00	9:03:00
Adding Cement	9:03:00	9:05:00
Dry mix	9:05:00	9:08:00
Adding 2/3 of water	9:08:00	9:10:00
Mixing	9:10:00	9:13:00
Adding 1/3 of water and mixing	9:13:00	9:16:00
Sample Testing	9:19:00	9:28:00
Mixing	9:30:00	9:33:00
Mixing	9:43:00	9:46:00
Sample Testing	9:50:00	9:57:00
Mixing	10:00:00	10:03:00
Mixing	10:13:00	10:16:00
Sample Testing	10:19:00	10:27:00
Mixing	10:30:00	10:33:00
Mixing	10:43:00	10:46:00
Sample Testing	10:48:00	10:57:00
Mixing	10:59:00	11:02:00
Mixing	11:13:00	11:16:00
Sample Testing	11:18:00	11:26:00
Mixing	11:31:00	11:34:00
Mixing	11:44:00	11:47:00
Sample Testing	11:51:00	11:59:00

Observation Sheet:
Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
9:19:00	36	9:22:00	7	11					
9:23:00	59	9:25:00	7	14	9:20:00	205	9:19:00	3.47	4.25
9:25:00	36	9:28:00	8	15					
9:50:00	38	9:52:00	16	6					
9:53:00	60	9:55:00	14	8	9:50:00	200	9:50:00	2.94	3.69
9:55:00	53	9:57:00	15	9					
10:19:00	46	10:22:00	18	5					
10:22:00	57	10:24:00	16	7	10:20:00	195	10:20:00	3.13	3.54
10:25:00	60	10:27:00	17	8					
10:48:00	32	10:50:00	22	4					
10:51:00	74	10:53:00	20	6	10:50:00	210	10:49:00	3.31	3.22
10:54:00	73	10:57:00	18	8					
11:18:00	33	11:20:00	28	3					
11:21:00	82	11:23:00	23	6	11:19:00	195	11:19:00	3.06	3.68
11:23:00	83	11:26:00	22	7					
11:51:00	48	11:54:00	34	3					
11:54:00	102	11:56:00	30	6	11:51:00		11:51:00	3.13	3.62
11:57:00	85	11:59:00	29	7					

Sheet Number: 28

Specimen: Mortar phase - River Sand
Test Date: 03-10-2018

Sample Quantities:

Ordinary Portland Cement (INSEE Rapid Flow)	Water	Fine Aggregate River Sand	Poly Carboxylic Ether (PCE) Hypercrete plus M
20.35 kg	8.55 l (w/c - 0.42)	40.30 kg	183 ml (0.9% - 0.9 l per 100kg Cement)

Test Procedure:

Description	Start	Finish
Mixing Started	10:45:00	
Dry mix	10:45:00	10:48:00
Adding 2/3 of water	10:48:00	10:49:00
Mixing	10:49:00	10:52:00
Breaking Residue	10:52:00	10:55:00
Adding 1/3 of water and mixing	10:55:00	10:58:00
Sample Testing	11:03:00	11:13:00
Mixing	11:15:00	11:18:00
Mixing	11:30:00	11:33:00
Sample Testing	11:36:00	11:44:00
Mixing	11:46:00	11:49:00
Mixing	11:59:00	12:01:00
Sample Testing	12:04:00	12:12:00
Mixing	12:15:00	12:18:00
Mixing	12:29:00	12:32:00
Sample Testing	12:35:00	12:42:00
Mixing	12:45:00	12:48:00
Mixing	12:58:00	13:01:00
Sample Testing	13:03:00	13:11:00
Mixing	13:13:00	13:16:00
Mixing	13:28:00	13:31:00
Sample Testing	13:35:00	13:41:00

Observations:
Test Results

Stress Growth Test		Flow Curve Test			Flow Table Test		V Funnel Test		
Time	SYS	Time	DYS	PV	Time	Flow	Time	T0	T5
11:03:00	44	11:06:00	6	10					
11:07:00	77	11:10:00	6	12	11:04:00	225	11:05:00	3.41	4.22
11:10:00	45	11:13:00	8	12					
11:36:00	27	11:39:00	11	5					
11:39:00	44	11:42:00	13	6	11:37:00	220	11:37:00	2.56	2.85
11:42:00	43	11:44:00							
12:04:00	29	12:07:00	15	4					
12:07:00	48	12:09:00	16	5	12:05:00	235	12:06:00	2.35	2.9
12:10:00	46	12:12:00	17	6					
12:35:00	28	12:37:00	21	3					
12:37:00	53	12:40:00	19	5	12:37:00	220	12:35:00	2.41	2.69
12:40:00	52	12:42:00	22	6					
13:03:00	33	13:05:00	21	4					
13:06:00	71	13:09:00	23	5	13:05:00	215	13:04:00	2.43	3.22
13:09:00	82	13:11:00	22	6					
13:35:00	48	13:37:00	29	3					
13:38:00	74	13:41:00	31	4	13:35:00	205	13:36:00	2.75	3.1
13:41:00	75	13:43:00	30	6					

Sheet Number: 29

Construction Site Location: Colombo City Centre project

Concrete Batching Plant: Madampitiya

Truck no: 222-7597

Test Date: 17-02-2018

	Static Yield Stress		Dynamic Yield Stress		Plastic Viscosity		Slump or Flow		Temperature	
	Time	SYS	Time	DYS	Time	Viscosity	Time	Slump/Flow	Time	Celcius
At the Plant	5:10	1427	5:11	222.74	5:11	39.3	5:07	200	5:06	31.3
	5:11	434	5:12	238.95	5:12	19.42		310,300		
	5:13	450	5:14	202.1	5:14	22.66				
Before Pumping	6:42	11:16	6:43	135.75	6:43	23.57			6:44	30.8
	6:44	240.84	6:45	115.06	6:45	14.42				
	6:46	266.99	6:47	138.34	6:47	10.03				
After Pumping	7:42	466.16	7:43	145.14	7:43	10.2	7:56	520,520	7:38	29.4
	7:43	192	7:44	156.18	7:44	6.84				
	7:44	193	7:46	157.92	7:46	6.09				

Sheet Number: 30

Construction Site Location: Colombo City Centre project

Concrete Batching Plant: Gangarama

Truck no:

Test Date: 20-02-2018

	Static Yield Stress		Dynamic Yield Stress		Plastic Viscosity		Slump or Flow		Temperature	
	Time	SYS	Time	DYS	Time	Viscosity	Time	Slump/Flow	Time	Celcius
At the Plant	19:48	1184	19:49	128.64	19:49	35.58	19:42	470,450	19:45	31.5
	19:51	333.97	19:52	210.87	19:52	12.25				
	19:53	320.27	19:54	171.58	19:54	19.4				
Before Pumping	20:44	2234	20:45	371.99	20:45	24.39	20:50	420,410	20:52	31.1
	20:46	390.97	20:47	158.77	20:47	38.25				
	20:47	432.32	20:48	149.24	20:48	37.28				
After Pumping	21:12	330.4	21:13	106.79	21:13	11.29	21:22	600,580	21:09	33.7
	21:14	204.11	21:15	105.36	21:15	8.94				
	21:16	229.88	21:16	129.42	21:16	6.01				

Time to fill a container of 30.8l volume: 3.93 s, 4.06 s, 3.95 s

Sheet Number: 31

Construction Site Location: Colombo City Centre project

Concrete Batching Plant: Madampitiya

Truck no: LK3402

Test Date: 07-03-2018

	Static Yield Stress		Dynamic Yield Stress		Plastic Viscosity		Slump or Flow		Temperature	
	Time	SYS	Time	DYS	Time	Viscosity	Time	Slump/Flow	Time	Celsius
At the Plant	1:36 1:38 1:39	989.87 380.57 407.99	1:37 1:39 1:40	130.23 173.82 169.14	1:37 1:39 1:40	32.61 20.31 17.07	1:40	380,350	1:35	32.7
Before Pumping	3:42 3:44 3:45	320.06 364.88 248.04	3:43 3:44 3:45	175.78 205.28 134.68	3:43 3:44 3:45	6.36 4.58 17.05	3:35 3:47	530,500 510,490	3:35	33.5
After Pumping	4:20 4:21 4:22	303.63 267.72 203.55	4:20 4:22 4:23	150.23 173.51 229.03	4:20 4:22 4:23	6.6 7.19 3.2	4:25	525,505	4:15	31.2

Time to fill a container of 30.8l volume: 3.32 s, 3.42 s, 3.44 s

Oil Pressure read from the pressure gauge: 220 bar

Sheet Number: 32

Construction Site Location: Colombo City Centre project

Concrete Batching Plant: Madampitiya

Truck no: 47-6567

Test Date: 22-03-2018

	Static Yield Stress		Dynamic Yield Stress		Plastic Viscosity		Slump or Flow		Temperature	
	Time	SYS	Time	DYS	Time	Viscosity	Time	Slump/Flow	Time	Celcius
At the Plant	9:56	762.44	9:57	126.8	9:57	40.66	9:52	520,510	9:50	29
	9:58	380	9:59	202.8	9:59	15.34				
	9:59	281	10:01	159.1	10:01	25.65				
Before Pumping	11:50	402.9	11:51	103.4	11:51	22.28	10:32	480,470	10:32	30.8
	11:51	194.3	11:52	97.8	11:52	18.98				
	11:52	181.7	11:53	98.1	11:53	19.11				

Sheet Number: 33

Construction Site Location: Luna Tower Project, Union Place

Concrete Batching Plant: Madampitiya

Truck no: LJ 0482

Test Date: 08-06-2018

	Static Yield Stress		Dynamic Yield Stress		Plastic Viscosity		Slump or Flow		Temperature	
	Time	SYS	Time	DYS	Time	Viscosity	Time	Slump/Flow	Time	Celsius
At the Plant	23:04 23:09 23:11	1203 436 524	23:05 23:10 23:14	144.91 171.69 225.4	23:05 23:10 23:14	48.48 31.08 18.31	23:06	510,510	23:00	31.5
Before Pumping	0:19	455.77	0:19	209.28	0:19	40.5	0:20	440,420	0:16	31.3
After Pumping	12:50 12:51 12:56	588.44 776 438.18	12:50 12:52 12:55	415.78 99.47 223.44	12:50 12:52 12:55	8.89 35.34 17.57			0:50	31.8

Time to fill a container of 30.8l volume: 2.94 s, 2.81 s, 2.37 s

Oil Pressure read from the pressure gauge: 80 bar and 140 bar alternatively

Sheet Number: 34

Construction Site Location: Luna Tower Project, Union Place

Concrete Batching Plant: Madampitiya

Experiment: tests on concrete pumpability

Test Date: 18-02-2019

Fresh concrete properties of the considered concrete pumping operations

Truck No:	Stress Growth Test		Flow Curve Test			Slump	Temperature before pumped	Temperature after pumped
	Time	SYS	Time	DYS	PV			
ZA 8346	2:52	60	2:54	205	20	210	32	31
	2:56	276	2:58	300	10			
	2:58	739	3:01	284	17			
LL 2894	3:15	1308	3:17	188	38	205	32	32
	3:17	404	3:20	232	27			
	3:20	435	3:22	271	23			
LL 5012	3:33	1444	3:36	118	73	195	32	31
	3:36	440	3:38	179	43			
	3:39	562	3:41	212	32			
LL 8638	3:56	1761	3:58	162	79	200	31	32
	3:59	1329	4:01	233	44			
	4:02	465	4:04	173	59			
LJ 0482	4:17	1919	4:19	173	76	195	33	33
	4:20	545	4:22	165	62			
	4:23	729	4:25	195	48			