EFFECTS OF FRESH CONCRETE TEMPERATURE ON FRESH AND HARDENED PROPERTIES OF CONCRETE UNDER HOT WEATHER CONDITIONS

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering

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Sri Lanka

July, 2024

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 the acknowledgement is made in the text.

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Prof. S. M. A. Nanayakkara Date

Abstract

Understanding and managing fresh concrete temperature is essential as it affects the properties of fresh and hardened concrete. Even though a maximum temperature is specified for mass concrete pouring, there is no proper guideline to control the temperature in normal concreting works.

Effects of fresh concrete temperature on fresh and hardened properties of concrete in normal concrete works under hot weather conditions were evaluated through an experimental investigation. This thesis reports the outcomes of the investigations carried out. A study was done on the past records of fresh concrete temperatures collected from concrete batching plants, where the temperature was not controlled in any manner during the batching process under hot weather conditions. For the experimental investigation, one mix proportion with Portland cement was selected. Test specimens were cast to check the temperature development of concrete, slump and slump variation with time, evaluation of plastic shrinkage cracking, evaporation rates throughout the experimental period, compressive strength development and splitting tensile strength. The fresh concrete temperature of the mixes was controlled at 30, 32, 34 and 36 °C by varying mixing water temperature under hot weather conditions where ambient temperature, humidity and wind conditions were monitored.

Slump and slump loss are directly related to the fresh concrete temperature as it showed considerable reduction when the fresh concrete temperature increased. Further, the test results revealed that the time taken to appear the first crack is lesser when the difference between the fresh concrete temperature and the ambient temperature increases and vise versa. Same time the evaporation rate is also higher when the difference between the fresh concrete temperature and the ambient temperature increases. When the evaporation rate is higher, the concrete mix tends to crack earlier. Hence, it can be concluded that it is beneficial to keep the fresh concrete temperature close to the ambient conditions to minimize the plastic shrinkage cracking. The highest test results for compressive strength and splitting tensile strength were also obtained when the fresh concrete temperature was close to the ambient conditions. Therefore, from the above analysis, it can be concluded that it is beneficial to keep the fresh concrete temperature close to the ambient conditions to get the optimum results in terms of plastic shrinkage cracking, compressive strength and tensile splitting strength.

Therefore, the recommendations given in the code of practices and project specification should be modified to reflect these findings along with the ambient conditions.

Keywords: fresh concrete temperature, concrete placing temperature, hot weather concreting, ambient temperature, plastic shrinkage, compressive strength development, splitting tensile strength

Specially dedicated to my supervisor Prof. S.M.A. Nanayakkara...

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LIST OF ABBREVIATIONS

Abbreviation	Description
°C	Celsius
°F	Fahrenheit
d	Cross-sectional dimension of the specimen (in mm)
D	Density (in kg/m^3)
F	Maximum load applied (in N)
FA/TA	Fine to total aggregate ratio
hr	Hours
l	Length of the specimen (in mm)
m	Mass of the concrete in the container (in kg)
T	Fresh concrete temperature
T_a	Temperature of aggregate
TA/C	Total aggregate to cement ratio
T_c	Temperature of cement
T_i	Temperature of ice
T_w	Temperature of batched mixing water from normal supply excluding ice
w/c	Water to c3ement ratio
W_a	Dry mass of aggregate
W_c	Mass of cement
W_i	Mass of ice
W_w	Mass of batched mixing water
W_{wa}	Mass of free and absorbed moisture in aggregate
Π	Pi
σ_{ct}	Splitting tensile strength (in N/m^2)

LIST OF APPENDICES

1 INTRODUCTION

1.1 Background

The emergence of Portland cement in the 19^{th} century created the path for the production of modern concrete. With the advancement of technology, modern concrete underwent transformations, giving rise to high-strength concrete, high-performance concrete, self-compacted concrete, anti-wash-out concrete etc. Even though the concrete changes its form, it is identified that the importance of workability, strength and durability factors remain crucial for any type of concrete.

In the construction of concrete structures, it is vital to control the temperature of fresh concrete before pouring and limit the maximum temperature rise of concrete placed during hot weather conditions. This requirement plays a crucial role in ensuring the quality and durability of the constructed concrete elements.

Considering the volume of the concrete pour, concreting works can be divided into two main categories i.e. mass concreting works and normal concreting works. In situations where mass concrete pouring takes place, the maximum temperature rise of concrete in the structural elements should be controlled to prevent adverse effects such as delayed ettringite formation (DEF) [1] due to the early age temperature rise. However, in normal concreting works, even though there is no requirement to control the temperature rise in the pour, it may be necessary to control the fresh concrete temperature as it can affect the properties of fresh and hardened concrete. Hence, there should be a predetermined maximum fresh concrete temperature for normal concreting works in hot weather conditions.

In ACI 305R-99 [2], hot weather is defined as any combination of the elevated ambient temperature, increased concrete temperature, low relative humidity, wind speed and solar radiation, that tends to adversely affect the quality of fresh concrete or hardened concrete by accelerating the rate of moisture loss and cement hydration rate or otherwise causing detrimental results. The definition given in ACI 308.1-98 [3] is a combination of elevated ambient temperature, heightened concrete temperature, low relative humidity, wind velocity, and solar radiation that leads to excessive evaporation. That implies that multiple factors can influence the hot weather condition.

ACI 305.1-06 [4] states that the operations carried out during hot weather conditions including preparation, production, delivery, placement, finishing, protection and curing of concrete as hot weather concreting.

When concreting works are undertaken in hot weather conditions, there can be many detrimental effects with respect to the fresh concrete such as higher water demand, increased rate of slump loss, increased rate of early setting resulting in cold joints and insufficient compaction, increased susceptibility for plastic shrinkage cracking and heightened challenges in effectively limiting the entrained air [2]. The potential issues for hardened concrete under hot weather conditions are an increased tendency for drying shrinkage, decreased durability due to cracking and high porosity, increased risk of reinforcing steel corrosion, higher permeability and increased early strength but decreased 28-day strength than in concreting works under lower temperatures [2].

Apart from the hot weather conditions, there are detrimental effects that can occur in concrete due to the changes happening in the temperature of fresh concrete. As per the ACI 305.1-06 [4], the measured temperature of concrete during the discharge and placement in accordance with ASTM C 1064/C 1064M [5] is known as the fresh concrete temperature.

Potential problems that can occur due to the high fresh concrete temperature are increased water demand for a given slump with the time or vice versa [6], an early set of concrete [6], decreased strength [6], [7] density [7] and an increased tendency for plastic shrinkage cracking [8].

Most of the standards and project specifications as given in Chapter 2 specify an allowable maximum fresh concrete temperature. Table 2.1 gives some of the data obtained from the existing standards. Further, it is identified that most of the contract documents (Work Specifications) also state a limiting temperature value for the fresh concrete works (See Table 2.2) in normal concreting works. However, there is no proper guideline to identify a specific value considering ambient temperature, humidity levels, wind speed etc. Despite these factors, contractors / ready mix suppliers are obliged to limit the temperature of the fresh concrete as specified in the standards or contract documents in hot weather conditions. Temperature control does have a time and a cost factor. Hence, it is essential to develop a proper guideline to identify the optimum limiting fresh concrete temperature for given ambient temperature.

After identifying the importance of the fresh concrete temperature factor, various studies have been carried out to identify the impact of fresh concrete temperature on the fresh and hardened properties of concrete. The temperature control in mass concreting works was widely discussed and researched, and the fresh concrete temperature values were decided considering the limiting maximum temperature value at the hydration peak, irrespective of the ambient conditions [9].

Numerous studies [10], [11], [12] have also been done to identify the effect of ambient temperature on the fresh and hardened properties of normal concreting works. However, very few studies have been done in the past to identify the effect of fresh concrete temperature on fresh and hardened properties of concrete in normal concreting works under different ambient conditions, for various cement types and various concrete grades.

In Sri Lanka, the current national standard published by CIDA [13] specifies a maximum allowable wet concrete temperature of 38 °C for normal concreting works. However, it does not provide any conditions related to the ambient conditions.

Sri Lanka experiences a temperature variation of 35 °C to 25 °C between daytime and night-time. Therefore, it is required to decide the limiting temperature value for fresh concrete considering this ambient temperature variation.

Hence, further research is essential to address this specific scenario and formulate comprehensive national guidelines. Thus, the quality of the concrete can be improved cost-effectively.

1.2 Problem Statement

Since most of the standards and project specifications specify the limiting temperature values, contractors and ready-mix concrete suppliers are obliged to limit the fresh concrete temperature or the placing temperature in fresh concrete. More importantly, it comes to the vicinity that almost all the standards and project specifications limit the temperature values, without considering the ambient conditions of the concrete mixing or placing location and the nature of the concreting works. Therefore, adhering to the prescribed temperature limits will be difficult and at the same time, there will be associated impacts on both time and cost, as the temperature controlling measure will take some additional time duration than the normal routine and the additional materials such as ice, frequent wetting of materials can have an additional cost.

Hence, the Contractors' and ready-mix concrete suppliers' frequently asked questions are;

1. Do we need to control the temperature of fresh concrete, which is used for normal concreting works other than mass concrete?
2. What is the appropriate limiting value of fresh concrete temperature to suit the ambient temperature and nature of the work?
3. Are we spending time, money and resources unnecessarily in controlling the fresh concrete temperature?

Therefore, it is required to identify the appropriate limiting fresh concrete temperature for normal concreting works.

1.3 Aim

This research aims to initiate the development of a guideline to decide appropriate fresh concrete temperatures under hot weather conditions for normal concrete works,

1. To minimize the risk of occurring defects at an early age
2. To achieve the specified strengths and other related hardened properties when cast under hot weather environments in normal concreting works (Other than mass concrete works)

1.4 Research Objective

The research objective was to investigate the effect of fresh concrete temperature on the fresh and hardened properties of concrete under hot weather conditions when the ambient temperature is in the range of 30 – 34 ˚C and find out the most appropriate fresh concrete temperature for normal concreting works.

The factors to be considered are;

1. Grade of concrete
2. Cement type

The properties to be investigated are;

1. Fresh concrete temperature and temperature development with time
2. Slump and slump loss with the time
3. Plastic shrinkage cracking of concrete
4. Evaporation characteristics of concrete
5. Compressive strength development
6. Tensile strength capacity

1.5 Scope of Work

The scope of this study is clearly defined as follows to ensure a focused and manageable research project.

1. Grade 30 concrete will be used
2. Ordinary Portland Cement will be used
3. Ambient condition considered is 32 ˚C
4. Wind condition 8 kmph
5. Relative humidity in the range of 65%-75%

This research will not cover different grades of concrete or cement types other than those defined above. Testing was carried out under natural weather conditions with an ambient temperature of 32 ˚C. The research did not consider the variation in ambient temperature throughout the year. Only one wind speed and a single range of relative humidity range were considered due to the time and resource limitations to carry out the testing under different wind and relative humidity conditions.

1.6 Methodology

Once the aim and the objectives of the research are established, the literature review was carried out to find out the research exposure in this said area. In which the main focus was to identify the research done on fresh concrete temperature and its effects on the properties of concrete in both fresh and hardened states. Further, the literature survey was done to find out the effect of hot weather conditions on fresh and hardened properties of concrete, to study the impact of mix proportions on the concrete properties in hot weather environments and to study the effect of curing and curing temperature on concrete properties in fresh and hardened states. During the literature survey, the research gap and the new research requirement was identified.

Other than the above literature survey, past data were gathered to identify the fresh concrete temperatures and the relationship between the ambient temperature and the fresh concrete temperature, where the fresh concrete temperature has not been controlled under hot weather conditions in any manner. Most of the data were collected from the batching plants.

Then an experimental study was undertaken to investigate a few selected concrete properties in fresh and hardened states, cast at different fresh concrete temperatures. Keeping the ambient temperature, wind and humidity constant, the fresh concrete temperature was varied by changing the temperature of the water for four different values in four consecutive days. After casting the concrete, temperature development of the concrete, slump and slump loss with the time, plastic shrinkage cracking, evaporation characteristics, compressive strength development and tensile strength capacity of concrete was investigated.

1.7 Outline of the thesis

Chapter 2 of this thesis presents a review of the existing literature. In Chapter 3 detailed methodology of the experimental process is described, followed by a discussion of the results in Chapter 4. Chapter 5 of this thesis presents the research conclusions while Chapter 6 outlines the recommendation for future research.

2 LITERATURE REVIEW

Initially, the literature survey was conducted to identify the sources where the requirement is specified to control the fresh concrete temperature. During this study, nationally and internationally published standards and project specifications were studied. Then the literature review was conducted on past research to identify whether there is any basis for the specified values in the national and international standards and project specifications.

2.1 Code Specifications of the Fresh Concrete Temperature

Nationally and internationally published standards in Sri Lanka and other countries were referred to identify the limiting fresh concrete temperature values.

Certain codes specify either a specific limiting value or a temperature range, whereas certain standards leave it to the discretion of the consulting engineer to determine the appropriate limiting temperature values.

The concreting works considered in this study referred to concreting carried out under hot weather conditions. Most of the standards did not provide an exact description for the hot weather concreting as well. Following are the definitions given in some foreign standards.

1. ACI 308.1-98 [3] defined hot weather as a combination of all adverse weather conditions that may cause excessive evaporation.

2. ACI 305.1-06 [4] defined hot weather as surrounding conditions where the concreting works are performed, that speed up the rate of moisture loss or rate of cement hydration of fresh concrete, including an ambient temperature of 27 °C (80 °F) or higher, and an evaporation rate that exceeds 1 $kg/m^2/hr$.

3. ACI 305.1-06 [4] states that operations carried out during hot weather conditions, including preparation, production, delivery, placement, finishing, protection, and curing of concrete as hot weather concreting.

4. IS 7861 (Part I) -1975 [14] defines hot weather concreting as any kind of concreting operation performed at ambient temperatures above 40 °C or any concreting operation (other than steam curing) where the placement temperature of concrete is expected to be higher than 40° C.

Table 2.1 shows the limiting temperature values of fresh concrete given in some of the standards. However, the basis for selecting limiting values is not revealed in those standards.

Table 2.1 : Specifying limiting temperature values for fresh concrete in standards

	Standard	Limiting Temperature Value
1.	CIDA Specifications for Building works (Vol. 1) [13]	Wet concrete temperature shall not exceed 38 °C in hot weather
2.	ACI 305.1-06 Specification for Hot Weather Concreting [4]	- when it is specified by the consultants, the specified value to be considered or else - < 35 °C (95 °F)
3.	Saudi Building Code 304-Structural – Concrete Structures [15]	< 35 °C at the time of placing
4.	AS 1379 - 2007 Specification and supply of concrete [16]	< 35°C in hot weather environments > 5°C in cold weather environments at the time of delivery

	Standard	Limiting Temperature Value
5.	ASTM C94/C 94M Standard specification for Ready Mix Concrete [17]	< 90F (32 °C)
6.	IS 14591 (1999): Temperature Control of Mass Concrete for Dams - Guideline [WRD 9: Dams and Spillways] [18]	~15.5°C Or - as desired
7.	IS 456 (2000): Plain and Reinforced Concrete - Code of Practice [CED 2: Cement and Concrete] [19]	Not specified. But required to record the "Maximum temperature of concrete at the time of placing;"
8.	IS 7861-1 (1975): Code of practice for extreme weather concreting, Part 1: Recommended Practice for hot weather concreting [CED 2: Cement and Concrete] [14]	< 40 °C at the time of placement
9.	IS 7861-2 (1981): Code of practice for extreme weather concreting, Part 2: Recommended Practice for cold weather concreting [CED 2: Cement and Concrete] [20]	> 5°C at the time of placing and maintained above 2°C until it is hardened thoroughly

	Standard	Limiting Temperature Value
10.	SS 289-4:2000 – Specification for Concrete Part 4: Specification for the procedures to be used in sampling, testing and assessing compliance of concrete (Replaced by SS EN 206-1:2009 and the SS 544 series)	< 37 ˚C or < 6 ˚C + the prevailing shade temperature
11.	SS EN 206: 2014 –Concrete –Specification, performance, production and conformity [21] (Newer version of SS EN 206-1:2009) SS 544 : Part 2 : 2009 Concrete – Complementary Singapore Standard to SS EN 206-1 Part 2 : Specification for constituent materials and concrete [22]	< 37 ˚C or < 6 ˚C + the prevailing shade temperature - when it is specified by the consultants, the specified value to be considered or else - 35 °C
12.	JSCE (Japan Society of Civil Engineers) – Standard Specifications for Concrete Structures 2012 [23]	< 35°C or less at the time of pouring But if the temperature exceeds the limit, the quality of concrete must be checked to ensure the compliance.

	Standard	Limiting Temperature Value
13.	JSCE (Japan Society of Civil Engineers) Guideline for Concrete No.16 – Standard Specification for Concrete Structures-2007 "Materials and Construction" [24]	< 35°C or less at the time of placing in hot weather - For cold weather concrete placing temperature shall be in the range of 5 to 20 °C
14.	BS 8110-1-1997 –Structural use of concrete - Part 1: Code of practice for design and construction [25]	< 30 °C, Or can go for a higher value if there are no any detrimental effects on the concrete
15.	BS 5328-3-1990 – Concrete - Part 3. Specification for the procedures to be used in producing and transporting concrete [26]	> 5 °C at the delivery, unless any other value is specified, or permitted, by the purchaser in cold weather < 30 °C at the delivery, unless any other value is specified, or permitted, by the purchaser in hot weather
16.	BS EN 206: 2013 Concrete - Specification, performance, production and conformity (Incorporating corrigendum May 2014) [27]	> 5 °C at the time of delivery in cold weather conditions - Value is not specified for the hot weather conditions
17.	BS 8500-2: 2015+A2:2019 –Concrete - Complementary British Standard to BS EN 206 [27] - Part 2: Specification for constituent materials and concrete [28]	At the time of delivery fresh concrete temperature shall be a) where specified, the specified value; or b) 35 °C in all other cases in hot weather conditions

2.2 Project Specification of the Fresh Concrete Temperature

Almost all the project specifications state a limiting temperature value for fresh concrete at the time of placing. Irrespective of the country, environmental condition, cement type, grade of concrete, and w/c ratio, consultants are specifying the values for fresh concrete temperature.

Table 2.2 shows the data on the project-specified temperature values for fresh concrete. This reveals that irrespective of the consultant's country and the project's country, a limiting value for the fresh concrete temperature has been specified. That leads the contractor/ ready mix suppliers to encounter numerous challenges in controlling the fresh concrete temperature and promptly everyone is questioning the necessity of such control.

Table 2.2 : Specifying limiting temperature values for fresh concrete in project specifications

	Project Country	Consultants' Country	Nature of Work	Limiting Temperature Value
1.	Sri Lanka (Mackson Project)	Sri Lanka	Normal Concreting works (Residential Tower Project)	30 ˚C
2.	Sri Lanka (Women Police Barrack at Colombo – 07)	Sri Lanka	Normal Concreting works (Residential Tower Project)	38 ˚C
3.	Sri Lanka (Water Front Project)	England	Both Normal and Mass Concreting works (Luxury mixed-use development)	30 ˚C

	Project Country	**Consultants' Country**	**Nature of Work**	**Limiting Temperature Value**
4.	Sri Lanka (The proposed Dusit Tani Beach Front Apartment at Balapitiya)	Sri Lanka	Normal concreting works (A Beach Front Apartment at Balapitiya)	30 ˚C
5.	Dubai, U.A.E	Dubai, U.A.E	Normal Concreting Work	< 35 ˚C for hot weather environments > 5 ˚C for cold weather environments
6.	Dubai, U.A.E	Dubai, U.A.E	Normal Concreting Work	< 32 ˚C
7.	Dubai, U.A.E	Dubai, U.A.E	Normal Concreting Work Mass Concreting Work	< 30 ˚C < 25 ˚C
8.	Dubai, U.A.E	Dubai, U.A.E	Normal Concreting Work Mass Concreting Work	< 30 ˚C < 25 ˚C
9.	Myanmar	Japan	Mass and Normal Concreting Work (Port Terminal Project)	Not Specified

	Project Country	Consultants' Country	Nature of Work	Limiting Temperature Value
10.	Maldives	Maldives	Normal Concreting Work (Resort Project)	30 ˚C
11.	Maldives	Maldives	Both Normal and Mass Concreting works (AirPort Works)	< 30 ˚C in hot weather condition > 5 ˚C in cold weather condition
12.	Maldives	Maldives	Normal Concreting works (Building Works)	Not Specified
13.	Maldives	Singapore	Normal Concreting works (Resort Project)	< 37 ˚C or < 6 ˚C + the prevailing shade temperature in accordance with the recommendations of SS 289.
14.	Maldives	Singapore	Normal Concreting works (Building Works)	< 37 ˚C or < 6 ˚C + the prevailing shade temperature in accordance with the recommendations of SS 289.
15.	Maldives	Maldives	Normal Concreting works (Multi Storey Building Works)	Not Specified

	Project Country	Consultants' Country	Nature of Work	Limiting Temperature Value
16.	Maldives	Maldives	Normal Concreting works (Resort Project)	Not Specified
17.	India	India+ Singapore	Both Normal and Mass Concreting works (Conference & Exhibition Hall)	< 37 ˚C or < 6 ˚C + the prevailing shade temperature in accordance with the recommendations of SS EN 206.
18.	India	India	Normal Concreting works (Residential Tower Project)	Not Specified
19.	Bangladesh	Japan	Both Normal and Mass Concreting works (Coal Power Plant)	< 35 ˚C
20.	Seychelles	Mauritius	Normal Concreting works (Resort Project)	32 ˚C
21.	Mauritius (The Garden Court Park Side)	Mauritius	Normal Concreting works (Resort Project)	32 ˚C

	Project Country	Consultants' Country	Nature of Work	Limiting Temperature Value
22.	The project for the reinforcement of Vaccine storage in Kenya	Japanese	Building works	35 ˚C

2.3 Overview of the Fresh and Hardened Properties of the Concrete

The fresh concrete temperature depends on the temperature of constituents' materials such as cement, aggregate and water. When hydration starts temperature of the concrete tends to rise. There can be some other external factors that can affect the temperature rise of the concrete.

Slump is the measurement of workability criteria. Workability is the measure of consistency which is mobility, compactability, deformability and finishability and cohesiveness which is the segregation resistance. Slump loss happens with time and that can be related to the reduction of the stiffness of the concrete.

Plastic shrinkage cracks occur shortly after the placement and while the concrete is in the plastic state. When concrete is restrained against plastic shrinkage, it undergoes tensile strain. Cracks will appear if the plastic shrinkage occurs before the full tensile strain capacity is obtained. If an adequate amount of tensile strength has been developed in the concrete, shrinkage cracks will not form [29].

There are many factors which can cause plastic shrinkage cracks. Shrinkage cracks are more likely to occur when exposed to high winds, low relative humidity and high temperatures [30]. If the combination of the above factors creates an evaporation rate of 1kg/m^2/hr (0.2lb/ft^2/hr), shrinkage cracks will occur [2]. The occurrence of these cracks is due to the rapid evaporation of water from the surface and simultaneously when the bleed water cannot replace the evaporated water effectively [31], [30].

Further, the low rate of bleeding can cause plastic shrinkage as well. The slow rate of bleeding is caused by the high content of cementitious material, abundant fine content, decreased water content, entrained air, elevated concrete temperature and the presence of thin sections [30]. The absorption of water by subsurface, formwork and aggregate will also create a low bleeding rate thus creating shrinkage cracks. Apart from the above any factor which delays the setting of concrete can also lead to plastic shrinkage cracks [30].

Plastic shrinkage cracks normally occur on the horizontal surfaces and are normally parallel to each other and 1 to 3 feet apart from each other and relatively shallow [32], [30]. Typically, these shrinkage cracks occur on surfaces where the concrete members possess significant surface-to-volume ratios [31].

Erection of temporary windbreaks to prevent direct exposure to the wind, erection of sunshades to prevent direct exposure to high temperatures, starting concrete pouring in the evening or night, use of fog sprays over the surfaces, damping the subsurface before pouring concrete, use of vapour retarders, starting of curing works as soon as the concrete starts to set, use of fibre in the concrete mix, accelerating of setting time and minimizing the difference of concrete and ambient temperatures can help to minimize plastic shrinkage [30].

The evaporation rate also depends on many factors such as the casting time, temperature gradient between the concrete surface and surroundings, humidity levels, wind speed etc.

Compressive strength and splitting tensile strength are hardened properties of concrete and they tend to gain strength with time. In this study, the strength development was studied for four concrete batches cast at four different fresh concrete temperatures.

2.4 Previous Studies Related to the Temperature Factor

2.4.1 Studies done on the effect of fresh concrete temperature on concrete properties

In hot weather, Nazir et al. [7] studied the influence of the casting temperature of concrete on tensile and compressive strengths as well as the density of concrete (using pulse velocity) with OPC and blended cement. They focused on the concrete prepared with Type I- Ordinary Portland Cement and blended cement concretes with 10% very fine fly ash (VFFA), 30% fly ash (FA), 7% silica fume (SF), 70% ground granulated blast furnace slag (GGBFS) and 20% natural pozzolan (NP). Testing was carried out under a humidity level of 34-40% and the recorded maximum ambient temperature was 45 ˚C. There is no clear indication about the ambient temperature at the time of testing, but in his other research [8] it was mentioned as 38 ˚C. The fresh concrete temperatures considered were 25 ˚C, 32 ˚C, 38 ˚C and 45 ˚C.

Altogether 24 numbers of distinct concrete mixtures were prepared outdoors, under hot weather conditions and allowed to cure for 24 hrs under an ambient summer environment while being covered with a plastic sheet until demoulding. After demoulding, specimens were cured by covering with a wet burlap under ambient conditions and misted with water twice daily for 14 days. Subsequently, after curing for 14-days, specimens were left in ambient conditions until testing. At 3 days, 7 days, 28 days, 90 days and 180 days, compressive strength and splitting tensile strength were assessed, whereas pulse velocity tests were carried out up to 90 days.

The results indicated that the compressive strength showed an increase in early ages (up to 7 days) with the increase of the fresh concrete temperature and the compressive strength tends to decrease with the increase of fresh concrete temperature in later ages. Tensile strength and pulse velocity results also had similar behaviour to compressive strength results.

Following is the summary of the results obtained for compressive strength results.

1. For concrete with Ordinary Portland Cement (OPC), in early ages (up to 7 days), maximum strengths were obtained when the fresh concrete temperature was 45˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 32 ˚C (See Figure 2.1).

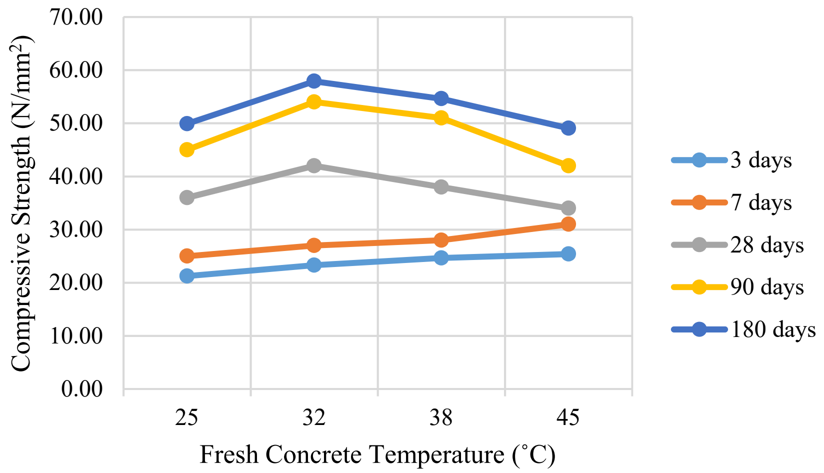


Figure 2.1 : Compressive strength results for OPC Concrete [7]

2. For concrete with 10% very fine fly ash (VFFA) cement, in early ages (up to 7 days), maximum strengths were obtained when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.2).

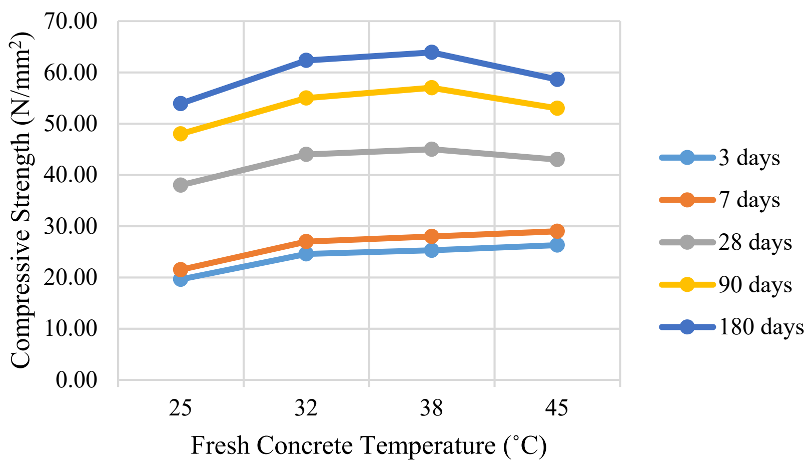


Figure 2.2 : Compressive strength results for 10% VFFA cement concrete [7]

3. For concrete with 30% fly ash (FA) cement, in early ages, maximum strengths were obtained when the fresh concrete temperature was 45˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.3).

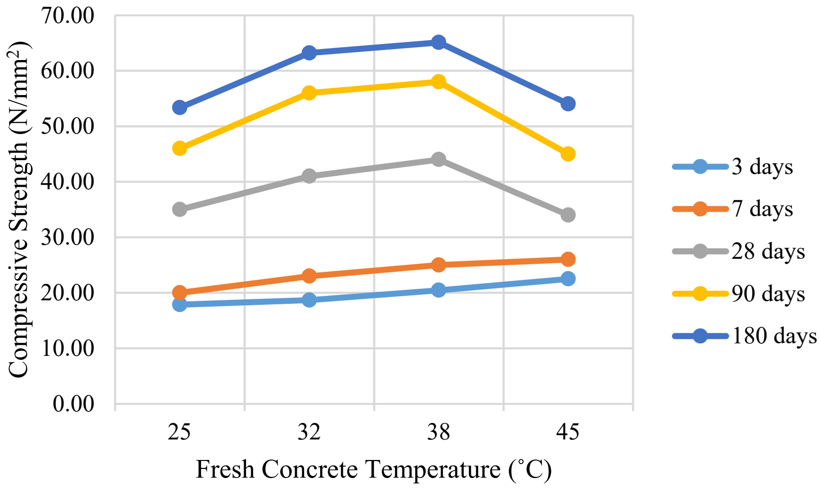


Figure 2.3 : Compressive strength results for 30% FA cement concrete [7]

4. For concrete with 7% silica fume (SF) cement, in early ages (up to 7 days), maximum strengths were obtained when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 32 ˚C (See Figure 2.4).

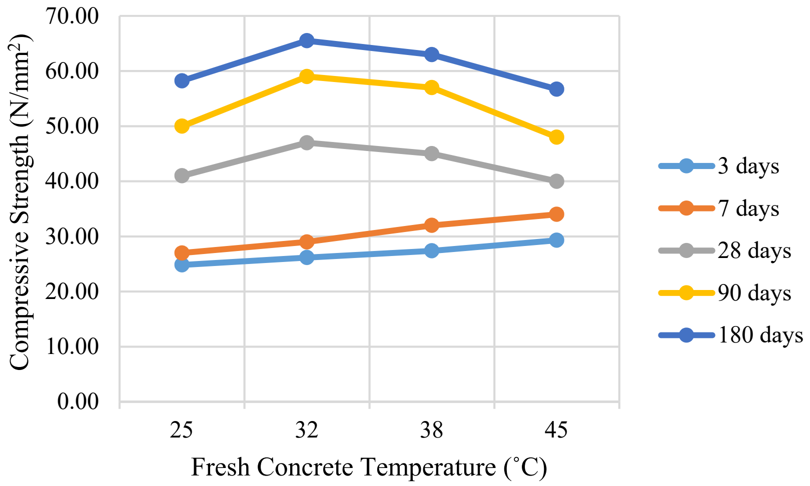


Figure 2.4 : Compressive strength results for 7% SF cement concrete [7]

5. For concrete with 70% ground granulated blast furnace slag (GGBFS) cement, in early ages (up to 7 days), maximum strengths were obtained when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.5).

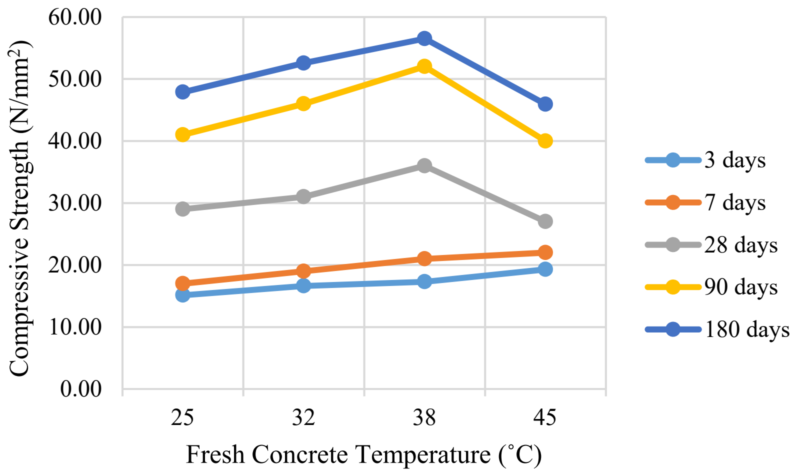


Figure 2.5 : Compressive strength results for 70% GGBFS cement concrete [7]

6. For concrete with 20% natural pozzolan (NP) cements, in early ages (up to 7 days), maximum strengths were obtained when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.6).

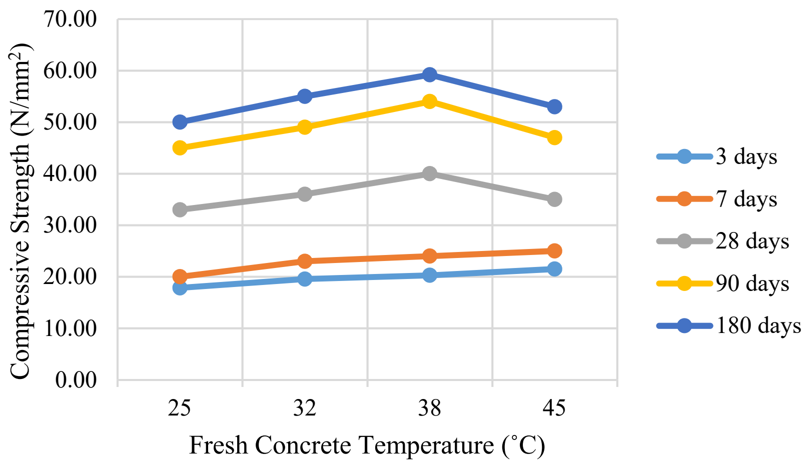


Figure 2.6 : Compressive strength results for 20 % NP cement concrete [7]

Following is the summary of the results obtained for splitting tensile strength results.

1. For concrete with Ordinary Portland Cement (OPC), in early ages (up to 7 days), maximum strengths were achieved when the fresh concrete temperature was 45˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 32 ˚C (See Figure 2.7).

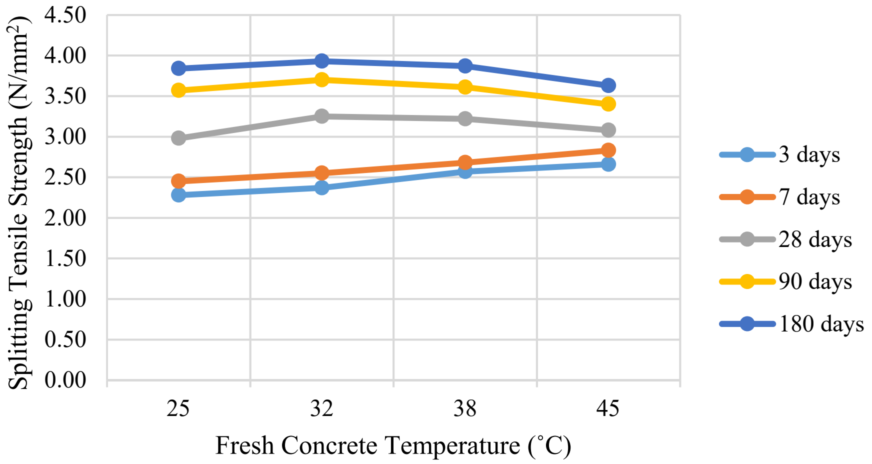


Figure 2.7 : Splitting tensile strength results for OPC concrete [7]

2. For concrete with 10% very fine fly ash (VFFA) cement, in early ages (up to 7 days), maximum strengths were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.8).

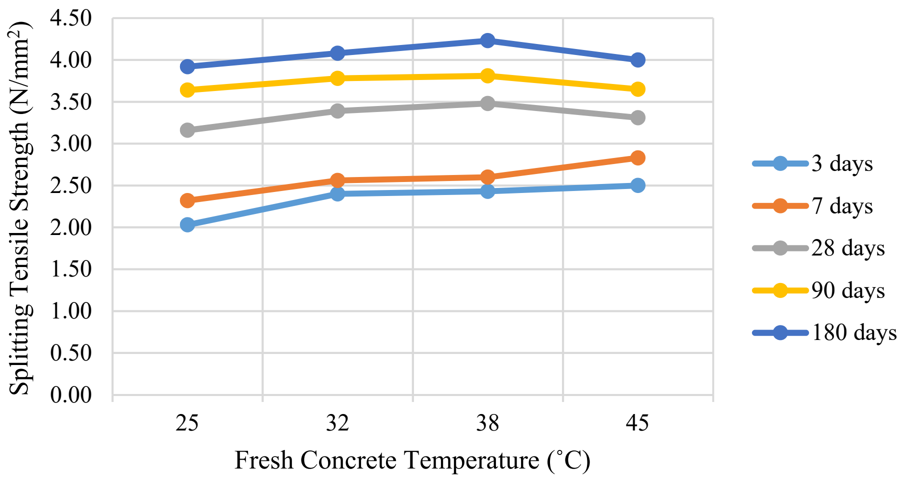


Figure 2.8 : Splitting tensile strength results for 10% VFFA cement concrete [7]

3. For concrete with 30% fly ash (FA) cement, in early ages (up to 7 days), maximum strengths were achieved when the fresh concrete temperature was 45˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.9).

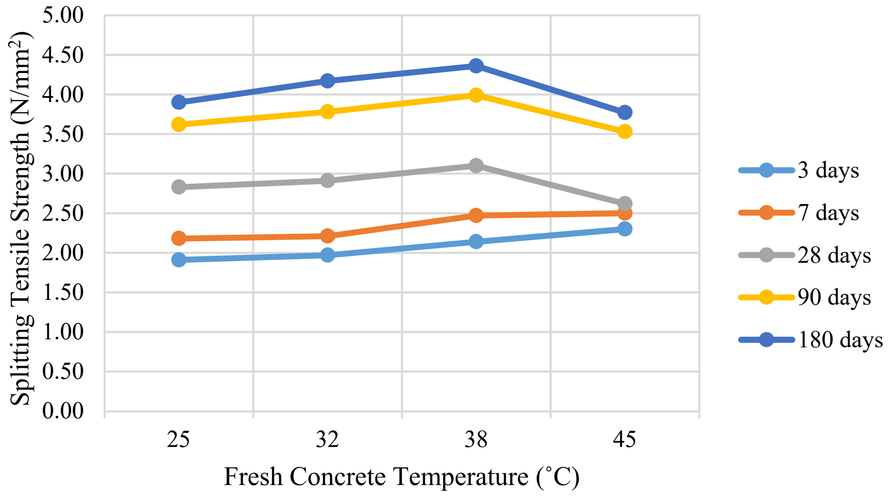


Figure 2.9 : Splitting tensile strength results for 30% FA cement concrete [7]

4. For concrete with 7% silica fume (SF) cement, in early ages (up to 7 days), maximum strengths were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 32 ˚C (See Figure 2.10).

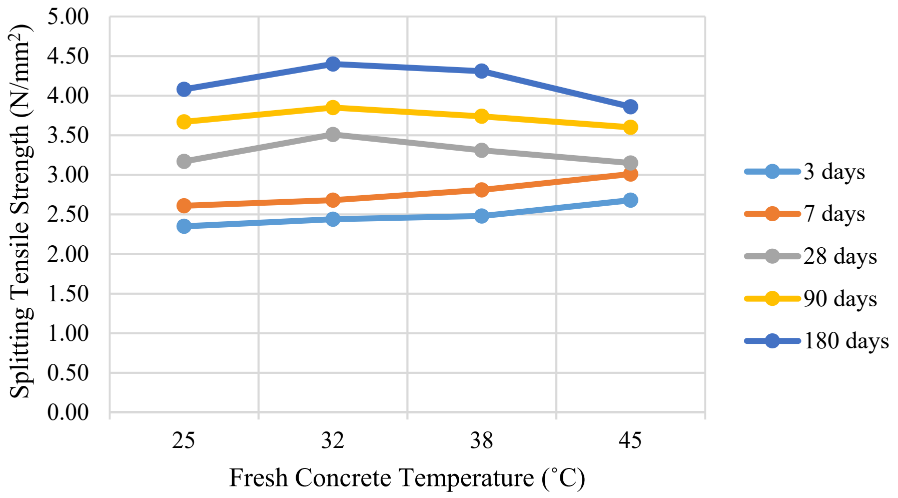


Figure 2.10 : Splitting tensile strength results for 7% SF cement concrete [7]

5. For concrete with 70% ground granulated blast furnace slag (GGBFS) cement, in early ages (up to 7 days), maximum strengths were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.11).

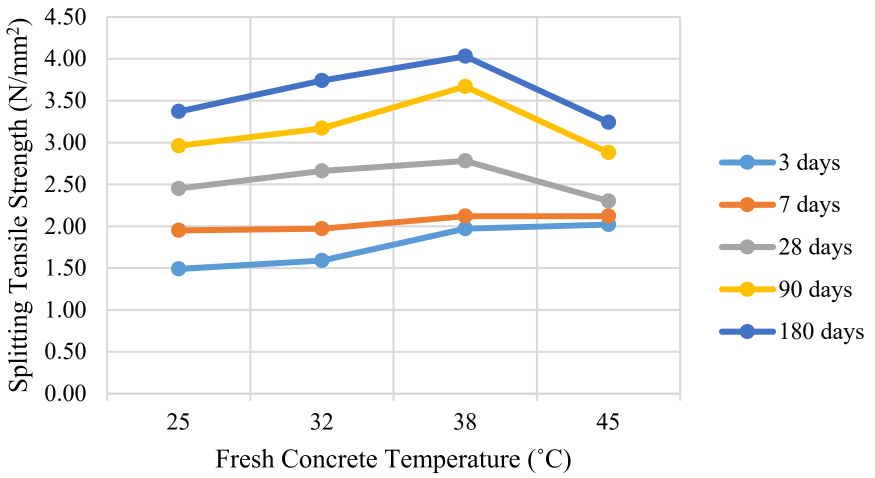


Figure 2.11 : Splitting tensile strength results for 70% GGBFS cement concrete [7]

6. For concrete with 20% natural pozzolan (NP) cement, in early ages (up to 7 days), maximum strengths were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days to 90 days), maximum strength was achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.12).

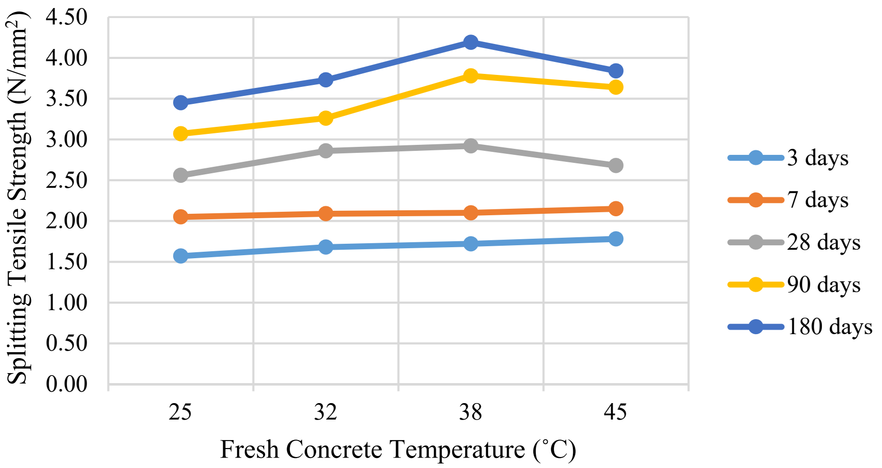


Figure 2.12 : Splitting tensile strength results for 20% NP cement concrete [7]

Following is the summary of the results obtained for pulse velocity results.

1. For concrete with Ordinary Portland Cement (OPC), in early ages (up to 7 days), optimum results were achieved when the fresh concrete temperature was 45˚C. However, in later stages (i.e. 28 days and 90 days), optimum test results were achieved when the fresh concrete temperature was 32 ˚C (See Figure 2.13).

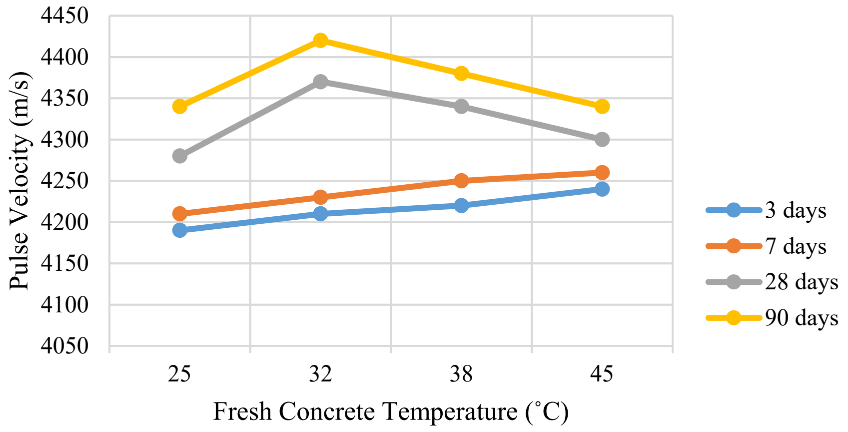


Figure 2.13 : Pulse velocity results for OPC concrete [7]

2. For concrete with 10% very fine fly ash (VFFA) cement, in early ages (up to 7 days), optimum results were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days and 90 days), optimum test results were achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.14).

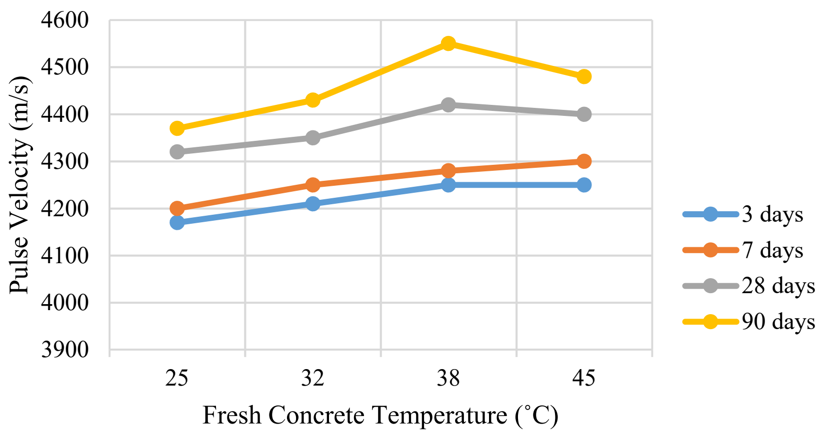


Figure 2.14 : Pulse velocity results for 10 % VFFA cement concrete [7]

3. For concrete with 30% fly ash (FA) cement, in early ages, optimum results were achieved when the fresh concrete temperature was 45˚C. However, in later stages (i.e. 28 days and 90 days), optimum test results were achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.15).

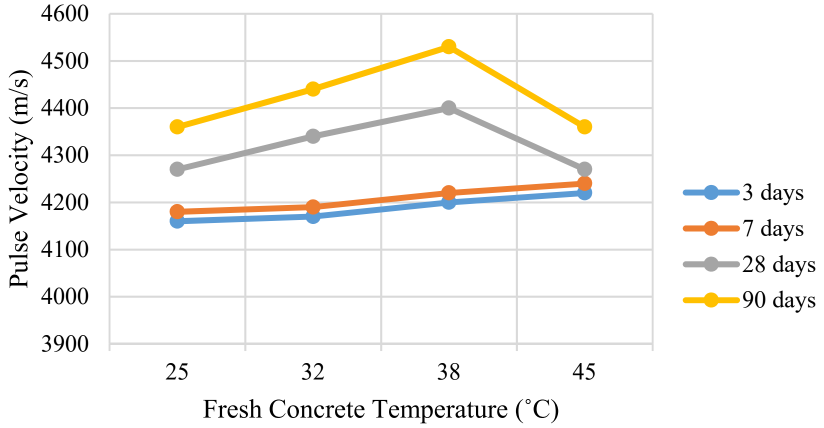


Figure 2.15 : Pulse velocity results for 30% FA cement concrete [7]

4. For concrete with 7% silica fume (SF) cement, in early ages (up to 7 days), optimum results were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days and 90 days), optimum test results were achieved when the fresh concrete temperature was 32 ˚C (See Figure 2.16).

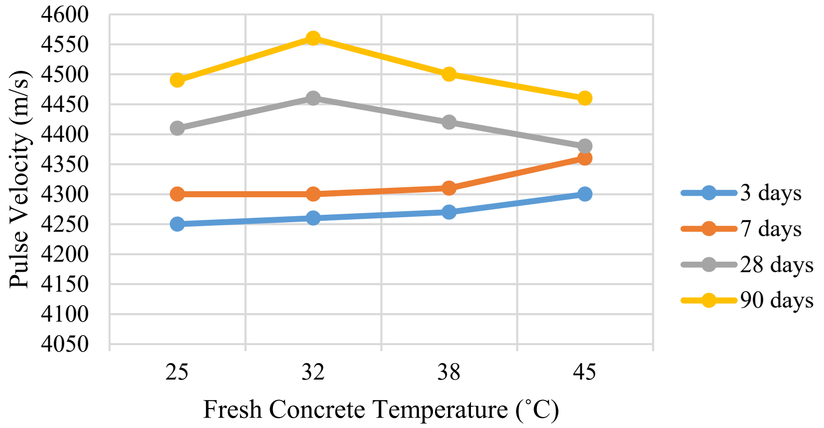


Figure 2.16 : Pulse velocity results for 7% SF cement concrete [7]

5. For cement with 70% ground granulated blast furnace slag (GGBFS) cement, in early ages (up to 7 days), optimum results were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days and 90 days), optimum test results were achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.17).

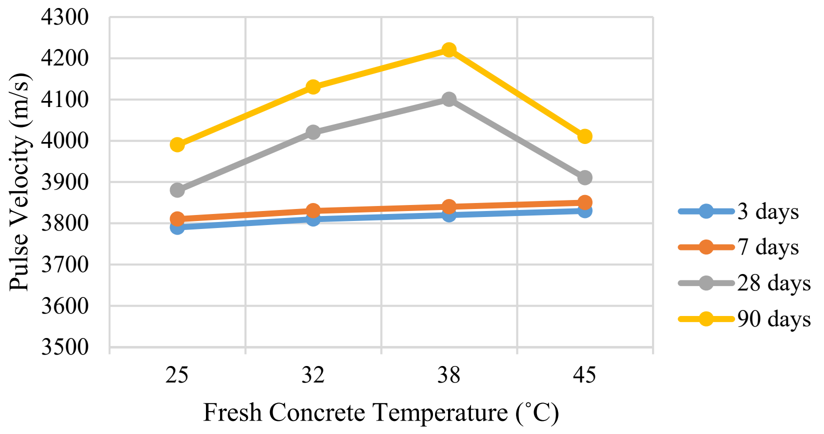


Figure 2.17 : Pulse velocity results for 70 % GGBFS cement concrete [7]

6. For concrete with 20% natural pozzolan (NP) cement, in early ages (up to 7 days), optimum results were achieved when the fresh concrete temperature was 45 ˚C. However, in later stages (i.e. 28 days and 90 days), optimum test results were achieved when the fresh concrete temperature was 38 ˚C (See Figure 2.18).

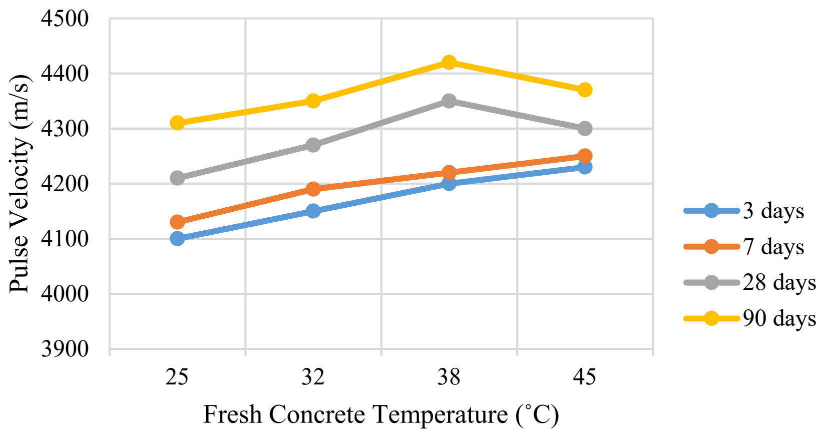


Figure 2.18 : Pulse velocity results for 20% NP cement concrete [7]

Early increases in mechanical characteristics could have been caused due to the accelerated hydration process and the pozzolanic reactivity of the cementitious materials at the elevated temperatures. However, this had a negative impact on the later age mechanical properties as the accelerated hydrating process forms a porous microstructure as the formed C-S-H is not evenly distributed over the concrete paste. It has been reported that this scenario causes the strength and pulse velocity to degrade at a later stage [7].

Hence, they concluded that Ordinary Portland Cement concrete and Silica Fume (SF) cement concrete give the optimum results when the placing temperature is 32 ˚C and all other blended types of cement give the optimum results when the placing temperature is 38 ˚C.

As there were no sufficient data on the temperature limits for plain and pozzolanic cement and the impact of curing methods, Nasir et al. [8] extended their research to determine the impact of placement temperature and the method of curing on plastic shrinkage under hot weather. Again, they used the same cement types as in the previous [7] case and the same fresh concrete temperatures. All tests were conducted under a humidity level of 34-40% and an ambient temperature of 36-40 ˚C.

Altogether 24 numbers of concrete mixtures were prepared. From each mix, two slabs, three cubes and three cylindrical specimens were cast and kept under ambient conditions. The curing of slabs was carried out by spreading a curing substance over the fresh concrete or by covering it with a plastic sheet. Compressive strength and pulse velocity measurements were measured using 100mm cubes while splitting tensile strength was measured on 75mm dia and 150mm dia. cylindrical specimens.

Experiments revealed that the plastic shrinkage cracks increased with time in all types of concrete specimens. Plastic shrinkage crack development is rapid at the beginning and stabilises with time and remains unchanged thereafter.

Further, they found out that, irrespective of the fresh concrete temperature, the curing method does affect the plastic shrinkage of plain and pozzolanic cement concretes in hot weather conditions. In which better results were given for the specimens covered with the curing compound than the specimens which were covered with a plastic sheet in all temperatures, which is a 15-28% reduction from the control specimen. See Table 2.3 and Table 2.4 for the plastic shrinkage strain values for both the curing methods.

The effect of curing compounds for the reduction of plastic shrinkage strain is more effective on Type I (OPC) and FA cement concrete specimens. They further revealed that irrespective of the curing method, 25 ˚C is the critical temperature for the maximum plastic shrinkage strain and the shrinkage strain decreases as the temperature of fresh concrete reaches the ambient temperature. That means plastic shrinkage increases when the difference between fresh concrete temperature and ambient temperature increases (See Figure 2.19). They revealed that the optimum temperatures for minimum plastic shrinkage were 32 °C and 38 °C for OPC Type I & SF cement and other types of blended types of cement respectively (See Table 2.5).

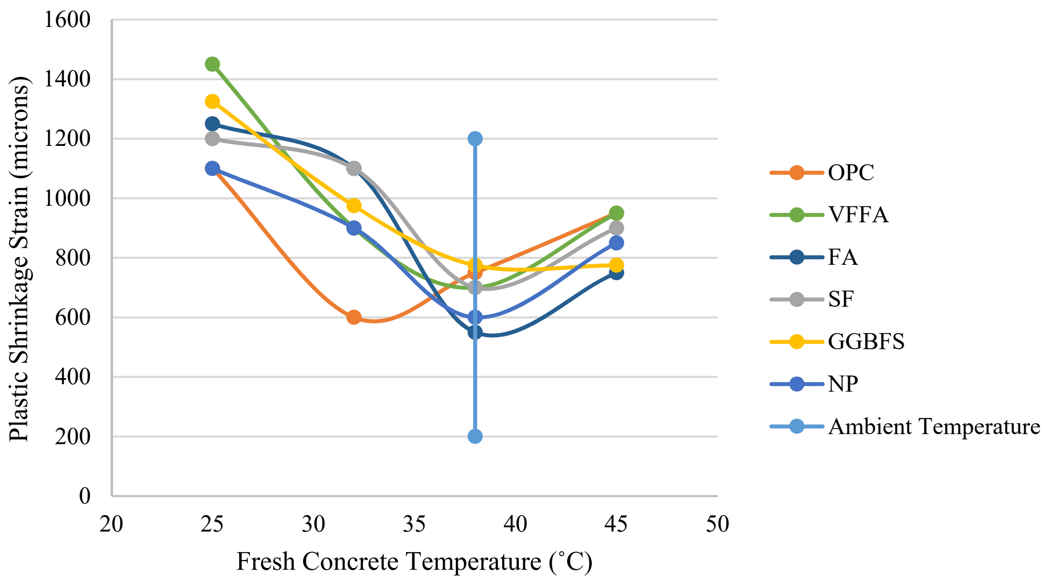


Figure 2.19 : Plastic shrinkage strain variation with varying fresh conc. Temp. [8]

Quantitatively the reduction of shrinkage strain in the specimens covered with the curing compound than the specimens covered with the plastic sheet is around 15-28%.

Table 2.3 : Plastic shrinkage strain values for the specimens cured by application of curing compound [8]

Cement Type	**Plastic shrinkage strain** **Cured by application of curing compound**			
	25˚C	**32˚C**	**38˚C**	**45˚C**
Type I	1150	600	750	950
VFFA	1450	900	675	1100
FA	1250	1150	550	750
SF	1200	1150	725	900
GGBFS	1300	950	775	775
NP	1175	900	600	950

Table 2.4 : Plastic shrinkage strain values for the specimens cured by plastic sheet cover [8]

Cement Type	**Plastic shrinkage strain** **Cured by plastic sheet cover**			
	25˚C	**32˚C**	**38˚C**	**45˚C**
Type I	1375	940	1000	1200
VFFA	1625	1025	750	1250
FA	1525	1400	950	1100
SF	1375	1300	940	1100
GGBFS	1575	1250	1050	950
NP	1250	1075	725	1025

Table 2.5 : Optimum and critical temperatures for the plastic shrinkage strains for the specimens cured by application of curing compound [8]

Cement Type	**Plastic shrinkage strain Cured by application of curing compound**	
	Optimum (˚C)	**Critical (˚C)**
OPC - Type I	32	25
VFFA	38	25
FA	38	25
SF	38	25
GGBFS	38 or 45	25
NP	38	25

Analysis of the compressive strength, tensile strength and pulse velocity results at 28 days, showed that the most effective placement temperature for Type I and SF cement concretes is 32 °C while the optimum range for other cement concretes is 38 °C.

The author has discussed only the results obtained for the specimens cured by applying a curing compound as they showed the best results. See Table 2.6, Table 2.7, Table 2.8 for the summary of compressive strength, tensile strength and pulse velocity results respectively at 28 days for the specimens cured with curing compound.

Results showed that the optimum temperature for Type 1 and SF cement concrete is 32 ˚C while for other blended types of cement optimum temperature is 38 ˚C.

Table 2.6 : Compressive strength values for the specimens cured by application of curing compound [8]

Cement Type	**Base Temperature**	**Compressive strength** **% Difference of the base value**			
		Cured by application of curing compound			
		25˚C	**32˚C**	**38˚C**	**45˚C**
Type I	32 ˚C	16	-	7.5	20
VFFA	38 ˚C	13.5	3.5	-	8
FA	38 ˚C	21.5	5.5	-	23.5
SF	32 ˚C	13	-	2	18.5
GGBFS	38 ˚C	23	15.5	-	30
NP	38 ˚C	18	7	-	12

Table 2.7 : Split tensile strength values for the specimens cured by application of curing compound [8]

Cement Type	**Base Temperature**	**Split tensile strength** **% Difference of the base value**			
		Cured by application of curing compound			
		25˚C	**32˚C**	**38˚C**	**45˚C**
Type I	32 ˚C	6.5	-	0	9.5
VFFA	38 ˚C	9	4	-	6
FA	38 ˚C	8	2.5	-	14.5
SF	32 ˚C	9.5	-	5	16.5
GGBFS	38 ˚C	9.5	2.5	-	17
NP	38 ˚C	10	5.7	-	10

Table 2.8 : Pulse velocity values for the specimens cured by application of curing compound [8]

Cement Type	Base Temperature	Pulse velocity % Difference of the base value			
		Cured by application of curing compound			
		25 ˚C	32 ˚C	38 ˚C	45 ˚C
Type I	32 ˚C	0.9	-	0	0.9
VFFA	38 ˚C	1.8	1.1	-	0.2
FA	38 ˚C	2.5	1.5	-	2.5
SF	32 ˚C	1.1	-	1.4	1.6
GGBFS	38 ˚C	5.1	2.2	-	4.7
NP	38 ˚C	2.3	1.4	-	0.7

From the above, it is understood that fewer studies have been conducted to find out the effect of fresh concrete temperature on fresh and hardened properties of concrete in normal concreting works. That is also in the range of 36 °C - 45°C ambient temperature and no records were found similar to the Sri Lankan context. Most of the experimental studies have been conducted to identify the effect of hot weather when the other factors are changed such as mix proportions and curing method. At the same time, few researches have been conducted to identify how the curing temperature and the curing procedure affect the properties of concrete in hot weather as well. The following outline provides summaries of these studies.

2.4.2 Studies done on the effect of hot weather on concrete properties

The effect of air temperature, wind velocity and relative humidity on plastic shrinkage, compressive strength, pulse velocity and pore structure were studied by Almusallam [10]. Type V Portland cement was used for the experiments and 915mm x 915mm x 50mm thick concrete slabs were cast to investigate the quantity and rate of water evaporation, time to cracking, cracked area and shrinkage strain of concrete. The specimen thickness was selected to represent a typical slab surface area to volume ratio. Testing specimens were cast in an environmental chamber in which the temperature, humidity and wind could be controlled as per the testing requirements.

The same specimens were used to get the pulse velocity readings as well. A 50mm dia. core specimens were taken from the same slab after evaluating the shrinkage effect to determine the compressive strength and pore size distribution.

Almusallam [10] assessed the quantity and rate of water evaporation, time to cracking, cracked area and shrinkage strain. As a result, he identified that the exposure conditions at the time of casting have a significant impact on all the criteria listed above. The evaporated water volume from the specimens was increased when the exposure temperature was increased. At the same time, wind also causes more water to evaporate from the concrete surface. High humidity level lowers the evaporation of water from concrete. The same behaviour was observed in the rate of water evaporation as well. The water evaporation rate under hot-dry conditions is 10 times which is under hot humid conditions.

The effect of environmental conditions on plastic shrinkage cracking was observed by observing the time for the appearance of the first crack and the total crack area. When the temperature was increased the time it took to appear the first crack was decreased.

Same time total area of cracks was increased when the exposure temperature increased. And total area of cracks decreased when the humidity levels were increased. The same behaviour was shown for the shrinkage strain as well.

Compressive strength, denseness and pore structure were measured to identify the impact of elevated temperature on the hardened properties of concrete. He identified that there is a significant change in the compressive strength as a result of being exposed to various temperatures. Avg of 5MPa reduction was observed when the temperature increased from 30°C to 45°C for all exposure conditions. However, it is observed that the wind velocity and the relative humidity have no major impact on the compressive strength of the concrete.

From the pulse velocity test, it was observed that the specimens cast at 30°C were denser than the specimens cast at 45°C. The cumulative pore volumes are higher in the specimens exposed to 45°C than in specimens exposed to 30°C. Humidity levels are also having a similar impact on the pore volume as the evaporation rates are higher when the humidity is lower.

So he concluded that the elevated temperature, high wind and low humidity levels increased the water evaporation, shrinkage strain and the area of cracks. Plastic shrinkage cracks appeared earlier when the specimens were subjected to high temperatures and low relative humidity than in the case of low temperature and high humidity. A similar phenomenon occurs during the high wind than in low wind speed conditions and no wind conditions. In hardened concrete also, compressive strength and pulse velocity are reduced when the specimens are subjected to high temperatures. Pore structure also showed similar behaviour.

It is known that compressive strength is an important strength-related factor in concrete. Previous researchers have mentioned that all other parameters such as splitting tensile strength, modulus of rupture, shear strengths and bond strengths depend on the concrete compressive strength. They believed that if the compressive strength is obtained by properly doing the mix design, mixing and placing, other strength parameters are some how can be obtained.

However, later it is found that the above conclusions are not accurate, and all other parameters are affected by the hot weather conditions even if the aimed compressive strength is achieved.

Abbasi et al. [11] conducted the tests, to ascertain the impact of hot weather on the modulus of rupture and splitting tensile strength of concrete. In which they concluded that the modulus of rupture and splitting tensile strength of concrete prepared and cured under hot weather conditions are decreased when the temperature increases, and they further proved that even if the necessary actions are taken to control the compressive strength values, those two parameters are affected by the hot weather conditions.

The same has been proved by some of the other researchers as well. They also showed that, even if the compressive strength is achieved other properties can be drastically affected by the hot weather.

Further to the above tests Abbasi et al [12], conducted tests to study how the hot weather affects pulse velocity and modulus of elasticity. They considered the variables of (i) concrete temperature at preparation, (ii) the size of the specimen, (iii) preparation and curing condition and (iv) the type of coarse aggregate.

Test results showed that the pulse velocity of concrete decreases with the increment of concrete mix temperature for the different types of coarse aggregates. Good quality aggregate gave higher results for pulse velocity readings. Modulus of elasticity also gave a similar behaviour when the concrete mix temperature increased. Abbasi et al. [12] showed that even if precautions are taken to maintain the required compressive strengths, other properties are affected by the elevated temperatures.

Burg [6] carried out experiments on non-admixtured Portland cement concrete to identify, how casting and curing temperatures affected the properties of freshly poured and hardened concrete. Specimens were cast at 10 °C, 23 °C and 32 °C, and the considered base casting and curing temperatures were 23 °C. To monitor the proper effect of the temperature factor, the researcher did not make any adjustments to the mix design to prevent changes occur in the workability due to high temperature.

Even though he mentioned the specified temperature as the casting temperature, it was meant to be the ambient temperature at the time of casting and not the fresh concrete temperature.

Two cement types were used such as high alkali cement (Cement Type A equivalent to the Type I cement of ASTM C150 [33]) and low alkali cement (Cement Type B, equivalent to the requirements of Type II and Type III in ASTM C 150 [33]).

The slump was affected by the casting temperature when the water content was kept constant for all the temperatures. They revealed that the slump of the concrete made with Cement Type A had a linear relationship to the temperature where the slump was decreased by approximately 20mm for each 10 °C increment in casting and curing temperature. And when the temperature was decreased by 10 °C, the slump was increased by 20mm. Concrete made with cement type B showed a nonlinear relationship, in which the slump was increased by 100% when the temperature decreased from 23 °C to 10 °C, and the slump reduction was around 20mm when the temperature rose from 23 °C to 32 °C.

Initial and final set times are also measured as per ASTM C 403. There was a significant difference in the setting times in absolute values, but the relative changes are somewhat similar in both cement types.

Approximately, a setting time change of 50% was observed for a temperature change of 10 °C from the base temperature of 23 °C. As expected, initial setting time and final setting time were delayed in lower temperatures while the same increased in elevated temperatures.

Early age strength at lower temperatures was lower than the results obtained for the specimens cast and cured at 23 °C, while specimens cast at higher temperatures received higher values at lower age (7 days). Vice versa, later age strength is higher or similar in the specimens which were cast at lower temperatures compared to base temperature values, while the later age strengths are lower in specimens which were cast at higher temperature levels. They identified that the concrete cast at 32 °C gave 70% strength of 28 days strength at 3 days.

Hasanain et al [31] studied the water evaporation characteristics from a fresh concrete surface under hot weather conditions. In which they studied the effect of the casting time and the environmental conditions on the evaporation rate and temperature developments in the concrete.

Results showed that the time of casting, ambient conditions, the temperature of concrete, moisture condition of the concrete surface and the shading provided are the factors affecting the evaporation rate from the fresh concrete surfaces.

The limit of evaporation rate exceeded 1.0 kg/m^2/hr even though the initial concrete temperature is well below 38 °C, in hot and humid weather conditions. So they highlighted the requirement of the upper limit of fresh concrete temperature in hot and humid weather conditions. As a precaution, they suggested that shading can reduce the evaporation rate by 50%.

The maximum rate of evaporation occurs during the first 1 hr period in the specimens cast in the noon and early afternoon. The specimens cast in the late morning hour showed two peak periods for the maximum rate of evaporation.

Abbasi et al [34] identified that the shear strength, moment capacity and steel stress with the increase of concrete mix temperature, and prepared and cured in hot weather were reduced by testing reinforced concrete beam specimens. Same time it is identified that the deflection also increases with the increase of the concrete temperature at higher load levels. The deflection is not much affected at lower load levels.

Some of the previous researchers have highlighted that if the required precautions are taken to get the intended compressive strength of the concrete, all other parameters such as shear strength, development length, modulus of elasticity, modulus of rupture and splitting tensile strength will also receive their desired values. But author showed that these parameters tend to change with the increase of concrete mixing temperature, even if the mix proportions of concrete are in order and the intended compressive strength is achieved in hot weather conditions.

Ghafoori and Diawara [29] carried out tests to identify the effect on fresh performances (unconfined workability, flow rate, passing ability and dynamic ability) of Self Compacted Concrete (SCC) by hot environmental conditions such as 43 ˚C, 36 ˚C, and 28 ˚C ambient temperatures and cold environmental conditions such as 14 ˚C, 7 ˚C, and 0.5 ˚C ambient temperatures. Their studies showed that both the hot and cold temperatures affect the workability. In which the slump flow loss increases when the exposed temperature levels are increased. Same time the flow rate or plastic viscosity per inference of SCC, and dynamic stability were increased by the hot temperatures. Cold temperatures tend to increase the workability marginally while slightly reducing the flow rate. However, the cold temperatures do not have much impact on the dynamic stability of the fresh SCC. They formulated that the fresh concrete properties were changed due to the admixture adsorption amount per specific surface area of concrete paste, changes in the aggregate moisture content and the partial evaporation of mixing water.

Drzymala et al [35] studied the physical and mechanical properties of high-performance concrete (HPC) exposed to the effect of high temperatures such as 300 ˚C, 400 ˚C and 600 ˚C. In which, the maximum compressive strength showed at 300 ˚C with respect to the strength measured at 20 ˚C, and decreased the compressive strength at other temperatures which are 450 ˚C and 600 ˚C with respect to the strength measured at 300 ˚C. At 450 ˚C compressive strength did not fall below the control specimen which was cast at 20 ˚C, but at 600 ˚C, compressive strength fell even below the values received for the control specimen at 20 ˚C. However, when the temperature rises from 20°C to 300°C, the tensile strength gradually declines. Same time linear relationship between the decrease in modulus of elasticity and the increase in temperature was identified. They concluded that the decrease in tensile strength leads to more brittle concrete at elevated temperatures.

Behfarnia and Shahbaz [36] did a comparison for the residual tensile strength and for mass loss between alkali-activated slag (AAS) and normal concreting subjected to elevated temperatures such as 20, 200, 400, 600 and 800 ˚C. Experiments showed, that the centre of the normal concrete specimen reached the desired temperature before the AAS concrete specimen thus it was subjected to a higher temperature than in AAS concrete.

Mass loss was also observed in both types of concrete. It showed a linear loss with temperatures up to about 600 ˚C and rapid loss from 600 ˚C – 800 ˚C.

Tensile strength results showed that 28-day test results are higher in normal concrete than in AAS concrete. And the same time when the adhesive materials are higher in the mix design, tensile strength also increases. Tensile strength in AAS concrete was decreased by 60% when the temperature reached 600 ˚C and it decreased up to 85% when the temperature rose to 800 ˚C. Tensile strength reduction is about 45% at 400 ˚C, 75 % at 600 ˚C and almost 100% at 800 ˚C in normal concrete.

Kocab et al [37] investigated the influence of continuous exposure to low ambient temperatures on its elastic properties and comprehensive strength. Elastic modulus is varied with the external parameters such as composition, type, fraction and amount of aggregate, w/c ratio and admixtures, even in the same strength class. Hence it is required to know which factors have a major impact on this. They concluded that the elastic modulus development and early age compressive strength are greatly affected by the ambient temperature and there is no significant impact of the ambient temperature on those properties at 28 days. And also they concluded that concrete cast and cured at very low temperatures such as 10 °C exhibits very low values at an early age compared to high ambient temperatures such as 20 °C. At 3 days, the strength is about 50% at 10 °C from the 20 °C strength. Kocab et al [37] further revealed that, compared to other parameters, the modulus of elasticity was not much varied with the ambient temperature. This conclusion is very much similar to the finding of Kim et al. [38]. They further concluded that the relationship between the modulus of elasticity and compressive strength is not affected by the ambient temperature at any age.

2.4.3 Studies done on the effect of water temperature on concrete properties

The use of concrete additives, high early strength (HE) cement, and heating of materials are common practices in cold weather concreting. It is said that the optimum temperatures for the heating of the material are not established. So that Eskandarsefat [39] investigated the effect of the temperature of mixed water in cold weather conditions, on the performance and mechanical properties of concrete made with high early strength cement.

Water temperature ranged from 5 °C – 90 °C to study the fresh and hardened properties of concrete. ACI 306 R-16 [40] limited the mixed water temperature to 80 °C while some other literature limited to temperature to 20 – 35 °C and 50 °C.

In this, it is identified that the increase of water temperature than 60 °C has increased the slump and workability. The bleeding effect also increased with the increment of water temperature than 60 °C, thus leading to segregation and visible cracks in the surface.

The optimum concrete mixture temperature is identified as 14-18 °C, which gave the highest compressive strength results in cold weather concreting works. Test results indicated that the optimum bleeding was observed when the water temperature was 50 +/- 5 °C for high early-strength cement. Not only bleeding optimum cylindrical compressive strength was also observed in this region.

2.4.4 Studies done on the effect of concrete mix proportions on concrete properties in hot weather conditions

Almusallam et al. [41] investigated the effect of mix proportions on plastic shrinkage cracking in hot weather conditions, in which they concentrated on the cement content and the w/c ratio. They measured the bleeding rate, the amount of evaporated water and time and the crack intensity to identify the cumulative effect of these parameters.

The w/c ratio and the cement content were varied from 0.40 – 0.65 and from 300 kg/m^3 to 400 kg/m^3 respectively, to identify the effect of mix proportions for ASTM C 150 [33] Type V Portland cement by them. The slump was designed to reach 50 – 75 mm, and a water reducer was used to achieve the required workability.

The test specimens were cast in a temperature–humidity controlled chamber, and a desired wind condition was also artificially generated using blowers. 450x450x20mm slab specimens were cast. Forms made with aluminium and plexiglass were used to reduce the moisture absorption from the fresh concrete. Materials were mixed with an electric mixer and consolidated using vibratory tables and then exposed to a 45 °C temperature, 50 % relative humidity and 15 km/h of wind speed. Then the bleeding, water evaporation, water evaporation rate, time to initiate cracks, and total crack area were measured.

As per the results obtained, the volume of bleed water was increased with the increment of the water-cement ratio for the same cement content. When the water-cement ratio is 0.65, the bleeding takes place for a prolonged period. The volume of cumulative bleed water again increases when the cement content increases from 300 kg/m3 to 350kg/m^3. However, there was no significant increment when the cement content increased from 350kg/m^3 to 400kg/m^3.

With the increment of cement content in the same w/c ratio, the percentage of water evaporation was increased, however, it was decreased when the w/c ratio was increased. The reason for the increment of percentage water evaporation with the increment of cement content is the increased capillary pressure due to the increase in the volume of the cement paste and the reduction of the volume of aggregate. The rate of water evaporation also increased in both cases when the cement content and the w/c ratio were increased.

The time to initiate the cracks and total crack area also increased with the increase of cement content and w/c ratio. Even though the lean stiff mixes crack earlier than the rich plastic mixes, the crack intensity is higher in rich plastic mixes than the lean stiff mixes. Due to this reason, they suggested that the mixes with 300kg/m^3 with 0.4 w/c are suitable for hot arid environments. They showed that the evaporation rate suggested by ACI Committee 305 [2] is on the higher side where the plastic shrinkage crack can be observed when the evaporation rate of 0.2-0.7kg/m^2.

San et al. [32] also studied the impact of mix proportions (cement content and water–cement ratio) on plastic shrinkage cracking of concrete under a constant evaporation rate and slump. Their focus was to identify the relationship between the crack formation time, the rate of increasing crack widths and the total crack area.

Water cement ratio from 0.38 to 0.67 was used to create a slump of 75+/-25mm without adding any special admixtures. Specimens were cast using aluminium forms expecting to reduce the absorption of moisture from fresh concrete. An evaporation rate of 0.4+/-0.02 lb/ft^2/hr was made using heaters and blowers.

Weight change was measured to evaluate the evaporation rate of water. The crack intensity was monitored for the first 3 hours of casting and images were captured at a specific interval to analyse using the photo processing method using Image J software. The crack width increasing rate and the crack area increasing rates were determined using the image processing method.

Using the analysed images, San et al. [32] concluded that when the cement content is high, the crack formation time is faster. Further, they concluded that the plastic shrinkage is a result of cement content and water-cement ratio rather than the slump of the concrete. Plastic shrinkage cracks are normally stated to appear after 30 minutes of placing. It was seen in his experiments that the plastic shrinkage cracks appeared when the cement content increased and the w/c ratio decreased.

Further, San et al. [32] concluded that the curing should be started after 30 minutes of placing if the w/c lies below 0.55 and if the evaporation rate is 0.4+/-0.02 $lb/ft^2/hr$.

When the w/c ratio increases, it gives the least in both crack width and crack appearing time. But for the total crack area highest values were given when the w/c ratio was 0.45.

The cement content and rate of evaporation are connected to the rate of increasing the crack width, and the crack formation time is related to the w/c ratio.

Al-Gahtani et al. [42] investigated the combined effect of (a) water-to-cement ratio (W/C), (b) total aggregate-to-cement ratio (TA/C), (c) fine-to-total aggregate ratio (FA/TA), and (d) hot-weather conditions in terms of concrete placement temperature and curing conditions on the workability and compressive strength.

Al-Gahtani et al. [42] identified that the strength of the concrete was reduced when they were cast and cured under hot weather conditions. In which they identified that the strength reduction increases with the increment of the concrete placement temperature and they derived a formula to calculate the strength reduction. Further, Al-Gahtani et al. [42] identified that the specimens cast in the laboratory but cured under hot weather had a strength reduction than which are cast and cured under laboratory conditions. Further, Al-Gahtani et al. [42] highlight that the specimens cast and cured under hot weather have somewhat higher strength results than the specimens cast under laboratory conditions and cured under hot weather. From which they showed that the reduction in placement temperature alone will not lead to achieving the required concrete strength, thus the curing should also be done under controlled conditions.

Al-Gahtani et al. [42] concluded that the sudden exposure to the hot environments increases the rate of hydration thus creating a protective layer on the hydrating cement grains. This will delay the balanced hydration process and create an uneven distribution of hydrated materials, which tends to reduce the strength of concrete.

So the specimens mixed, cast and cured under ambient conditions will give better results than the specimens mixed and placed in controlled conditions and cured under ambient conditions.

He further identified that for a given w/c ratio, the Total aggregate to Cement ratio (TA/C) does not make a considerable impact on the compressive strength of the concrete mixed and cured under hot weather conditions but has a considerable impact on the workability.

Slump gets increased when the TA/C is decreased, in this case, cement slurry predominantly controls the slump of the mixture. But for any TA/C, the w/c has a considerable impact on the slump and the compressive strength.

2.4.5 Studies on the effect of curing on concrete properties

Curing is required to assist the hydration process of cement by keeping it continuously saturated. Once the free water is lost in concrete, the hydration process gets stopped. Most used concrete curing methods are either spraying water, ponding with water, covering it with a plastic sheet or applying a curing compound. The curing compound will act as a guard to prevent the evaporation of water from the surface of concrete.

Cement Control & Aggregates Australia [43] stated that the curing process controls the rate and extent of moisture loss from the concrete during the hydration process until it gains strength. The ambient conditions such as the temperature and the relative humidity mainly decide the curing start time and the curing period.

Concrete properties are affected by the duration of curing. It is shown that the concrete which is dried out soon after casting achieves only about 40% of the strength which is moist cured for a period of 180 days [43]. Three days of water curing does achieve 90% strength and 28 days of water curing does achieve 95% of 180 days of full water curing strength. Same time curing does affect the permeability of concrete. Long-time curing reduces permeability [43].

ASTM C 31 [44] defines two methods of curing such as standard curing and field curing. But the argument is what is the correct curing practice in the field. NRMCA research laboratory [45] conducted experiments to check the effect of standard curing and field curing. They conducted experiments in winter and summer months, and specimens were cured under three different conditions which are standard curing, field curing and conditions which is not fully comply with the standard curing.

Test results indicated that strength reduction is possible in the early stages if the standard curing procedure is not followed, but there is no significant reduction in strength at later stage such as 90 days, even if the standard curing procedure is not followed and when the external temperature is between 40 °F-75 °F (4.5-24 °C).

They further carried out the tests under hot environmental conditions, to test the strength of the concrete cylinders under three different curing conditions;

1. Standard Curing
2. Outside for 48 hr, moist cured
3. Outside until the time of tests

Effect on elastic modulus, sorptivity and rapid chloride permeability were also tested. The average daily temperature of the first 48 hrs was between 81 °F-83 °F (27-28 °C). The peak daily temperature was 89 °F (32 °C) in the next seven days and the average daily temperature was about 10 °F (5.5 °C) above the standard curing temperature.

The standard cured cylinders showed a low chloride iron penetrability while outside cured cylinders showed a moderate chloride iron penetrability, indicating that good curing leads to durable concrete. They further showed an average 20% reduction in strength parameters in outside cured temperatures than the standard cured cylinders at 90 days under hot weather conditions. However, their lower age strengths are very much higher than the standard cured conditions results. They further found out that the elasticity was not very much dependent on the curing condition.

Al-Amodi et al [46] did investigations on silica fume (SF) cement concrete against plain cement concrete to identify the effect of the size of the specimen and the curing method on plastic and drying shrinkage and some of the other mechanical properties of concrete under hot weather conditions. Supplementary cementing materials (SCMs) are widely used in the world due to their impact on the durability factor. But same time it is understood that these SCMs have disadvantages over plastic and drying shrinkages. From all the SCMs it is said that the silica fumes greatly affected the plastic and drying shrinkages while it has so many advantages over other properties than the other blended types of cement.

To measure the above mentioned property, 300cm X 300cm X 30 cm and 500cm X 500cm X 30cm slab specimens were cast from both cement types. Soon after casting and finishing, all slabs were covered with a plastic sheet for 24 hrs, and then half of the specimens were covered with wet burlap and the other half was cured by water ponding. The specimens made with plain cement were cured for 7 days while the other set of specimens were cured for 21 days. Plastic shrinkage cracks were observed in the first 24-hour period. After the completion of the curing period, drying shrinkage measurements were started.

Concrete specimens of size 75 mm dia. X 150mm high were cast and cured in the field and in the laboratory under controlled conditions to determine the compressive strength, split tensile strength and pulse velocity at 3, 7, 14, 28, 90 and 180 days.

They concluded that the plastic shrinkage in silica fume concrete is higher than which is in plain cement concrete and plastic shrinkage increases with the period of exposure to the ambient conditions.

Further, the comparison of the results in both sizes of specimens indicated that the variance of results in both samples is very small. Hence, they concluded that the specimen size does not have a major impact on the plastic shrinkage values.

Similarly, irrespective of the curing method, time of exposure to the ambient conditions has also led to an increase the drying shrinkage. However, drying shrinkage values in both plain and silica fume concrete specimens cured with water ponding are lesser than that of cured with covering with wet burlap. Drying shrinkage in the silica fume cement concrete specimens is higher than that of the plain cement specimens and drying shrinkage is higher in the larger specimen than in the smaller specimen.

Further, they identified that continuous water ponding gives better results than covering with wet burlap.

Specimens which were cured by water ponding gave higher results in pulse velocity, compressive strength and split tensile strength of plain cement than that cured with wet burlap. The silica fume concrete also showed a similar pattern. However, the results showed that silica fume concrete specimens performed better than the plain cement concrete specimens under both curing conditions. Somehow in both the cement types, strengths increased with time.

Al-Gahtani [47] assessed the plastic and drying shrinkage, compressive strength and pulse velocity in plain, very fine fly ash (10% VFFA), silica fume (7%) and fly ash (30%) cement concrete to study the effect of the curing method. After the preparation of concrete specimens, they were covered either by a wet burlap or by applying an acrylic-based or water-based curing compound.

Specimens covered with plastic sheets showed higher shrinkage strain values than those of the specimens cured with curing compounds in normal concrete. From this, the plastic shrinkage values in the specimens cured with acrylic-based curing compound are lesser than that of the specimens cured with water-based curing compound. Similar behaviour is shown in all other three cement types as well. However, the shrinkage strains are much lesser in silica fume cement concrete. Curing Efficiency is in the range of 150-400%.

Drying shrinkage strain in normal concrete specimens was higher when cured with water water-based curing compound. In VFFA, silica fume and fly ash cement concrete specimens, drying shrinkage strains were higher in specimens cured with wet burlap for 7 days.

Acrylic and water-based curing compounds are more effective in reducing the plastic and drying shrinkage for both plain and blended cement concretes than covering with wet burlap. The curing efficiency index is at the rate of 105-122%.

Compressive strength increased with age irrespective of the curing method in all concrete specimens. The specimens cured by covering with a wet burlap showed a higher strength development than the specimens cured with curing agents either acrylic-based or water-based. From the two curing compounds, the acrylic base curing compound gave higher results than the specimens cured with the water-based curing compound. Similar behaviour was shown in VFFA cement, silica fume cement concrete and fly ash cement. The curing efficiency index for compressive strength measurements was 84-96%.

The pulse velocity also increased with time irrespective of the curing method. However, the pulse velocity of the specimens which were cured by covering them with a wet burlap is higher than that of the specimens cured with curing compounds in all types of cement. From which also acrylic based curing compound shows greater results than the specimens cured with a water-based curing compound. The curing efficiency index for pulse velocity measurements was 95-97%.

San et al. [32] identified that the crack formation time is lower when the cement content is higher. They recommended that the curing starts after 30 minutes of casting under an evaporation rate of 0.4 +/-0.02 lb/ft^2/hr.

2.4.6 Studies on the effect of mixing and curing temperature on concrete properties

Al-Amoudi et al. [48] experimented the effect of hot weather curing on the compressive strength of plain and blended cement mortars. They used ASTM C 150 [33] Type V ordinary Portland cement and three blended types of cement such as fly ash, silica fume and blast furnace slag cement.

100 cube specimens were cast and placed in the laboratory at 20+/-2 °C for 24 hrs and after demoulding they were exposed to 25, 40, 55 and 70 °C temperatures in batches.

At an early age, ASTM Type V cement mortar specimens showed a higher compressive strength for the curing temperatures of 40 °C and above than the specimens which were cured at 25 °C. However, it was identified that the compressive strength of specimens at 28 days, cured at higher temperature levels tends to reduce than specimens cured at 25 °C.

Fly ash cement mortar also exhibited accelerated strength gain in the early-age specimens for elevated curing temperatures. However, later age strengths were similar to the results obtained for 25 °C. Therefore, they concluded that beneficial effects can be obtained up to about 55 °C curing temperatures in fly ash blended cement.

However, silica fume cement mortar showed higher strengths even at elevated temperatures at any age than at 25 °C. At 40 °C, it showed the most beneficial results. Blast furnace slag cement also showed similar behaviour to the silica fume cement mortar but a little higher than silica fume results.

All above are for w/c of 0.4. But for 0.3 w/c the results obtained for Type V cement and fly ash blended cement were a little bit different and it gave some higher values compared to 0.4 w/c. Specimens made with silica fume gave beneficial effects at 40 °C only. Specimens made with blast furnace slag cement also exhibited some similar behaviour to the Type V cement at 0.3 w/c ratios.

They concluded that the reasons for the above behaviour in blended types of cement are due to the reaction of pozzolanic materials with $Ca(OH)_2$, which were produced as a result of the process of hydration at elevated temperatures. Thus, blended cement concrete tends to increase its strength properties with ageing. Therefore, the author concluded that the reduction in strength can be offset by reducing the w/c ratio. Further, they concluded that the strength of the mortar as it ages mostly depends on the w/c ratio rather than the hot weather conditions.

Kim et al. [38] carried out experiments to find out how the curing temperature and ageing affect the properties of concrete such as compressive strength, splitting tensile strength and elastic modulus. They were tested according to ASTM C 39, ASTM C 496, and ASTM C 469 respectively to identify the effect of ageing. Type I, V, and V cement with fly ash were used for their experiments and 10 °C, 23 °C, 35 °C and 50 °C were considered as curing temperatures to identify the temperature effect at 1, 3, 7, and 28 days. Cement type, w/c ratio and temperature at curing were considered as the experimental variables at 100% humidity levels.

Results indicated that in Type I cement, the compressive strength increases with the increase of curing temperature in 1 and 3 days. But when it reached 28 days, the tendency was reversed and gave the lowest values for 50 °C and the highest values for 10 °C. The same pattern appears in the splitting tensile strength results as well as in elastic modulus. The results obtained for elastic modulus are not significant as in compressive strength results but the cross-over effect can be seen. That is due to the difference in strength development rates in both cases.

For type V cement, the cross-over effect is not so significant due to the slow hydration effect of the cement type. They concluded that both 0.4 and 0.5 w/c ratios have the same tendency. The tendency is the same for Type V+ fly ash concrete as well.

Their results suggested that the cement type, curing temperature and age do not have a significant impact on the relationship between the compressive strength and the modulus of elasticity.

Further, they concluded that the relationship between splitting tensile strength and compressive strength is not significantly influenced by cement type, curing temperature and age.

Klieger [49] studied how the temperature at mixing and curing affected the concrete properties such as compressive and flexural strengths for specimens made out of various Portland cement types mixed placed and cured at various temperatures such as 25 °F (-4 °C) to 120 °F (49 °C). ASTM Type I, II and III cement were used with and without calcium chloride as an accelerator and air-entraining agent to have a prescribed amount of air in all of the concrete.

Temperatures considered for the mixing, placing and curing were 40, 55, 73, 90, 105 and 120 °F (5, 12, 22, 32, 40 and 49 °C), and the specimens were tested at ages of 1, 3, 7, 28 days, 3 months and 1 year. Then all the specimens were cured at their mixing and placing temperature until their test age reached or until 28 days in part I of the testing series. After 28 days, half of the remaining test specimens were cured at 73 °F (22 °C) and 100% humidity while the other half were cured at 73 °F (22 °C) and 50% humidity. Another set of specimens was mixed and placed at 40 °F (5 °C) and stored at 25 °F (-4 °C) immediately after placing them in the moulds. After 1 day, specimens were demoulded and kept under the same condition up to their test age and a maximum of 28 days. After 28 days, they were kept as in the previous condition. In part II experiments, half of the specimens were moist cured for 7 days and the other half was cured by spraying moisture for 28 days at the casting temperatures. After 7 days and 28 days, each set was again divided into two parts and one set was cured at 73 °F (22

°C) at 100% humidity level and the other half at 73 °F (22 °C) and 50 % humidity level.

Generally, they observed different slumps at different concrete temperatures. An approximately 1-inch reduction in a slump was observed for every 20 °F (11 °C) temperature increment. They further observed that the water demand is increased when the temperature increases to cater for the 1-inch slump loss during high temperatures than in low temperatures. Therefore, they concluded that the slump decreases when the temperature increases and an increase of water to maintain a constant slump leads to a decrease the strength.

High initial and curing temperatures give high early strength values at 1 day, 3 days, and 7 days for compressive strengths and flexural strengths while giving lower strength at 3 months to 1-year ages.

They indicated that for all types of cement, there is an optimum casting temperature value considering the optimum results in later stages. The optimum temperature for Type I and II cements is 55 °F (12 °C) while for Type III concrete it is 40 °F (5 °C).

They further concluded that cement temperature does not have any impact on the strength parameters, and it only affects the concrete's final mixing temperature.

2.5 Testing methodologies used in the past to determine the shrinkage characteristics of concrete

Yılmaztürk [50] presented a method to calculate the shrinkage in a concrete sample using digital photogrammetry. A similar thing will be used in this experimental procedure as well. The camera setup was arranged approximately 1.2 m above the concrete sample to take the images.

An experimental methodology was developed by Sivakumar and Santhanam [51] to investigate the plastic shrinkage cracks in high-strength concrete. They emphasised the photographs taking method and it was a simple and reproducible method. They used a rectangular-shaped concrete slab with a stress riser in the centre.

For the control concrete specimen where there are no steel fibres or hybrid fibres, shrinkage cracks were observed within 4.5 hours after casting. Concrete with steel fibres and hybrid fibres took extended times for the shrinkage cracks to occur which were respectively 5.5 hr and 7 hrs. In the steel fibre concrete, the crack widths were reduced by 25% and in the hybrid fibre concrete, the crack width was reduced by 55%. They further identified that the reduction in crack area is 25.7% and 57.6% respectively for Steel Fiber Reinforced Concrete (SFRC) and Hybrid Fiber Reinforced Concrete (HFRC) concrete than the control system which is made out of OPC.

A liner test method was developed by Newlands et al. [52] to determine the plastic shrinkage in concrete and to determine the effects of new materials on early volume stability.

Newlands et al. [52] reviewed the published test methods and showed that there are unrestrained and restrained shrinkage test methods. He further mentioned that these restrained test methods have been developed to measure shrinkage-related cracking instead of measuring the shrinkage mechanism itself. After studying all, he was able to develop an unrestrained method.

Weerasinghe et al. [53] introduced a new test method to determine the tensile strain capacity of fresh concrete. They identified that the tensile strain capacity in the concrete decreases non-linearly with time during the plastic stage. From the plastic stage, concrete turns to a semi-liquid state before moving to an early hardening state. During this semi-liquid state cohesiveness decreases in concrete and again increases in hardened state. At early ages or when it moves from a liquid state to a semi-liquid state, strain capacity decreases. The test results further showed that the fly ash blended cement has a higher tensile strain capacity than that of the OPC and PLC. Fly ash particles do have a spherical shape, hence they concluded that this particular shape of the fly ash particles causes the higher tensile strain capacity in concrete. They further recommended measuring the local strain rather than the average strain, as the peak values of the strain lead to the cracking of concrete.

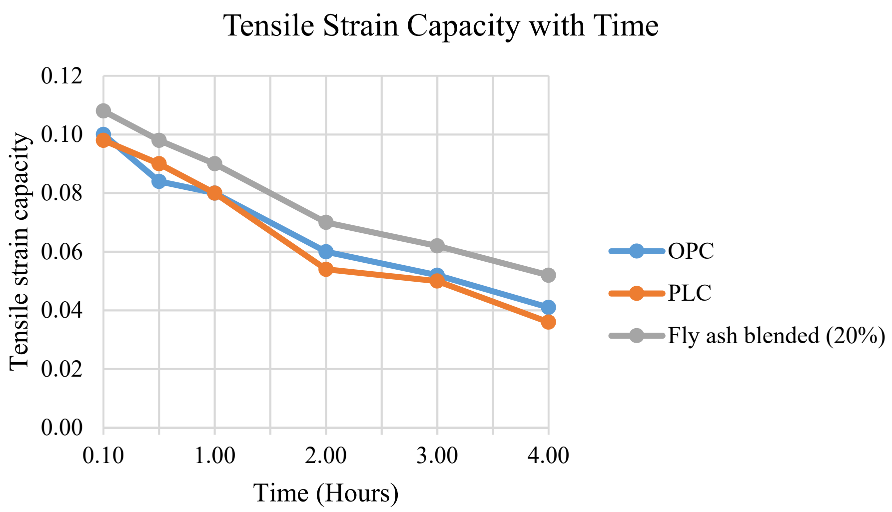


Figure 2.20 : Tensile strain capacity variation with time during plastic shrinkage [53]

Their test method aimed at using a flexible casing to ensure the proper grip. The strain was applied to the mould to have a uniform strain on the concrete, a contactless method was used to take the strain measurements which is based on a photo processing technique, and the test was repeatable.

2.6 Fresh Concrete Temperature Controlling Methodologies

From the literature, it is understood that the following methods can be used to control the fresh concrete temperature.

1. Moisten the aggregates
2. Cooling of coarse aggregate by shading or by spraying water
3. Controlling the temperature of cement by shading the cement silos
4. Using chilled water
5. Use ice cubes or flakes as the part of the mixing water
6. Using of liquid nitrogen for cooling mixing water
7. Mixing with liquid nitrogen

From the literature survey, it is understood that the studies have been vastly carried out to identify the effect of hot weather on concrete properties [6], [10], [11], [12], [29], [31], [35], [36], [37], [38], the effect of water temperature on concrete properties [39], the effect of curing on concrete properties [32], [43], [45], [46], [47] the effect of mixing and curing temperature on concrete properties [38], [48], [49] and the effect of concrete mix proportions on concrete properties [32], [41], [42] . However, very few studies have been carried out to identify the effect of fresh concrete temperature on fresh and hardened properties of concrete in normal concreting works. Further, there is not enough literature available to understand the basis of the limiting temperature values given in the standards or in any other project specifications.

From the limited literature [7], [8] it was identified that the ambient temperature considered in these studies is in the range of 36°C - 45°C. There are no enough information to suit with the Sri Lankan context, where the ambient temperature typically falls in the range of 32 +/- 2 °C.

Therefore, the ultimate objective of this research is to investigate the effect of fresh concrete temperature on fresh and hardened properties of concrete when the ambient temperature is in the range of 30 – 34 ˚C and find out the most appropriate fresh concrete temperature for normal concreting works.

2.7 Summary of Literature Survey

Almusallam [10], Abbasi et al. [11], [12], [34] and Burg [6] showed that hot weather conditions such as air temperature, wind velocity and relative humidity have an impact on plastic shrinkage, compressive strength, pulse velocity, pore structure of concrete, modulus of rupture, modulus of elasticity, shear strength, moment capacity and deflection. When the air temperature increases plastic shrinkage, early age compressive strength, splitting tensile strength and pore volume tend to increase and later age compressive strength, later age splitting tensile strength, modulus of rupture, shear strength, moment capacity and denseness tend to decrease. Similarly, when the wind velocity increases, the plastic shrinkage tend to increase. When relative humidity increases, the plastic shrinkage and pore volume reduces. However, they showed that the wind velocity and the relative humidity do not have any major impact on the compressive strength and pulse velocity of the concrete.

Eskandarsefat [39] identified that when the water temperature is greater than 60 ˚C, slump and workability increase, thus the bleeding effect increases and leads to the segregation of visible cracks in the surface. He further identified that the optimum concrete mixture temperature in cold weather for the highest compressive strength is 14-18 ˚C.

Al-Amoudi et al. [48] and Kim et al. [38] also showed that the concretes cured at elevated temperatures at an early age attain higher early strength (compressive & splitting tensile strength) but lower later age strengths than concrete cured in normal weather conditions. Plastic shrinkage also has the same behaviour.

Nasir et al. [7] showed that OPC and SF cement concrete gives optimum results when the placing temperature is 32 ˚ C while all other blended cement concrete gives optimum results when the placing temperature is 38 ˚ C. They obtained similar results for the splitting tensile strength and pulse velocity results as well. Nasir et al. [8] further showed that the plastic shrinkage cracks increased with time in all types of concrete specimens and the curing compound was effective in decreasing the shrinkage strain in all concretes. However, the critical casting concrete temperature at which the maximum plastic shrinkage strain occurred was 25˚C and as the concrete temperature approached the ambient temperature, the shrinkage strain decreased. Hence, they concluded that the critical placement temperature for compressive and split tensile strength and pulse velocity for OPC and SF cement concretes was 32˚C while the optimum temperature for all cementitious materials was either 38˚C.

3 METHODOLOGY

Experimental studies were carried out to find out the effect of fresh concrete temperature on fresh and hardened properties of concrete under hot weather conditions. The fresh concrete temperature was considered as the variable while keeping the ambient temperature, wind speed and humidity as same for all cases. The ambient temperature of 32 °C was considered, which is the most common ambient temperature level in Sri Lanka. The fresh concrete temperature was varied from 30 °C to 36 °C. Grade 30 concrete with Ordinary Portland Cement was used for the experimental investigations.

Measured parameters were the temperature development of concrete, slump and slump loss with time, development of plastic shrinkage cracks, evaporation characteristics of concrete, compressive strength development and splitting tensile strength.

At the same time, past data from the industry were collected on the fresh concrete temperature where no temperature controlling measures were used before preparing the concrete, to study the fresh concrete temperature with respect to the ambient condition.

3.1 Experimental Investigations

3.1.1 Materials

Tests were carried out for the commonly used Ordinary Portland Cement (CEM I) as specified in BS EN 197-1. Concrete of grade 30 with 0.44w/c ratio was produced aiming at a 175mm+/-25mm slump. The initial selected cement content was 400kg/m^3.

3.1.1.1 Cement

Ordinary Portland Cement (CEM I) as specified in BS EN 197-1 was used to carry out the experimental investigation. The chemical composition and the physical properties of each cement type are given in Table 3.1 and Table 3.2.

Table 3.1 : Chemical composition of Type I cement

Parameter	**Weight, %**
	Type I Cement
Lime Saturation Factor	0.92
Alumina Modulus	1.02
MgO (%)	1.20
SO_3 (%)	2.82
C_3A	5.40
Chloride (%)	0.018
Insoluble Residue (%)	1.53 %
Loss on ignition (%)	3.7 %

Source: Test Certificate for Grade 43 Ordinary Portland cement

Table 3.2 : Physical properties of Type I cement as per BS EN 197-1

Parameter	**Type I Cement**
Fineness (m^2/kg)	291
Soundness -Le Chatlier Expansion (mm) -Autoclave Expansion (%)	 2 0.09
Setting time -Initial (mins) -Final (mins)	 190 280
Normal Consistency (%)	28.4
Compressive Strength -72+/- 1 hr (MPa) -168+/-2hr (MPa) -672+/-4hrs (MPa)	 31 38 49

Source: Test Certificate for Grade 43 Ordinary Portland cement

3.1.1.2 Fine aggregate

Manufactured sand was used as the fine aggregate. These are the by-products of the production of coarse aggregate. The particle size distribution has been conducted as per the BS EN 933-1:2012. The grading was checked against the BS EN 12620. The grading and other properties of fine aggregate are given in Table 3.3, Table 3.4 and Figure 3.1 .

Table 3.3 : Grading of fine aggregate

Test Sieve Size (mm)	% Passing
6.30	100.0
4.00	94.0
1.00	69.0
0.500	34.0
0.250	16.0
0.063	5.0

Source: Report on particle size distribution of aggregates (R1SH23-009308)

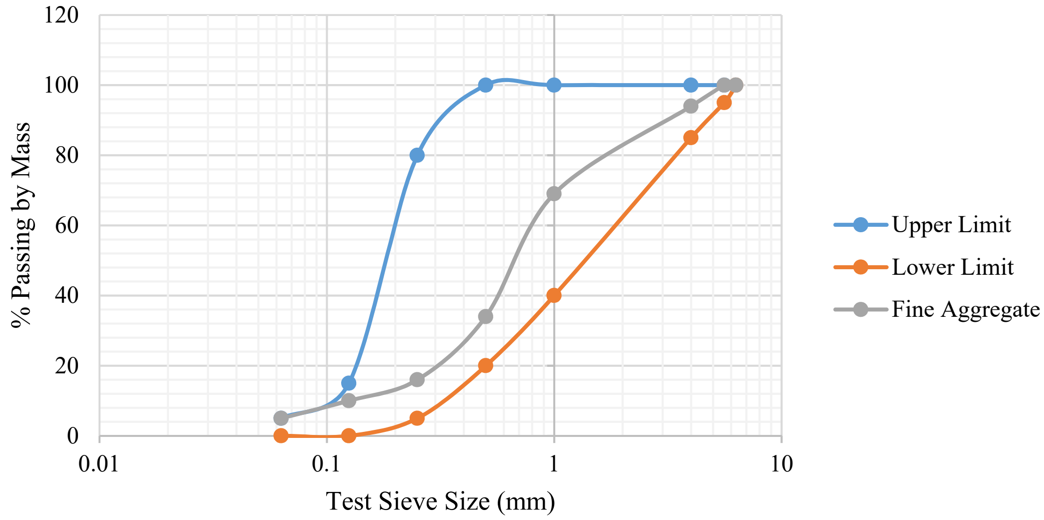


Figure 3.1 : Grading of fine aggregate

Source: Report on particle size distribution of aggregates (R1SH23-009308)

Table 3.4 : Other properties of fine aggregate

Property	Value
Particle density (Apparent basis) (Mg/m^3)	2.92
Particle density (Oven dry basis) (Mg/m^3)	2.85
Particle density (Saturated& Surface Dry Basis) (Mg/m^3)	2.87
Water absorption (%)	0.9
Moisture Content	0.5
Sand equivalent value	67
Material finer than 63 µm test sieve %	5.1
Clay lumps and friable particles %	NIL
Liquid limit (%)	-
Plastic limit (%)	-
Plasticity Index	Non Plastic
Acid soluble sulphate SO_4 (% by mass)	0.02
Acid soluble chloride Cl^- (% by mass)	0.01

Source: Reports on fine aggregate properties (R1SH23-009309/ R1SH23-009310/ R1SH23-009311/ R1SH23-009312/ R1SH23-009313/ R1SH23-009314/ R1SH23-009315/ R1SH23-009317)

3.1.1.3 Coarse aggregate

Crushed gabbro aggregate was used as the coarse aggregate. The particle size distribution has been conducted as per the BS EN 933-1:2012. The grading was checked against the BS EN 12620. The grading and other properties of coarse aggregate are given in Table 3.5, Table 3.6 and Figure 3.2.

Table 3.5 : Grading of coarse aggregate

Sieve Size (mm)	% Passing
31.5	100.0
20.0	94.0
14.0	39.0
5.0	5.0

Source: Report on particle size distribution of aggregates (R1SH23-009334)

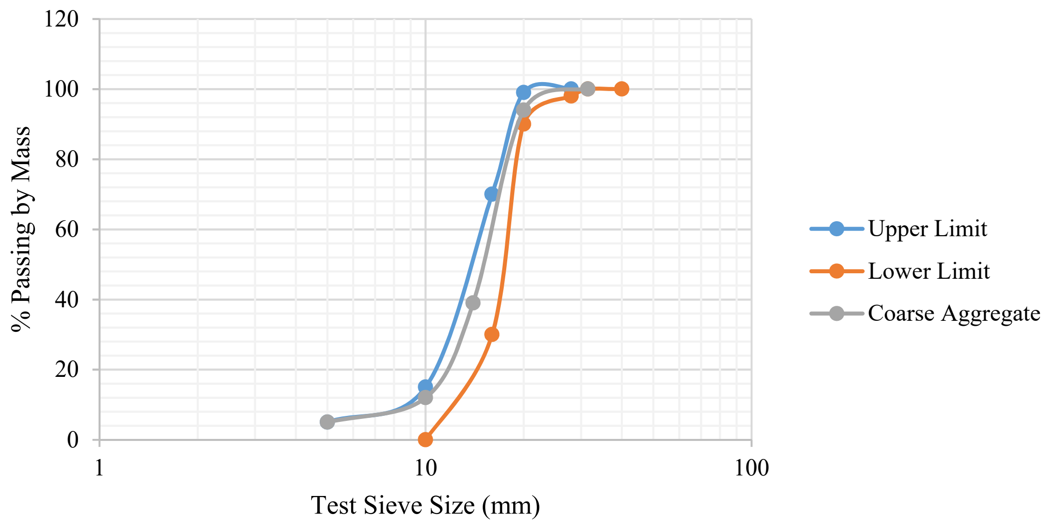


Figure 3.2 : Grading of coarse aggregate

Source: Report on particle size distribution of aggregates (R1SH23-009334)

Table 3.6 : Other properties of coarse aggregate

Property	Value
Particle density (Oven Dry Basis) (Mg / m^3)	2.91
Particle density (Saturated and Surface Dry Basis) (Mg / m^3)	2.92
Particle density (Apparent Basis) (Mg / m^3)	2.94
Water absorption	0.3
Moisture Content %	0.2
10% fine values (kN)	320
Aggregate impact value %	10
Los Angeles Coefficient (LA)	14
Flakiness Index	8
Elongation Index	10
Material finer than 75µm Test sieve by washing (%)	0.4
Shell Content %	NIL

Source: Reports on fine aggregate properties (R1SH23-009335/ R1SH23-009336/ R1SH23-009337/ R1SH23-009338/ R1SH23-009339/ R1SH23-009340/ R1SH23-009341/ R1SH23-009342/ R1SH23-009343/ R1SH23-009344/ R1SH23-009345/ R1SH23-009346/ R1SH23-009347/ R1SH23-009348/ R1SH23-009349)

3.1.1.4 Water

Potable water was used for mixing and curing of concrete.

3.1.1.5 Admixtures

Superplasticizers are necessary to improve the workability of concrete with manufactured sand. These superplasticizers will create a coat around the irregular shape M-Sand particle with cohesive cement paste, thereby enhancing the deformability. These superplasticizers are polycarboxylate ether (PCE) based admixtures. SikaPlast 204 H was used as the plasticizer. The data sheet is attached in Appendix B.

3.1.2 Characteristics of Selected Concrete Mix

3.1.2.1 Strength

Grade 30 concrete with a 0.44 w/c ratio was finalized to carry out the testing. See Table 3.7 for the mix proportion to achieve the stipulated strength with Type I cement type. Appendix A gives the mix design calcualtions.

Table 3.7 : Mix proportions of the concrete for 1m^3

Material	Quantity
Cement (kg)	400.00
Coarse aggregate (kg)	1049.00
Fine aggregate (kg)	825.00
Water (kg)	176.00
Admixture (ml)	3000.00
w/c ratio	0.44

3.1.2.2 Slump

The design was done to achieve a slump of 175mm +/- 25mm. The required slump was achieved by adding a PCE-based superplasticizer. As per the research carried out by San et al [32], it is identified that there is no impact of the slump on the plastic shrinkage and that depends on the cement content and the w/c ratio. Further they showed that plastic shrinkage crack increases when the cement content increases and the w/c decreases and accelerates the crack formation time under a constant evaporation rate.

One trial mix was carried out as per the given ratios in Table 3.7, to verify the slump and strength prior to starting the experiments. In which the intended slump and the strength were obtained.

3.1.2.3 Fresh concrete temperature

The expected fresh concrete temperatures were 30 ˚C, 32 ˚C, 34 ˚C and 36 ˚C. The temperature of the mixing water was changed to get the required fresh concrete temperature.

3.1.3 Environmental & Exposure Conditions

The concrete was mixed under ambient conditions outside the laboratory. The average ambient temperature was 32 ˚C at the time of casting the specimens. The more specific temperature variations during the testing periods are given in Section 3.1.3.1. Relative humidity and wind speed were the same for all four experiments. Measured RH and wind speeds are given in Section 3.1.3.2 and Section 3.1.3.3.

Daily maximum, minimum and mean temperatures, mean humidity and mean wind speed are given in Table D.1 in Appendix D. The testing was carried out in August, during which the ambient temperature fell between 31 -33 ˚C.

3.1.3.1 Ambient temperature

Efforts were taken to carry out the testing under similar ambient conditions for all testing. Since testing were carried out on four consecutive days, there were no considerable differences in the ambient weather condition. Air temperature was measured at approximately 4 to 6 ft above the evaporation surface using a digital thermometer at about every 15minutes intervals. Table E.1 ~ Table E.2 in Appendix E show the variations of the temperature throughout the experiments at the testing location.

3.1.3.2 Relative humidity

Relative humidity was not artificially controlled. Since four consecutive days are considered, there were no considerable differences in the values. In this experiment, the relative humidity varied between 65%-75%. Humidity was measured using a digital humidity-anemometer at about 15 minutes intervals. Relative humidity was measured at approximately 4 to 6 ft above the evaporation surface. Table E.1 ~ Table E.2 in Appendix E show the variations of the relative humidity throughout the experiments at the testing location.

3.1.3.3 Wind speed

Sivakumar and Santhanam [51] used a chamber with a high-speed fan to generate a 24km/ hr wind speed to accelerate the drying of concrete. Similarly, an average wind speed of 8km/hr was obtained using a fan and the speed was measured using a digital humidity-anemometer. Wind speed was also kept constant for all the mixes. Table E.1 ~ Table E.2 in Appendix E shows the variations of the wind speed throughout the experiments at the testing location.

Wind speed was measured at 20 inches above the evaporation surface as per ACI 305R-99 [2] and this is the average horizontal wind speed.

3.1.3.4 Evaporation rate

Sivakumar and Santhanam [51] created an environment to generate an evaporation rate of 0.31 kg/m^2/hr. Similarly, the surrounding conditions were set to evaporate the water from the surface.

The probable surface evaporation rate for each mix was identified using the nomograph given in ACI 305R-99 [2]. Table 3.8 gives the expected surface evaporation rates for each fresh concrete temperature.

Table 3.8 : Expected evaporation rates for each fresh concrete temperature

Ambient Temperature	Relative Humidity	Fresh Concrete Temperature	Wind Speed	Evaporation Rate
° C	%	° C	km/h	kg/m2/h
32.60	60.00	34.20	8.00	0.60
32.60	60.00	32.70	8.00	0.40
32.60	60.00	36.00	8.00	0.70
32.60	60.00	30.10	8.00	0.30

Actual evaporation rates are given in Table 4.5.

3.1.4 Exposure & Curing Condition

Curing is an important factor as it can make a large impact on the fresh and hardened properties of concrete.

In actual field conditions, temperature varies throughout the day unlike in standard curing conditions. Peak temperature occurs over a few hours of the day in the daytime, while lower temperatures occur in the night and in the early morning. It is a cycle of 24 hours. Since it is difficult to model the actual conditions in a laboratory it was decided to cure the samples in the ambient conditions.

Therefore, one slab specimen (test panel) was exposed to the normal environmental conditions without any curing while the other slab specimen was cured with water spraying. All other test specimens were water-cured under normal conditions until the test age.

Normal drinking quality water was used in the curing tank and it was observed that the temperature of the water inside the curing tank was varied from 25 ˚C to 30 ˚C during 24 hr cycle.

3.1.5 Specimen Preparation & Testing Methodology

3.1.5.1 Test specimens

Test specimens were prepared to test the development of plastic shrinkage cracks, compressive strength development and splitting tensile strength. The slump, the slump loss and the temperature development were also measured using the samples from the same concrete mix. Apart from the above, a small slab panel was cast to measure the evaporation of the concrete.

See Section 3.1.5.2 for the mould selection details and their dimensions and other characteristics.

A total of 27 test specimens were prepared as given in the Table 3.9 for each mix.

Table 3.9 : Details of test specimens

	Test	Mould Details	No of Test Specimens
1.	Plastic shrinkage development	560mmx360mmx105mm slab panel	02 (1-Test Panel, 1-Standard Panel)
2.	Evaporation rate of moisture of concrete	400mm x 400mm x 40mm slab panel	01
3.	Compressive strength development	150mmx150mm standard cubes	12
4.	Splitting tensile strength	150mm dia. x 300mm long standard cylinders	12

Altogether 108 nos of specimens were cast to do the testing for one cement type at four different fresh concrete temperatures.

3.1.5.2 Mould selection

A special mould was prepared to carry out the plastic shrinkage test. Sivakumar and Santhanam [51] used a mould made from laminated board with a polythene sheet at the bottom to reduce the friction between both faces. Similarly, many researchers emphasised the requirement of reducing the friction between the mould and the concrete [29], [41] & [53]. Hence most of them used a fibre moulds or Perspex moulds or laminated timber moulds.

Therefore, moulds made out of laminated plywood with low moisture absorption were used to carry out the plastic shrinkage test. As given in ASTM C1579-06 [54], moulds of size 560mm x 360 mm x 105mm were used. The depth was selected considering the 20mm as the maximum aggregate size as stated in the ASTM Standard [54]. From Figure 3.3 to Figure 3.6 shows the mould arrangement used to measure the plastic shrinkage cracking. Further Al-Amodi et al [46] identified that there is no impact of mould size on the plastic shrinkage values. Hence, the mould size was not a considered variable in this experimental study.

Figure 3.3 : Plan view and dimensions of the mould

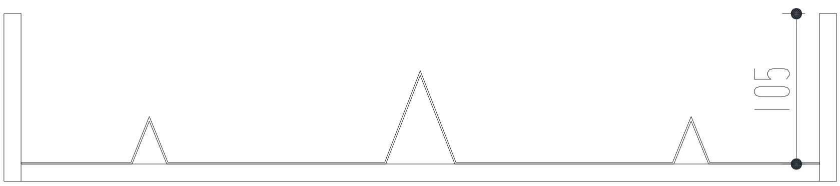


Figure 3.4 : Cross sectional view of the mould

Figure 3.5 : Plan view of the mould for the measurement of plastic shrinkage cracks

Figure 3.6 : 3D view for the mould for the measurement of plastic shrinkage cracks

A sheet metal stress riser and internal restraints as shown in Figure 3.7 and Figure 3.8 was fitted at the bottom of the above mould. The middle-stress riser helped to initiate the crack in a prescribed location on the concrete surface. Further, a releasing agent was applied on all surfaces, to create an easy movement between the mould and the concrete by reducing the bond between two surfaces. As in literature [55], water movement is allowed only in an upward direction.

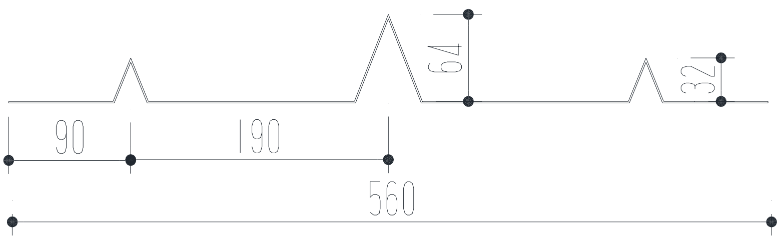


Figure 3.7 : Dimensions of the stress riser and internal restrain geometry

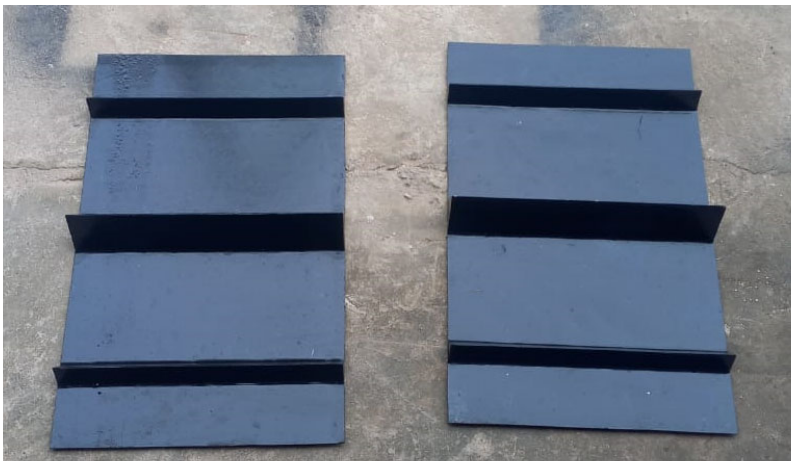


Figure 3.8 : Stress riser and internal restrain geometry

A 400 mm X 400 mm X 40 mm sized mould made out of the same coated plywood was used to measure the evaporation of the concrete surface as shown in Figure 3.9.

Figure 3.9 : Mould to measure the evaporation rate

For other tests, standard moulds were used. The slump was measured using the standard cone specified in BS 1881-102 [56].

The mould specified in BS 1881-108 [57] was used for the specimen casting for the compressive strength measurements. The used mould size was a 150mm x 150mm x 150mm symmetrically arranged cube with rigid elements.

For the splitting tensile strength testing, 150mm dia. x 300mm high cylindrical steel moulds were used as per the BS 1881-110 [58].

3.1.5.3 Fresh concrete temperatures

The temperature of fresh concrete can vary by changing the temperature of the constituent's materials. That can be done by either cooling or heating the used materials.

The equation given in ACI 305R-99 [2] was used as a guideline to identify the required material temperatures to control the fresh concrete temperature. Material temperatures were calculated using Equation 3.1, to get the desired fresh concrete temperature. The ingredients were heated to the required temperatures to get the final concrete temperature. The expected fresh concrete temperatures were 30 ˚C, 32 ˚C, 34 ˚C and 36 ˚C. Table 3.10 gives the temperatures of the materials used for experiments.

$$T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w + T_a W_{wa}}{0.22(W_a + W_c) + W_w + W_{wa}}$$ Equation 3.1

T_a = Temperature of aggregate (˚C)

T_c = Temperature of cement (˚C)

T_w = Temperature of batched mixing water from normal supply excluding ice (˚C)

W_a = dry mass of aggregate (kg)

W_c = mass of cement (kg)

W_w = mass of batched mixing water (kg)

W_{wa} = mass of free and absorbed moisture in aggregate (kg)

(It is assumed that the temperature of both free and absorbed water on the aggregate is same as the aggregate temperature.)

Table 3.10 : Measure actual temperatures of the constituent's materials and fresh concrete mix

Material	**Expected fresh concrete temperatures**			
	28 ˚C	**32 ˚C**	**35 ˚C**	**38 ˚C**
Cement	31.2	30.4	31.3	31.4
Aggregate	28.5	28.2	27.0	27.5
Water	7.0	25.0	31.7	45.0
Expected fresh concrete temperatures as per Equation 3.1	23.3	27.6	28.8	32.6
Measured fresh concrete temperatures	30.1	32.7	34.2	36.0

The temperature of the fresh concrete was measured by immersing a thermometer into the concrete mix as given in ASTM C 1064/C 1064M [5]. The thermometer was immersed 75mm deep into the freshly mixed concrete for 2-minute period before taking the readings. This was to make sure that the thermometer reading was not affected by environmental conditions.

3.1.5.4 Mixing of concrete

After bringing the materials to the required temperatures, mixing was started. A tilting drum-type concrete mixer was used to mix the concrete. The capacity of the mixture was 2.5 m^3. As given in BS1881-125 1986 [59], the following sequence was used in mixing the concrete;

1. Half of the coarse aggregate was added to the mixer drum
2. Then total fine aggregate was added to the drum
3. Thirdly cement was added to the mixer drum
4. Balance coarse aggregate was added into the mixer and started mixing
5. Half of the water was added in the first 30s and mixed
6. Balance water was added along with the admixture
7. Whole mixture was mixed for 2-3 min after adding all the materials

Concrete mixing was done outside under ambient conditions. Once the sampling was done the balance materials were agitated at a slow rate in the same concrete mixer. This is to represent the transportation of the concrete materials by an agitator truck from the batching plant to the project sites. Specimen preparation details are given in Section 3.1.5.6.

3.1.5.5 Sampling of fresh concrete

The very first discharges were disregarded from the concrete mixer and collected the materials from the middle portion into a clean container as stated in BS 1881-101: 1983 [60]. A middle portion was used to cast the specimens.

3.1.5.6 Specimen preparation & testing methodology

3.1.5.6.1 Measurement of fresh concrete temperature

As per C1064 [5], concrete was discharged into a non-absorptive and large container. It was large enough to have a 75mm clearance from the temperature-measuring probe. At this point, the fresh concrete temperature was measured for each concrete batch.

The following steps were followed to get measure the fresh concrete temperature.

1. The thermometer was immersed minimum of 75mm into the fresh concrete mixture.
2. The thermometer was immersed into the concrete mixture and left for a minimum of 2 minutes period until the temperature readings get stabilized.
3. Temperature reading was read and recorded.
4. Temperature measuring process was completed within 5 minutes of obtaining samples.
5. Measured temperature was presented to the nearest 0.1˚C.

After the initial sample, the temperature development of the concrete was measured and recorded at 30-minute intervals until the materials in the concrete mixer lost its workability.

Figure 3.10 shows the fresh concrete temperature measurement on testing day 1.

Figure 3.10 : Temperature reading on the fresh concrete in day 1

3.1.5.6.2 Measurement of slump

The procedure given in Appendix C, Section C.1 was adopted to measure the slump of the concrete for each concrete batch. The slump is the height difference between the mould height and the topmost point of the specimen after the removal of the mould from the concrete. The slump was measured to the nearest 5mm as per BS 1881-102:1983 [56].

Figure 3.11 and Figure 3.12 show the preparation for the slump test and the readings taken on Day 1.

Figure 3.11 : Preparation for the slump test

Figure 3.12 : Slump measurement of the fresh concrete in day 1

3.1.5.6.3 Specimen preparation and measurement of plastic shrinkage

The following steps were adopted to prepare two specimens of size 560mm x 360 mm x 105 mm to measure plastic shrinkage.

1. A sample of fresh concrete was obtained as given in Section 3.1.5.5 into a clean container.
2. The sample was thoroughly mixed before adding it into the mould.
3. Internal faces were cleaned and damped and extra moisture was removed from the surfaces.
4. All the joints were sealed to prevent any leakage of cement grout from the joints.
5. Moulds were placed on a flat surface. The mounting floor was rigid and free from vibration and shock. See Figure 3.13 and Figure 3.14.
6. Concrete was placed in the mould in two layers and compacted using a steel rod.
7. Extra concrete was removed from the top surface and smoothened the top surface using a mason trowel.
8. Both specimens were kept back to back exposing to the ambient conditions.
9. An artificial wind was created across both slab panels using a fan with a wind speed of 8 kmph.

10. One specimen is considered as the controlled specimen while the other specimen is considered as the test specimen.
11. Controlled specimen was subjected to curing to prevent the shrinkage cracks, while the test specimen was not cured.

According to the literature, plastic shrinkage cracks occur within the first 4-6 hours [61]. Therefore, a contactless measuring method was adopted to identify the time taken to initiate cracks and to measure the crack widths. Slab specimens were inspected visually and the surface was captured by using a camera for 6 hour period. Photographs were taken every 3 minutes for the first 6 hours. Two measuring scales were placed in two corners of the slab specimen to scale out the images. Later, image processing was done to evaluate the crack widths. Sivakumar and Santhanam [51] also used image analysis software to process the obtained images.

Figure 3.13 : Test setup for the monitoring of shrinkage cracks

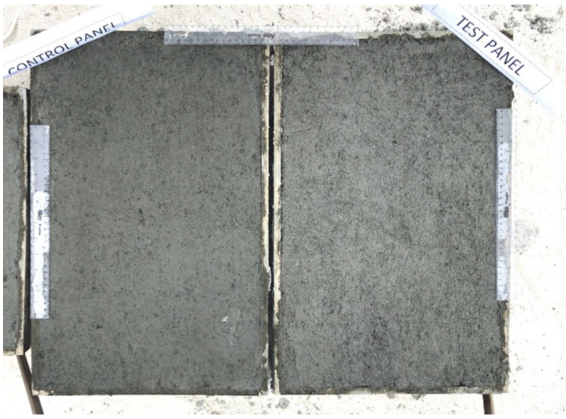


Figure 3.14 : Plan view of the test setup for the monitoring of shrinkage cracks

3.1.5.6.4 Specimen preparation and measurement of evaporation

The following steps were adopted to prepare specimens of size 400mm x 400 mm x 40 mm to measure the evaporation.

1. A sample of fresh concrete was obtained as given in Section 3.1.5.5 into a clean container.
2. The sample was thoroughly mixed before adding it into the mould.
3. Internal faces were cleaned and damped and extra moisture was removed from the surfaces.
4. Moulds were placed on a flat surface. The mounting floor was rigid and free from vibration and shock. The top surfaces of all three specimens including the two samples prepared to measure the plastic shrinkage, were kept at the same level. See Figure 3.13.
5. Concrete was placed in the mould in two layers and compacted using a steel rod.
6. Extra concrete was removed from the top surface and smoothened the top surface using a mason trowel.
7. Weight of the concrete was measured along with the container by using a scale with an accuracy of 1g.
8. Specimen was kept near the previous two specimens and exposed it to the same environmental conditions.
9. Weight of the container with concrete was measured at every 15-minute intervals. See Figure 3.15.

From the measured data, the following information was obtained;

1. Evaporated water mass from the surface during the testing period – This was calculated using the difference between the initial weight and the final weight of the specimen.
2. Rate of water evaporation at the first crack – This was calculated using the evaporated water mass within 15min period at the first crack.
3. Average rate of water evaporation during the shrinkage crack monitoring period - This was calculated using the total evaporated water mass and the time taken to evaporate that water mass from the concrete body.

Figure 3.15 : Weighting the weight of the sample prepared for the measurement of evaporation

3.1.5.6.5 Specimen preparation and measurement of compressive strength development

To measure the compressive strength development, 12 Nos of 150mm x 150mm x 150mm cubes were cast and tested after water curing for each concrete batch for 3 days, 7 days, 14 days and 28 days.

The procedure given in Appendix C, Section C.2 was adopted when preparing the specimens to measure the compressive strength of concrete as per BS 1881-108: 1983 [57].

3.1.5.6.6 Specimen preparation and measurement of splitting tensile strength

To measure the splitting tensile strength, 12 Nos of 150mm dia. x 300mm cylinders were tested after water curing for each concrete batch for 1 day, 3 days, 7 days and 28 days.

The procedure given in Appendix C, Section C.3 was adopted when preparing the specimens to measure the splitting tensile strength of concrete as per BS 1881-110: 1983 [58] and BS 1881-117: 1983 [62].

Figure 3.16 : Casting of test cubes and cylinders

3.2 Collection of Industry Data on Fresh Concrete Temperature and its Development

Past data were gathered to identify the fresh concrete temperatures and the relationship between the ambient temperature and the fresh concrete temperature, where the fresh concrete temperature has not been controlled under hot weather conditions in any manner. Most of the data were collected from the batching plants. Refer Appendix G for the collected data.

4 RESULTS AND DISCUSSION

4.1 Temperature Development of Concrete

Table 4.1 shows the recorded temperature values for all four batches of concrete. The temperature was monitored for two hours since the mixing.

Table 4.1 : Fresh concrete temperature variations with time

Mix	Casting Date	Ambient Temp (°C)	Fresh Conc. Temp. (°C)	Time	Duration (min)	Conc. Temp. (°C)	Remarks
1	8/13/2023	32.9	34.2	12.34 pm	0	34.2	Mixing stage
				1.06 pm	32	36.1	
				1.32 pm	58	38.6	
				2.03 pm	89	37.9	
				2.39 pm	125	37.0	
2	8/14/2023	32.3	32.7	11.02 am	0	32.7	Mixing stage
				11.20 am	18	34.3	
				11.31 am	29	35.6	
				12.01 pm	59	36.0	
				12.35 pm	93	35.8	
				1.01 pm	119	35.5	
3	8/15/2023	32.6	36.0	11.23 am	0	36.0	Mixing stage
				11.45 am	22	36.9	
				12.02 pm	39	37.7	
				12.16 pm	53	39.5	
				12.50 pm	87	38.6	
				1.23 pm	120	37.6	
4	8/16/2023	32.7	30.1	12.12 pm	0	30.1	Mixing stage
				12.51 pm	39	34.2	
				1.11 pm	59	35.5	
				1.46 pm	95	35.3	
				2.17 pm	125	34.8	

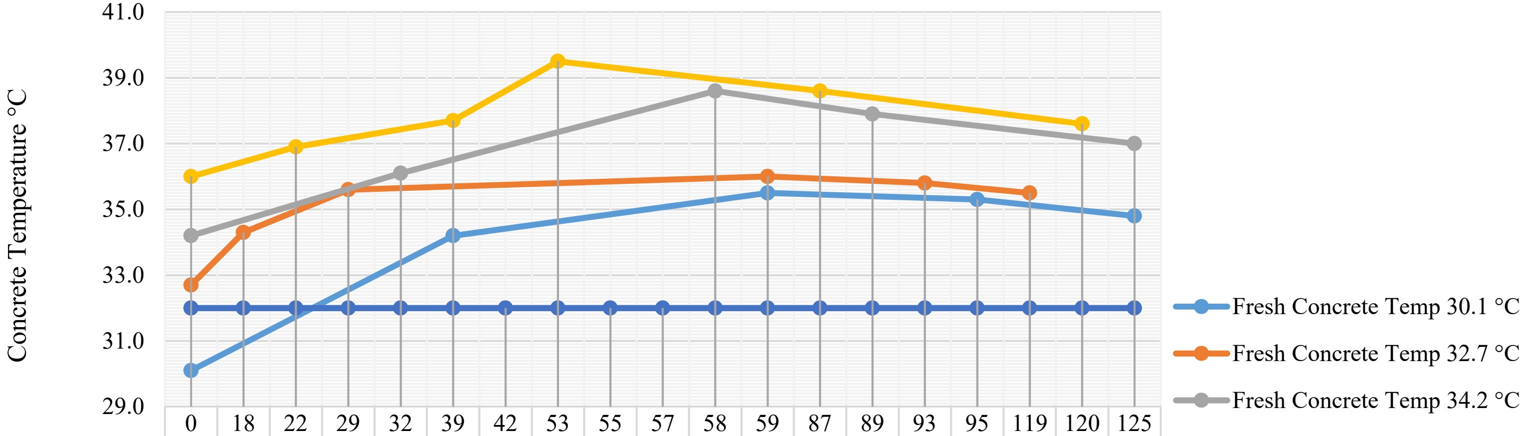
From Figure 4.1, it is understood that the temperature rise depends on the initial fresh concrete temperature. The data given in Table 4.1 was taken from the samples which were continuously agitated in a concrete mixer. This is to simulate the transportation of materials from the mixing location to the placing location.

From Figure 4.1, the mixing temperature and the maximum temperature values during first two hours can be summarized as follows in Table 4.2.

Table 4.2: Fresh concrete temperature variations with time

Mix	Ambient Temperature °C	Mixing Concrete Temp. (°C)	Maximum Concrete Temp. (°C) within first 2 hrs
1	32.7	30.1	35.5
2	32.3	32.7	36.0
3	32.9	34.2	38.6
4	32.6	36.0	39.5

The impact of temperature rise needs to be evaluated with the shrinkage characteristics and the mechanical properties of the concrete. This will be discussed in Sections 4.3, 4.4, 4.5 and 4.6.



	0	18	22	29	32	39	42	53	55	57	58	59	87	89	93	95	119	120	125
Fresh Concrete Temp 30.1 °C	30.1					34.2						35.5				35.3			34.8
Fresh Concrete Temp 32.7 °C	32.7	34.3		35.6								36.0			35.8		35.5		
Fresh Concrete Temp 34.2 °C	34.2				36.1						38.6			37.9					37.0
Fresh Concrete Temp 36.0 °C	36.0		36.9			37.7		39.5					38.6					37.6	
Ambient Temperature	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32

Duration (min)

Figure 4.1 : Fresh concrete temperature development with the time

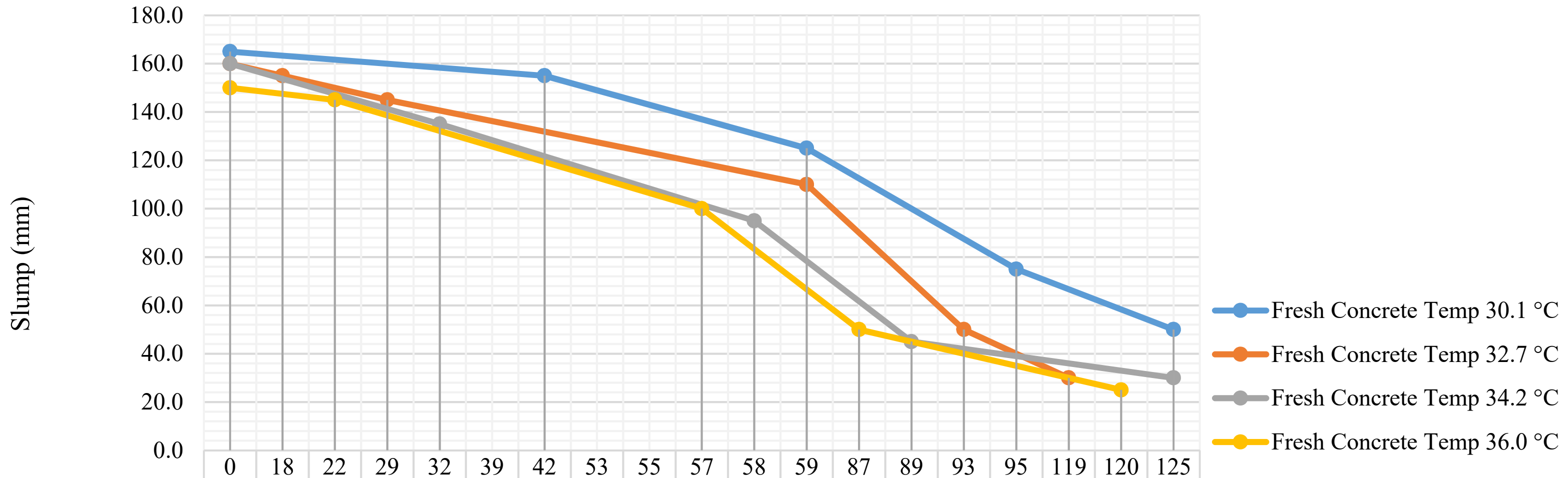
4.2 Slump Variation with the Time

Table 4.3 shows the recorded slump values for all four batches of concrete. The slump was monitored for about two hours/ the concrete became stiff after the mixing.

Table 4.3 : Slump variations with time

Mix	Casting Date	Fresh Concrete Temp. (°C)	Time	Duration (min)	Slump (mm)	Remarks
1	8/13/2023	34.2	12.34 pm	0	160.0	Mixing stage
			1.06 pm	32	135.0	
			1.32 pm	58	95.0	
			2.03 pm	89	45.0	
			2.39 pm	125	30.0	
2	8/14/2023	32.7	11.02 am	0	160.0	Mixing stage
			11.20 am	18	155.0	
			11.31 am	29	145.0	
			12.01 pm	59	110.0	
			12.35 pm	93	50.0	
			1.01 pm	119	30.0	
3	8/15/2023	36.0	11.23 am	0	150.0	Mixing stage
			11.45 am	22	145.0	
			12.16 pm	53	100.0	
			12.50 pm	87	50.0	
			1.23 pm	120	25.0	
4	8/16/2023	30.1	12.12 pm	0	165.0	Mixing stage
			12.51 pm	39	155.0	
			1.11 pm	59	125.0	
			1.46 pm	95	75.0	
			2.17 pm	125	50.0	

From Figure 4.2, it can be concluded that the slump retention also depends on the initial fresh concrete temperature. The data given in Table 4.3 was taken from the samples, which were continuously agitated in a concrete mixer. This is to simulate the transportation of materials from the mixing location to the placing location.



	0	18	22	29	32	39	42	53	55	57	58	59	87	89	93	95	119	120	125
Fresh Concrete Temp 30.1 °C	165.0						155.0					125.0				75.0			50.0
Fresh Concrete Temp 32.7 °C	160.0	155.0		145.0								110.0			50.0		30.0		
Fresh Concrete Temp 34.2 °C	160.0				135.0						95.0			45.0					30.0
Fresh Concrete Temp 36.0 °C	150.0		145.0							100.0			50.0					25.0	

Duration (min)

Figure 4.2 : Slump variation with the time

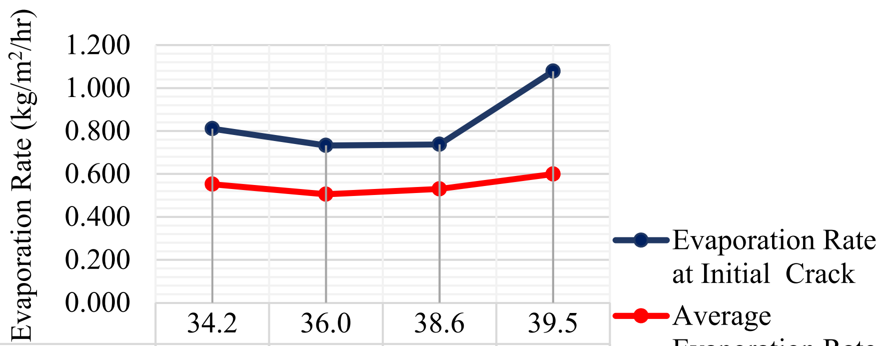
From the Figure 4.2 and its gradient, it is evident that the rate of slump loss is increased when the fresh concrete temperature is higher. And for the increment of 5 °C, there was a 15mm slump loss. Burg [6] also showed in his experiments that the slump was affected by the casting temperature. In his experiments, he showed that there was about 20mm loss for a 10 °C increment of casting concrete temperature.

Klieger [49] also identified that a 20 °F (11 °C) difference in concrete gives a 1-inch (25mm) reduction in concrete slump.

4.3 Evaporation Characteristics

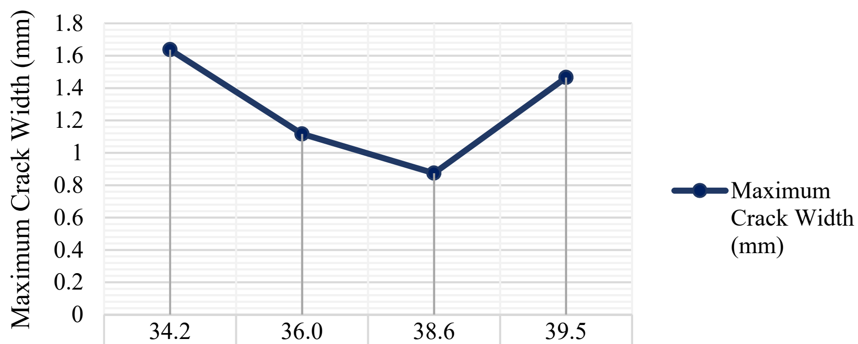
Table 4.4 ~ Table 4.5 give the data corresponding to the evaporation characteristics. From Table 4.4 and Table 4.5, it is evident that the evaporation rate at the first crack, the average evaporation rate and the maximum crack width are minimal when the fresh concrete temperature is in proximity to the ambient temperature where the ambient temperature varies between 32.3 °C – 32.9 °C throughout all four tests. From Figure 4.3 and Figure 4.4, it is seen that the evaporation rate at the first crack, the average evaporation rate and the maximum crack width are minimum when the placing temperature of the concrete is in the range of 38.0 °C – 39.0 °C and the fresh concrete temperature is 34.0 – 35.0 °C.

The impact of evaporation characteristics on other properties will be discussed in Sections 4.4, 4.5 and 4.6.



Placing Concrete Temperature (°C)	34.2	36.0	38.6	39.5
Evaporation Rate at Initial Crack	0.810	0.733	0.738	1.0781
Average Evaporation Rate	0.552	0.505	0.530	0.599

Figure 4.3 : Evaporation rate at the first crack vs placing concrete temperature



Placing Concrete Temperature (°C)	34.2	36.0	38.6	39.5
Maximum Crack Width (mm)	1.637	1.116	0.874	1.465

Figure 4.4: Maximum crack width vs placing concrete temperature

Table 4.4 : Temperature development in concrete

Test No.	Date	Type of Water Used	Ambient Temperature °C	Mixing / Fresh Concrete Temperature °C	Placing Temperature °C	Time Gap Between Mixing and Placing
Test 1	8/16/2023	Ice + Cold water	32.7	30.1	34.2	43 mins
Test 2	8/14/2023	Cold water	32.3	32.7	36.0	50 mins
Test 3	8/13/2023	Normal Water	32.9	34.2	38.6	49 mins
Test 4	8/15/2023	Hot water	32.6	36.0	39.5	53 mins

Table 4.5 : Shrinkage crack development data in concrete

Test No.	Time Gap Between Placing & Crack Propagation	Time Gap Between Placing & Crack Propagation (mins)	Time Gap Between Mixing & Crack Propagation (mins)	Time Gap Between Mixing & Crack Propagation	Curing Start Time	Evaporation at the Time of First Crack ($kg/m^2/hr$)	Average Evaporation ($kg/m^2/hr$)	Maximum Crack Width (mm)
Test 1	1 hr 31 mins	91	2 hr 14 mins	134	65 mins	0.810	0.552	1.637
Test 2	1 hr 17 mins	77	2 hr 07 mins	127	60 mins	0.733	0.505	1.116
Test 3	1 hr 18 mins	78	2 hr 07 mins	127	69 mins	0.738	0.530	0.874
Test 4	0 hr 50 mins	50	1 hr 43 mins	103	44 mins	1.0781	0.599	1.465

4.4 Plastic Shrinkage Crack Development

Table 4.5, Figure 4.5, Figure 4.3 and Figure 4.4 gives the analysis of data for the time taken to initiate the cracking of concrete with respect to the mixing time and casting time, evaporation at the time of cracking, average evaporation during the testing period and maximum crack width.

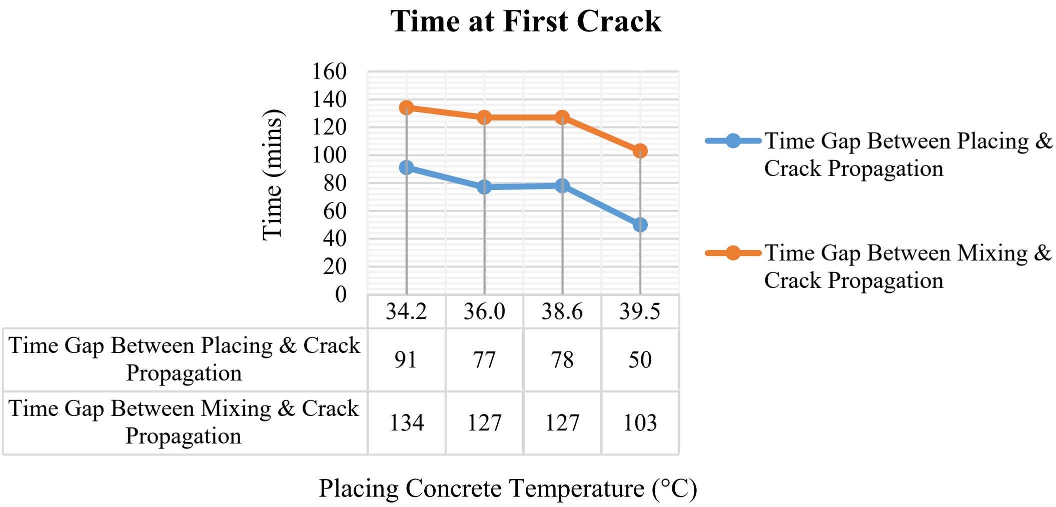


Figure 4.5: Time at first crack from the mixing and placing

The difference between the ambient temperature and placing temperatures of the concrete for the first crack is given in Table 4.6.

Table 4.6 : Difference between ambient temperature and placing temperature for the first crack

Mix	Fresh Concrete Temp. (°C)	Ambient Temperature °C	Placing Concrete Temp. (°C)	Difference (°C)
1	30.1	32.7	34.2	1.5
2	32.7	32.3	36.0	3.7
3	34.2	32.9	38.6	5.7
4	36.0	32.6	39.5	6.9

From Table 4.5 and Table 4.6, it is understood that when the difference between the ambient temperature and the concrete temperature at the time of placing is decreased, the time taken to crack is increased. That may be due to the delay in heat transfer between the concrete body and the surrounding environment or due to the slower evaporation and the adequate bleeding taken place to replace the evaporated water from the surface. And when the difference between the ambient temperature and the concrete temperature at the time of placing is increased, the time taken to crack is decreased. That may be due to the higher and early heat transfer between the concrete body and the surrounding environment or the higher evaporation and also the inadequate bleeding taken place to replace the evaporated water from the surface.

As given in Table 4.5, the highest crack width 1.637mm was occurred at the lowest casting temperature out of four specimens. Due to the low heat transfer between the concrete body and the surrounding, the concrete may have shown a plasticity until sometime, but showed the highest crack width at a later stage. Almusallam et al. [41] also indicated in his experiments that the plastic mixes shows higher crack intensity / crack width at a later stage. Similar results showed here as well.

The second highest crack width 1.465mm was shown in the mix where the fresh concrete temperature was 36 °C and the placing temperature was 39.5 °C. This mix showed the highest difference between the ambient temperature and the placing temperature of the concrete. When the concrete temperature deviates from the ambient condition the temperature difference between the two bodies increases, hence creating more evaporation from the concrete surface. This was explained by Nasir et al. [8] as the higher temperature difference between the concrete body and surrounding environment can cause more water evaporation from the surface. When heated surfaces evaporate the mixing water into the surroundings from its surfaces the mix become stiff early. When the concrete mix is stiff the tensile strength capacity also decreases, that leads to an early cracking. Almusallam et al. [41] concluded in his experiments that the lean stiff mixes cracks earlier than the rich plastic mixes, but the crack intensity is higher in rich plastic mixes than the lean stiff mixes.

As explained in Section 4.3, evaporation rate at the first crack, the average evaporation rate and the maximum crack width are minimal when the placing concrete temperature is in the range of 38.0 °C – 39.0 °C. That may be due to the minimum heat transfer from the concrete to the environment or the minimum heat gain from the outside into the concrete specimen. The behaviour of concrete mixes 2 and 3 is in between the mixes 1 and 4. The balance between the evaporation rate and the bleeding rate can prevent the shrinkage crack occurrence in the concrete surfaces.

Data in Appendix G showed that for Grade 30 concrete, the average difference of ambient temperature and fresh concrete temperature will be 2 °C – 4 °C. Therefore, we can always expect a temperature rise of 2- 4 °C in a concrete mix than the ambient temperature. With this detail and with the above mentioned criteria, it seems that the temperature controlling methodology is not necessarily required in normal concreting works for crack controlling purpose as long as the temperature at placing of the concrete is maintained at 38 °C.

For hot weather concreting works, it is advantageous to go for the naturally occurred temperature values without putting much effort in reducing the fresh concrete temperature than the ambient conditions or the placing concrete temperature than the ambient. But it is recommending to use standard practices such as shading of raw materials, wetting of materials. This finding is contradictory with the idea that the lower temperatures will reduce the cracking of concrete thereby increasing the durability of concrete. From the above analysis, it is understood that the optimum fresh concrete temperature will be when the mixing temperature is close to the ambient conditions.

Regardless of the fresh concrete temperature, the specimens cured with water showed a good control in shrinkage crack development than the test specimens without curing. The reason for lower or no shrinkage crack is due to the reduction of water loss from the concrete body as the evaporated water is always replaced by external sources. Further, this will lead to the full hydration process in the concrete.

Therefore, the curing shall be started at the correct time to protect the fresh concretes from shrinkage cracks, which have an impact on the durability and reduction in strength due to the formation of micro-cracks.

The crack area (See Figure 4.6. Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11, Figure 4.12 and Figure 4.13) also follows the same pattern as the crack width. In which, minimum crack area in concrete was observed when the fresh concrete temperature of 34.2 °C and placing concrete temperature 38.6 °C. Meantime the mixes with 34.2 °C and 39.5 °C placing concrete temperatures gave the largest crack areas. The first mix was a rich plastic mix, and showed a higher intensity of crack area. As Almusallam et al. [41] highlighted, the first mix gave a high crack intensity as this showed plastic characteristics for a longer period than the other mixes. While the latter mix also gave a higher crack intensity within a shorter period as it loses its plasticity within a very short period. From the Figure 4.6. Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11, Figure 4.12 and Figure 4.13 it is evident that the mixes placed at 36.0 °C and 38.6 °C gave a reasonably low crack intensity.

Figure 4.6 : Crack pattern of the concrete mix of fresh concrete temp. 30.1 °C

Figure 4.7: 150% enlarged view of the crack

Figure 4.8: Crack pattern of the concrete mix of fresh concrete temp. 32.7 °C

Figure 4.9: 150% enlarged view of the crack

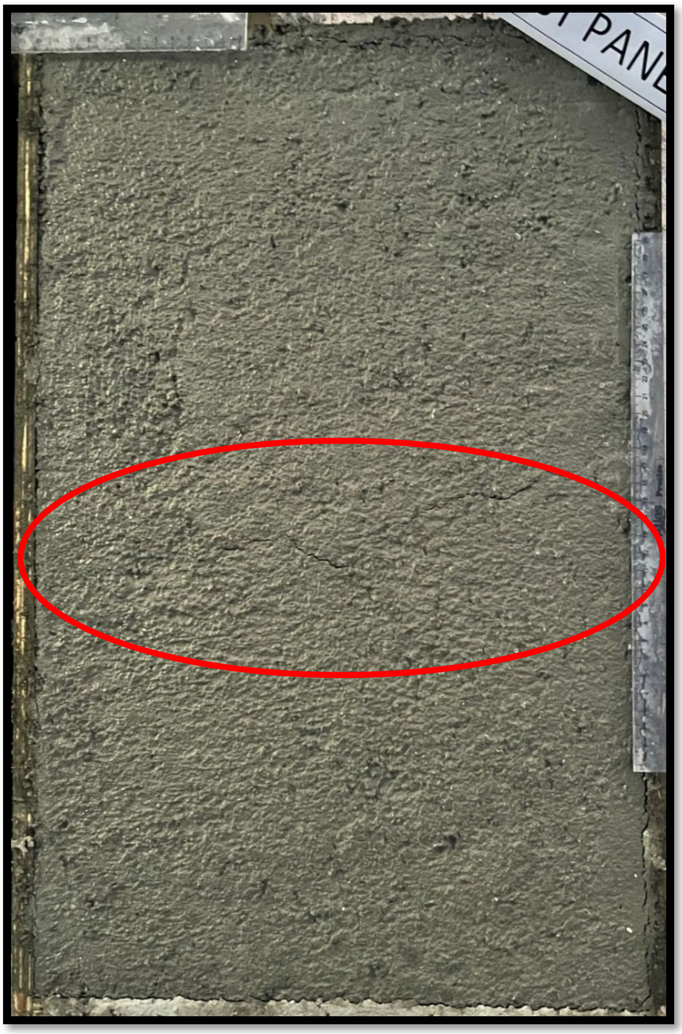


Figure 4.10 : Crack pattern of the concrete mix of fresh concrete temp. 34.2 °C

Figure 4.11 : 150% enlarged view of the crack

Figure 4.12 : Crack pattern of the concrete mix of fresh concrete temp. 36.0 °C

Figure 4.13 : 150% enlarged view of the crack

4.5 Compressive Strength Development

Compressive strength development in the concrete for all four concrete mixes is given in Table 4.7. Figure 4.14 shows the development of compressive strength in concrete through a graphical representation.

Table 4.7 : Compressive strength development

	Compressive Strength of Concrete (N/mm^2)			
Test	**1**	**2**	**3**	**4**
Casting Date	**8/16/2023**	**8/14/2023**	**8/13/2023**	**8/15/2023**
Fresh Concrete Temperature (°C)	**30.1**	**32.7**	**34.2**	**36.0**
3 days	30.500	32.500	33.000	33.500
7 days	38.000	38.500	38.500	39.000
14 days	40.000	40.500	43.500	40.000
28 days	47.000	46.500	47.500	42.000

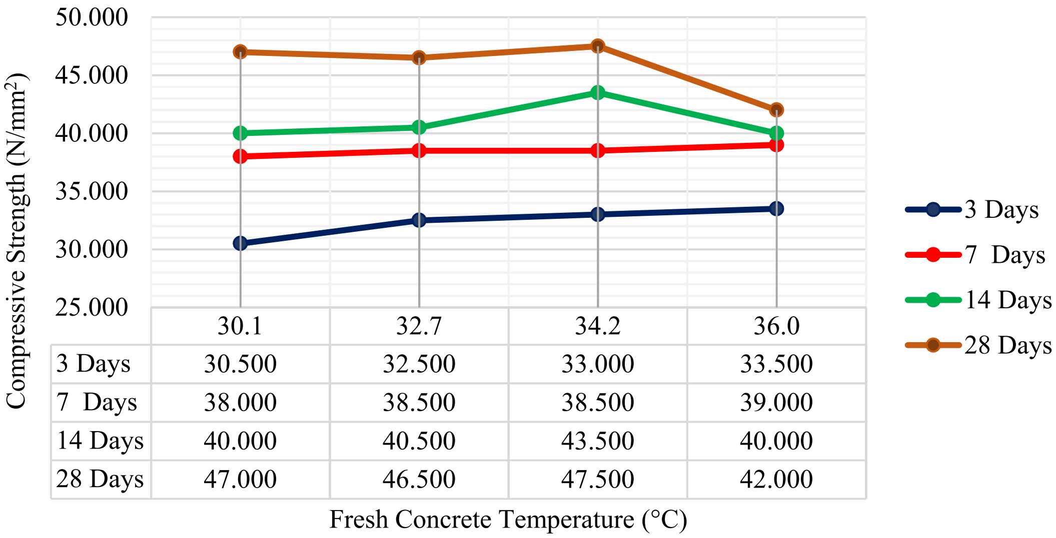


Figure 4.14 : Compressive strength development of concrete

Figure 4.14 shows that the early age compressive strength values are higher when the fresh concrete temperature is higher. That is due to the rapid rate of hydration in early ages due to the higher temperature at the initial stages. In the same mixes, the poor later-age strength performances of the hardened concrete could be due to the accelerated early hydration process at an early age, which forms porous micro-structure thus the C-S-H formed is not uniformly distributed there by leading to degradation of strength at later stage.

Nazir et al. [7] explained that this phenomenon is due to the non-uniform diffusion of hydration products and the difference in the coefficient of thermal expansion of concrete constituents, the cement paste becomes porous and even micro cracks may form at the interface between the aggregate and mortar that adversely affects the long-term strength and pore structure of concrete.

Gahtani et al. [42] explained that the reduced early strength performances of hardened concrete which are having lower fresh concrete temperatures could be due to the sudden exposure of the concrete specimens to high temperature levels. This may have prevented the full development of hydration products at early ages and resulted in the formation of internal micro-cracks or the non-uniform distribution of the hydration products. However, with the time, it is noticed that the specimens with lower fresh concrete temperature gain much more strength than the specimens which had higher early strength.

The optimum temperature for compressive strength development of concrete with OPC cement was found to be 34.2 °C, which is much closer to the average ambient temperature during the testing period. A similar trend was noticed by Nazir et al. [8] in their experiments when they tried to study the effect of placement temperature and curing method on plastic shrinkage and mechanical properties of plain and pozzolanic cement concretes under hot weather.

4.6 Splitting Tensile Strength Development

Splitting tensile strength values for the concrete for all four concrete batches are given in Table 4.8. Figure 4.15 shows the development of splitting tensile strength in concrete with time.

Table 4.8 : Concrete splitting tensile strength values

	Splitting Tensile Strength (N/mm^2)			
Test	**1**	**2**	**3**	**4**
Casting Date	**8/16/2023**	**8/14/2023**	**8/13/2023**	**8/15/2023**
Fresh Concrete Temperature (°C)	**30.1**	**32.7**	**34.2**	**36.0**
1 day	1.700	1.650	1.750	1.500
3 days	2.150	2.200	2.400	2.300
7 days	2.350	2.450	2.700	2.450
28 days	2.750	3.050	3.100	2.750

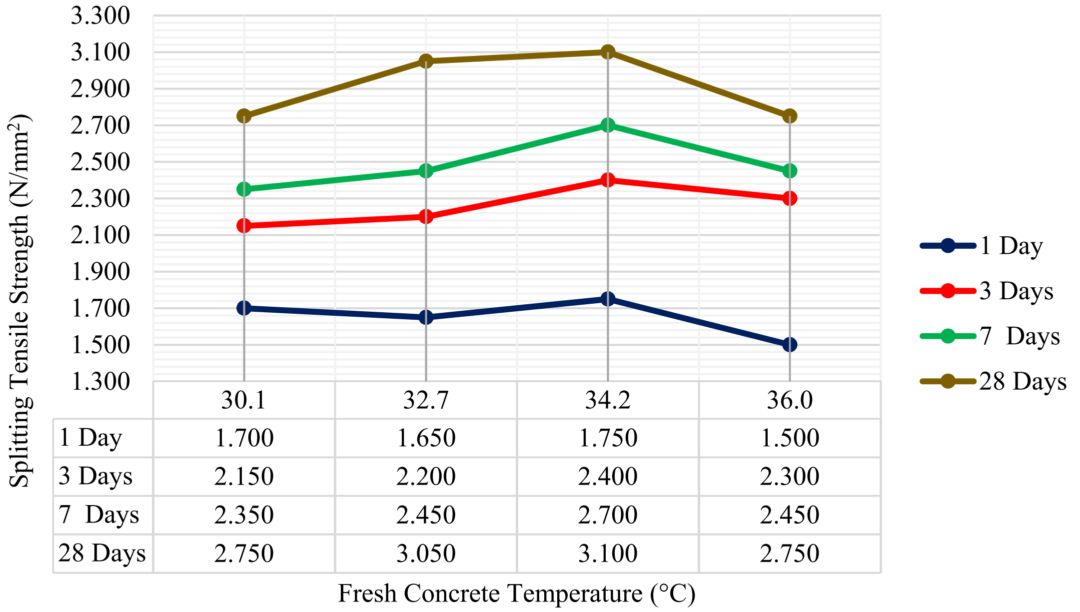


Figure 4.15 : Splitting tensile strength development of concrete

Splitting tensile strength values also have a similar trend as in compressive strength development. It is noticed that the highest splitting tensile strength value was achieved when the fresh concrete temperature is 34.2 ˚C. Even in early age, the highest tensile strength value was observed when the fresh concrete temperature was 34.2 ˚C. This observation coincides with lower crack width showed at this temperature value. This also proves that in order to prevent shrinkage cracks at an early age, the temperature of fresh concrete should be closely align with the ambient temperature to the greatest extend possible.

5 CONCLUSIONS

The results of the study led to the following conclusions.

<u>Fresh concrete temperature and temperature development with time</u>

The maximum temperature rising levels of the concrete due to hydration process depends on the fresh concrete temperature of the concrete. The relationship between the fresh concrete temperature and its subsequent temperature rise is shown in Figure 4.1. Thus it can be concluded that the risk of excessive rise of concrete temperature can be mitigated by controlling the fresh concrete temperature in the first place.

<u>Slump and slump loss with the time</u>

The increase in fresh concrete temperature is associated with slump loss as well. As depicted in Figure 4.2, a 6 °C temperature rise in the fresh concrete results in approximately 50% slump loss after one hour. This implies that if the slump needs to be retained, the fresh concrete temperature needs to be lowered.

<u>Evaporation characteristics of concrete</u>

Further, it was observed that cracks occurred when the evaporation rate reached approximately 0.7 kg/m^2/hr, which is 30% lower than the prescribed value (1.0 kg/m^2/hr) in ACI 305R-99 [2]. Hence, considerable attention needs to be paid to the curing process and to eliminate plastic shrinkage cracks.

Further, the evaporation rate is lower when the fresh concrete temperature is close to the ambient temperature, and it leads to a lower plastic shrinkage crack width compared to the specimens cast at other fresh concrete temperature values. Hence, it can be concluded that it is beneficial to keep the fresh concrete temperature as much as close to the ambient conditions.

The continuous water curing can prevent or decrease risk of occurring shrinkage cracks as it replaces the evaporated water from the surface. Therefore, the start of curing at the correct time is recommended as soon as the bleed water disappears from the surface.

Plastic shrinkage cracking of concrete

Concrete mix which took the lowest time to exhibit the shrinkage cracks had the fresh concrete temperature of 36.0 °C and a placing temperature of 39.5 °C, while the ambient temperature was recorded as 32.6 °C. This sample had the highest temperature difference between the fresh concrete temperature and the ambient temperature.

Same time, the highest evaporation was recorded when the placing temperature of concrete was 39.5 °C, concurrently the temperature of fresh concrete was recorded as 36.0 °C. This is attributed to the high heat transfer between the concrete body and the surrounding environment.

Conversely, the lowest evaporation was recorded when the placing temperature of concrete was 38.6 °C, coinciding with the placing temperature which created the lowest shrinkage crack width. In both instances, the fresh concrete temperature was 34.2 °C, which is closely aligning with the ambient temperature.

The time taken to appear the first plastic shrinkage crack reduces when there is a significant temperature difference between the concrete temperature at placement and the ambient temperature. The rapid stiffening of the concrete mix may cause the early cracking of concrete. When the difference between the concrete temperature at placement and the ambient temperature is lower, it takes longer time to appear the first shrinkage crack as the concrete mix exhibits some plastic characteristics for first few hours than in the previous case. The placing temperature of the concrete depends on the fresh concrete temperature. Therefore, minimizing the difference between fresh concrete temperature and ambient temperature proves advantageous in reducing plastic shrinkage.

Compressive strength development of concrete

The compressive strength at early ages, specifically at 3 days and 7 days, is higher when the fresh concrete temperature is 36 °C. However, as depicted in Figure 4.14, the 28 day compressive strength is maximum when the fresh concrete temperature is 34.2 °C, which is closely aligned with the ambient temperature. Hence keeping the fresh concrete temperature much closer to the ambient temperature is beneficial in getting the optimum results for compressive strength values in later ages.

Tensile strength capacity of concrete

From Figure 4.15, the mix with the highest splitting tensile strength values in both the early age and later ages was observed when the fresh concrete temperature was 34.2 °C, which is very much close to the ambient temperature.

These results are very similar to the plastic shrinkage results where the minimum crack width is shown when the fresh concrete temperature is 34.2 °C. Since there is a relationship between plastic shrinkage cracking and splitting tensile strength, it can be concluded that optimum results in terms of splitting tensile strength and plastic shrinkage cracks are given when the fresh concrete temperature is close to the ambient conditions.

Based on the aforementioned findings, it can be concluded that keeping the fresh concrete temperature close to the ambient temperature or keeping a maximum of 2-4 °C difference from the ambient temperature is beneficial not only in terms of strength and durability but also in terms of cost as well. The data presented in Appendix G showed a temperature difference of 2 – 4 °C between fresh concrete temperature and the ambient temperature when no artificial control measures are used, except for shading of raw materials. In this experimental studies also, the difference between the fresh concrete temperature and the ambient temperature was around 2 °C when there were no artificial temperature controlling measures other than the shading of raw materials. The shading of raw materials incurs a minimal cost, primarily associated with the initial setup cost of the shading huts. Hence, it is not required to deliberately reduce the temperature below the ambient conditions, and no additional costs will be incurred in this regard.

Although the codes mentioned in Table 2.1, specified limits for the fresh / placing concrete temperatures, it does not mention anything related to the ambient conditions. As per Table 2.1 and Table 2.2, it is understood that the fresh / placing concrete temperature limitations vary from 30 °C to 38 °C in various codes and project specifications. The temperature at the time of placing depends on the time taken to transport the concrete from the mixing location to the placing location. However, it is clearly understood from this study that lowering the fresh concrete temperature than the ambient temperature has no additional benefit.

The CIDA specifications for building works (Vol. 1) – [3rd Edition (Revised)] – SCA/4/I [13], which is the Sri Lankan national guideline, prescribes a limiting value for the "wet concrete temperature" as 38 °C. The wet condition of concrete is being considered from the mixing to the initial setting time. Hence the limiting value given in Sri Lankan national standard is to be more specific than how it is specified currently. Nazir at el. [8] emphasized that the liming values for fresh concrete temperature can be beneficial up to 38 °C as he did his studies under 38 °C ambient temperature. Therefore, these two studies strongly emphasized that the limitation value of fresh / placing concrete should always be defined in relation to the ambient temperature of the casting location.

Therefore, the recommendations given in the code of practices and project specification should be modified accordingly to suit the ambient conditions.

6 RECOMMENDATIONS FOR FUTURE STUDIES

It is understood that very limited number of researches [7], [8] have been carried out in this topic, but in which also, the considered ambient temperature is in the range of 36°C – 45°C. Further, it is understood that there is not much data on the effect of hardened properties of the blended cement concretes.

Nazir et al. [7], [8] showed that these blended cement types can be effectively utilized at high ambient temperatures despite the assumption that the blended cement types do not perform well at high temperatures due to their extra consumption of water during the process of cement hydration and pozzolanic reaction. Nazir et al. [7], [8] also limited their studies to a selected ambient temperature in the range of 36 °C – 45 °C.

Hence, it is recommended to conduct the same testing for the different cement types, different grades, different cement contents and different ambient temperatures and as well as the testing can also be expanded to varying wind and relative humidity conditions.

After investigating the effect of these parameters on the fresh and hardened properties of concrete, it shall be decided the most influential parameters from all the above parameters. Those parameters shall be used as the deciding parameters of the fresh concrete temperature to develop guidelines.

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Appendix A Mix Design Data Sheets

Table A.1: Mix design for Grade 30 concrete

Concrete Mix Design Data (British Method of Design of Normal Concrete Mixes)

Project Name	:
Record No.	: MD-G30-001-R00 (180mm)
Date	: 2023-07-17
Purpose/ Description	: Mix Design for G30 concrete to be used in the water villa sub structure works

CONC. GRADE : 30 N / mm ^{2} ***DESIGN SLUMP : 180 +/- 25 mm***

Stage	Item	Reference or Calculation	Values
01	1.1 Characteristic strength	Specified	Compressive 30 N/mm ^{2} at 28 Days
			Proportion defective 5 percent
	1.2 Standard deviation		- N/mm ^{2} or no data 6 N/mm ^{2}
	1.3 Margin	C1	(k = 1.64) 1.64 x 6.0 = 9.84 N/mm ^{2}
	1.4 Target mean strength	C2 & Para 8.1	30 + 9.84 = 39.84 N/mm ^{2}
	1.5 Cement type	Specified	OPC
	1.6 Aggregate type : Coarse	Crushed	
	Aggregate type : Fine	Quarry Dust (M Sand)	
	1.7 Free water / cement ratio	Table 2 , Fig 4	
	1.8 Maximum free water / cement ratio	Specified	Use the lower value 0.44
02	2.1 Slump or V-B	Assumed	Slump 180 mm or V-B - s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free water content	Table 3 & Para 8.2	(From past experience) 176 kg/m ^{3}
03	3.1 Cement content	C3	176/0.44 = 400 kg/m ^{3}
	3.2 Maximum cement content	Specified	kg/m ^{3} 550
	3.3 Minimum cement content	Specified	kg/m ^{3} 300
			use 3.1 if < 3.2
			use 3.3 if > 3.1
	3.4 Modified free water/cement ratio		0.44 400 kg/m ^{3}
04	4.1 Relative density of aggregate (SSD)		known / assumed 2.70
	4.2 Concrete density	Fig 5& Para 8.3/ ~~Past Experience~~	= 2450 kg/m ^{3} *
	4.3 Total aggregate content	C4 =	2,450-176-400 = 1874 kg/m ^{3}
05	5.1 Grading of Fine aggregate	Percentage passing 600 mm sieve Maximum 50 Minimu	30.0% percent
	5.2 Proportion of Fine aggregate		44 percent
	5.3 Fine aggregate content	C5	1,874X0.44 825.00 kg/m ^{3}
	5.4 Coarse aggregate content	C5	1,874-825.00 1,049.00 kg/m ^{3}

Quantities	Cement	Water	Fine aggregate	Coarse aggregate (10-20mm)		Admixture SIKA PLAST 204H	
	(kg)	(kg)	(kg)	(kg)		(ml)	
Per m ^{3}	400.00	176.00	825.00	1,049.00		3,000.00	
Per trial mix of 0.147 m ^{3}	200.00	88.00	412.50	524.50		1,500.00	

Notes :
1. This is a general mix design, and should be changed to suit with the material conditions and/or after doing the first trial mix.
2. The air content of the fresh concrete should be measured. (Average allowable air content shall be 1%)
3. Temperature of the fresh concrete should be monitored. (Maximum allowable temperature is 35ºC)
4. Ambient temperature should be measured.
*5. * Concrete wet density to be verified at site.*

Appendix B Data sheet of SikaPlast 204H

BUILDING TRUST

PRODUCT DATA SHEET

SikaPlast®-204 H

PCE BASED SUPERPLASTICIZING AND SET RETARDING CONCRETE ADMIXTURE

DESCRIPTION

SikaPlast®-204 H is a 3rd generation polymer based high performance superplasticizer for producing soft consistency concrete.
SikaPlast®-204 H meets the requirements of BSEN 934-2

USES

SikaPlast®-204 H is mainly suitable for the manufacture of concrete for RMC plants and site batch concrete.
SikaPlast®-204 H is used for the following types of concrete:

- High strength bored piles
- Bridges and cantilever
- Ground and suspended slabs
- Columns and walls

CHARACTERISTICS / ADVANTAGES

SikaPlast®-204 H combines different modes of actions. By adsorption on the surface of the fines and keeping them apart while the hydration is in progress, SikaPlast®-204 H effects the following concrete properties:

- Long slump keeping and high water reduction
- High flowability (considerably reduced placing and compacting work)
- Faster evolution of early strength development
- Workability can be maintained up to 4–6 hours (still depends on admixture dosage, cement type, temperature)
- Improved creep and shrinkage resistance characteristics
- When used at higher dosages, SikaPlast®-204 H can give extended working time

SikaPlast®-204 H contains neither chlorides nor other corrosion-inducing subsances and can therefore be used without any restrictions for reinforced concrete structures.

PRODUCT INFORMATION

Composition	Modified poly carboxylate in water
Packaging	1000 L
Appearance / Colour	Liquid / brownish colour
Shelf life	12 months if stored properly in original unopened packaging
Storage conditions	Stored in dry conditions, protected from direct sunlight.
Density	1.105–1.125 kg/l
pH-Value	4.50–6.00

APPLICATION INFORMATION

Recommended Dosage	0.5–2 L per 100 kg of cement
Compatibility	SikaPlast®-204 H may be combined with all Sikament, Sika® Aer, Sika® Pump, Sikacrete® PP-1 products, but must be added separately to the mix and not pre-mixed prior its addition. SikaPlast®-204 H is compatible with all Portland cement types.

IMPORTANT CONSIDERATIONS

Overdosing will result in increased workability and setting
time of the concrete; however provided that curing is effective, ultimate concrete strength and properties will not be affected.
Accurate dispensing equipment can be supplied by Sika Limited (Vietnam).
Use an appropriate concrete mixer and do not mix by hand.
Trial mixes are recommended to establish exact dosage rates required to suit individual requirements. Please contact Sika Technical Department for further assistance.

BASIS OF PRODUCT DATA

All technical data stated in this Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

LOCAL RESTRICTIONS

Note that as a result of specific local regulations the declared data and recommended uses for this product may vary from country to country. Consult the local Product Data Sheet for the exact product data and uses.

ECOLOGY, HEALTH AND SAFETY

Protective measures: Avoid prolonged contact with skin. Wash off thoroughly with soap water.
In case of contact with eyes or mouth, rinse immediately with clean warm water and seek medical attention without delay.
Avoid contact with food stuff and utensils.
Ecology/ Waste disposal: Do not dispose of into water or soil, but according to local regulations.
Transportation: Non-hazardous
Toxicity: Non-toxic

LEGAL NOTES

Sika Lanka (Private) Limited
No. 58/12-B
Raja Mawatha
Ekala, Ja-Ela
Sri Lanka

Appendix C Testing Procedures

C.1. Measurement of slump

The following steps were adopted when measuring the slump of fresh concrete as per BS 1881-102: 1983 [56].

1. A sample of fresh concrete was obtained as given in Section 3.1.5.5 into a clean container.
2. The sample was thoroughly mixed before adding it into the mould.
3. Internal faces were cleaned and damped and extra moisture was removed from the surfaces.
4. Moulds were placed on a flat surface. The mounting floor was rigid and non-absorbent and free from vibration and shock.
5. Mould was kept firmly in place by standing on the mould.
6. Concrete was poured into the mould using a funnel and a scoop. Slump cone was filled in three layers and each layer was tamped by applying 25 strokes. The standard tamping rod was used and tamping was done as per the recommended guidelines.
7. The top layer was heaped before tamping. After that the extra concrete was struck off and rolled the tamping rod over the top surface to level it.
8. The excess concrete in the surrounding was removed keeping the mould in position.
9. The mould was raised slowly in 5s – 10s from the concrete, while ensuring there was no torsional movement or lateral motion applied onto the concrete surface.
10. The process was completed within 150 s as stated in the code.
11. After removing the mould, the height was measured to the nearest 5mm, from the top of the mould position to the topmost point of the concrete specimen.
12. Slump was measured every 30 mins interval until it loses its workability.

C.2. Specimens preparation and measurement of compressive strength development

The following steps were adopted when preparing the specimens to measure the compressive strength of concrete as per BS 1881-108: 1983 [57].

1. A sample of fresh concrete was obtained as given in Section 3.1.5.5 into a clean container.
2. The sample was thoroughly mixed before adding it into the mould.
3. Internal faces were cleaned and damped and extra moisture was removed from the surfaces.
4. Moulds were kept on a rigid, flat surface and filled them with concrete.
5. Moulds were filled in three approximate 50mm deep layers and compacted each layer with the compacting bar.
6. A minimum of 35 strokes were applied for each layer for proper compaction.
7. Extra concrete was removed from the top surface and smoothened the top surface using a mason trowel.
8. Moulds were demoulded after 24 hours and cubes were immersed in a curing tank.
9. Standard test methods were followed when testing for compressive strength.
10. Failure loads were recorded.

The following procedure was followed to calculate the compressive strengths as per the BS1881-116:1983 [63].

1. Calculated the cross-sectional area of the cube from the nominal dimensions.
2. Recorded the maximum load applied on the cubes in Newton.
3. Calculated the compressive strength using the following equation.

$$\sigma c = \frac{F}{A}$$

Equation C.1

Where;

F = Maximum load in N

A = Calculated cross-sectional area from the nominal dimensions mm^2

4. Expressed the compressive strength results to the nearest 0.5 N/mm^2.

C.3. Specimens preparation and measurement of splitting tensile strength

The following steps were adopted when preparing the specimens to measure the splitting tensile strength of concrete as per BS 1881-110: 1983 [58] and BS 1881-117: 1983 [62].

1. A sample of fresh concrete was obtained as given in Section 3.1.5.5 into a clean container.
2. The sample was thoroughly mixed before adding it into the mould.
3. Internal faces were cleaned and damped and extra moisture was removed from the surfaces.
4. Moulds were placed on a rigid flat horizontal surface and filled them with concrete.
5. Moulds were filled in three approximate 50mm deep layers and compacted each layer with the compacting bar.
6. A minimum of 30 strokes were applied for each layer for proper compaction.
7. Extra concrete was removed from the top surface and smoothened the top surface using a mason trowel.
8. Moulds were demoulded after 24 hours and cubes were immersed in a curing tank.
9. Cylinders which were tested for 1-day strength were immersed in water for 5 mins before testing.
10. Standard test methods were followed when testing for compressive strength.
11. Failure loads were recorded.

As per the BS1881-117:1983 [62], the following steps shall be followed to calculate the splitting tensile strength.

1. Measured the length (*l*) and cross-sectional diameter (*d*) of the specimens.
2. Recorded the maximum load applied on the cubes in Newton (F).
3. The splitting tensile strength σ_{ct} was calculated by the following formula in N/mm^2.

$$\sigma ct = \frac{2F}{\pi \, x \, l \, x \, d}$$ **Equation C.2**

Where;

F = Maximum load (N)

l = Length of the specimen (mm)

d = Diameter of the specimen (mm)

4. Expressed the calculated values to the nearest 0.05 N/mm^2.

Appendix D Weather Condition of the Testing Region

Table D.1: Climate graph of testing region

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (ms^{-1})
1/1/2023	31.5	25.4	28.4	72	5.14
1/2/2023	30.8	26.2	28.3	71	5.65
1/3/2023	31	25.5	28.4	70	6.68
1/4/2023	31.1	26.5	28.3	72	7.20
1/5/2023	31.2	26.4	28.6	72	7.20
1/6/2023	31.4	26.9	28.7	73	6.17
1/7/2023	31.5	25.9	28.6	79	7.71
1/8/2023	31.6	26.9	28.7	76	8.22
1/9/2023	31.2	26.5	28.7	77	7.20
1/10/2023	30.6	26.4	28.3	78	5.65
1/11/2023	30.6	25.6	28	75	4.63
1/12/2023	31.6	25.1	28.1	69	4.63
1/13/2023	30.5	25.8	28	64	3.60
1/14/2023	30.5	25.5	28.1	69	3.08
1/15/2023	31	26.2	28.3	72	4.11
1/16/2023	31	26.6	28.5	74	3.60
1/17/2023	31.2	26.9	28.6	78	5.14
1/18/2023	31.6	27.3	28.9	80	6.68
1/19/2023	31.5	26.2	28.8	74	8.22
1/20/2023	31.3	25.6	28.5	62	7.20
1/21/2023	30	24.6	27.6	72	4.63
1/22/2023	32.2	27.2	28.8	73	7.20
1/23/2023	31.7	24	28.4	78	6.68
1/24/2023	28.6	23.5	25.6	91	5.14
1/25/2023	30.1	23.9	26.7	86	3.08
1/26/2023	30.8	25.5	28.2	80	5.65
1/27/2023	31.1	26.7	28.5	80	6.17
1/28/2023	31	25.8	28.3	78	4.63
1/29/2023	29.8	24.6	26.8	86	2.57
1/30/2023	30.9	26.2	28.1	77	2.57
1/31/2023	30.6	26.8	28.3	79	3.60
2/1/2023	30.6	26.7	28.3	79	4.63
2/2/2023	30	26.4	28.1	77	4.63
2/3/2023	30.5	26.8	28.3	75	5.14
2/4/2023	30.8	25.9	28.7	76	3.08

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (m/s)
2/5/2023	31.2	27.4	29	73	5.14
2/6/2023	31	26.8	28.7	78	5.14
2/7/2023	31.4	26.3	28.5	80	3.60
2/8/2023	31.6	27.6	28.9	76	3.08
2/9/2023	31	25.6	28.4	78	3.60
2/10/2023	31.6	25.6	28.5	77	3.08
2/11/2023	31.4	24.8	28.3	74	3.60
2/12/2023	30.8	24.5	28	73	4.11
2/13/2023	31.1	26.4	28.1	71	4.11
2/14/2023	31.4	26.5	28.5	76	5.14
2/15/2023	31.4	26.1	28.5	70	6.17
2/16/2023	31.8	25.9	28.6	67	6.68
2/17/2023	31.2	26.5	28.5	72	6.17
2/18/2023	31.2	26.1	28.5	75	5.14
2/19/2023	32.1	26.1	28.8	72	5.14
2/20/2023	31.4	26.6	28.8	76	4.63
2/21/2023	32	26	29.1	79	4.11
2/22/2023	31.8	26.1	29	78	4.11
2/23/2023	31.2	26.6	28.8	73	4.11
2/24/2023	32.3	26	28.3	78	4.11
2/25/2023	31.5	26.6	28.9	80	5.14
2/26/2023	31.9	26.4	28.9	75	6.17
2/27/2023	31.5	26.8	28.9	71	7.20
2/28/2023	31.6	26.5	29.2	72	6.17
3/1/2023	31.6	26.9	29.1	79	6.17
3/2/2023	32.3	27.6	29.2	77	7.71
3/3/2023	32	26.5	29.1	75	7.71
3/4/2023	32	26.1	29	78	6.17
3/5/2023	31.6	24.2	28	85	7.20
3/6/2023	30.5	26.4	28.1	83	4.63
3/7/2023	31.6	27.5	29.4	79	5.65
3/8/2023	32	27.5	29.6	78	7.20
3/9/2023	32.2	26.8	29.3	79	6.68
3/10/2023	31.1	26.5	28.6	82	6.68
3/11/2023	32	27.8	29.5	78	5.14
3/12/2023	32	27.7	29.5	79	6.68
3/13/2023	31.9	27.8	29.5	81	6.17
3/14/2023	32	25.7	29.3	83	5.65
3/15/2023	31.7	25.6	28.5	84	2.57

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (m/s)
3/16/2023	28.7	24	26.5	90	2.57
3/17/2023	31.3	26.1	28.7	82	2.57
3/18/2023	32	27.2	29.3	81	2.57
3/19/2023	32.3	27.8	29.6	78	2.57
3/20/2023	32.1	25.6	29.1	82	4.11
3/21/2023	31.8	26.6	29.1	81	3.60
3/22/2023	31.3	27	29	81	1.54
3/23/2023	32.6	27.4	29.6	77	2.57
3/24/2023	31.5	27.6	29	78	2.57
3/25/2023	32	27	29.6	80	3.60
3/26/2023	32.1	26.8	29	85	2.57
3/27/2023	32.1	28	29.8	81	3.60
3/28/2023	32.5	27.7	29.8	80	3.08
3/29/2023	31.8	27.6	29.6	79	2.57
3/30/2023	31.6	28.2	29.7	80	3.60
3/31/2023	32.6	24.3	29.9	79	2.57
4/1/2023	31.6	24.4	28.7	82	2.57
4/2/2023	32.1	27.1	29.8	75	2.57
4/3/2023	32.4	27.5	29.8	76	2.57
4/4/2023	32.8	26.5	29.8	76	3.08
4/5/2023	32.4	27.6	29.8	77	2.06
4/6/2023	31.5	26.8	29.4	81	2.06
4/7/2023	33.5	26.6	29.6	78	2.06
4/8/2023	33.3	27	30	76	2.57
4/9/2023	33.4	27.6	29.7	77	3.08
4/10/2023	33.8	28	30.4	75	4.63
4/11/2023	33.9	25.5	30.2	77	3.60
4/12/2023	33	26.2	29.9	78	4.63
4/13/2023	33.5	28	30.3	79	3.60
4/14/2023	33.6	28.6	30.5	78	2.06
4/15/2023	33.2	27.5	29.4	82	2.06
4/16/2023	33	27.8	29.7	80	2.57
4/17/2023	33.3	27.9	30.1	78	1.03
4/18/2023	33.6	28.1	30.3	78	2.06
4/19/2023	33	26.8	30.3	77	2.06
4/20/2023	32.7	27.9	30.1	75	1.54
4/21/2023	33	28	30.3	78	3.08
4/22/2023	32.6	29.1	30.5	79	3.60
4/23/2023	33.2	29.1	30.9	78	3.60

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (m/s)
4/24/2023	33.8	24.5	30.2	81	2.57
4/25/2023	32.8	26.4	30.4	80	3.60
4/26/2023	33.6	28.4	30.6	79	3.08
4/27/2023	33.7	26.4	30.6	79	2.57
4/28/2023	33.2	27.8	30.1	80	2.57
4/29/2023	32	26	29	85	3.08
4/30/2023	32.7	27	29.3	84	2.57
5/1/2023	31.9	27.4	29.7	72	6.17
5/2/2023	32	28.5	29.7	73	6.68
5/3/2023	32.6	24.6	30.2	71	6.68
5/4/2023	30.9	23.5	27.4	74	7.20
5/5/2023	32.3	27.7	29.8	73	6.68
5/6/2023	31.8	25.9	29.1	76	6.17
5/7/2023	32.4	28.6	30.1	71	5.65
5/8/2023	32.2	28.7	30.2	73	5.14
5/9/2023	32.1	27.6	29.9	72	5.14
5/10/2023	32.3	25.7	29.8	73	6.17
5/11/2023	31.9	25.3	27.9	77	5.14
5/12/2023	31.7	25.6	28	76	6.17
5/13/2023	31.6	26.3	28.7	77	6.68
5/14/2023	31.7	25	28.9	75	8.22
5/15/2023	31.7	27.6	29.5	77	9.25
5/16/2023	31.6	27	29.8	74	7.20
5/17/2023	32	27.6	30	73	3.08
5/18/2023	32.1	27	29.7	75	1.54
5/19/2023	32.9	27.9	30	66	1.54
5/20/2023	32.8	28.7	30.3	71	3.08
5/21/2023	33.1	26.8	30.3	74	3.60
5/22/2023	31.8	24.3	28.2	76	2.57
5/23/2023	32.9	26.9	29.8	66	1.54
5/24/2023	33.3	28.6	30.5	69	2.57
5/25/2023	32.8	28.4	30.4	71	4.11
5/26/2023	33.2	28.6	30.4	67	4.11
5/27/2023	32.6	25.5	30.3	70	5.65
5/28/2023	32.1	27	29.5	65	5.14
5/29/2023	32.7	27.8	30	70	4.63
5/30/2023	32.9	27.5	30.3	72	5.14
5/31/2023	31.9	26.1	29.4	74	7.20
6/1/2023	31.4	26.8	29.00417	80	8.29

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (m/s)
6/2/2023	31.2	26.5	28.96667	79	7.88
6/3/2023	31	26.8	29.47083	79	8.97
6/4/2023	32.2	25.5	28.63333	78	8.70
6/5/2023	31.9	27	29.6	76	5.85
6/6/2023	32.7	28.1	30.05417	73	4.97
6/7/2023	31	24.5	28.74583	82	5.50
6/8/2023	31.8	28	29.9625	78	6.64
6/9/2023	32.6	28.4	29.93333	74	4.75
6/10/2023	32.7	27.9	30.1	73	3.79
6/11/2023	31.8	27.5	29.89167	69	5.16
6/12/2023	32.6	28.1	30.22917	75	7.07
6/13/2023	32.2	29.2	30.45417	73	6.96
6/14/2023	31.5	29	30.19583	77	5.08
6/15/2023	31.6	28.7	30.225	77	4.84
6/16/2023	31.5	28.3	29.74583	74	5.01
6/17/2023	32.3	28.6	30.2375	71	4.35
6/18/2023	32.3	28.9	30.17083	68	5.95
6/19/2023	32	28.6	30.29167	72	5.87
6/20/2023	32.4	27.4	30.22917	71	6.28
6/21/2023	31.6	27	30.05	74	7.00
6/22/2023	31.5	26.6	29.74583	72	5.89
6/23/2023	31	26.6	29.39583	74	6.62
6/24/2023	31.5	24.5	28.95833	70	8.20
6/25/2023	30	24.1	26.95	76	6.28
6/26/2023	30.6	27.4	28.97083	76	5.80
6/27/2023	30.9	28	29.15	71	4.58
6/28/2023	31.9	27.6	29.6875	69	4.71
6/29/2023	32.1	27.6	29.84583	68	4.41
6/30/2023	31.8	26.9	29.6125	70	2.21
7/1/2023	31.8	27.9	29.5	63	2.06
7/2/2023	32.6	25	29.2	64	4.63
7/3/2023	31.7	25.3	28.4	77	6.68
7/4/2023	29.9	24.2	27.7	75	7.20
7/5/2023	31.6	24.5	28.4	73	6.17
7/6/2023	31.6	25.9	29.2	69	3.08
7/7/2023	31.9	28.1	29.5	72	3.60
7/8/2023	31.6	28.4	29.8	70	3.60
7/9/2023	31.8	28.3	29.9	67	5.14
7/10/2023	31.8	28.1	30	67	4.63

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (m/s)
7/11/2023	31.4	28.3	29.7	70	3.60
7/12/2023	31.8	27.9	29.9	69	3.60
7/13/2023	32.7	28.3	30.2	68	3.08
7/14/2023	32.5	28.3	30.1	66	2.06
7/15/2023	32	27.2	30	70	2.57
7/16/2023	32.3	27.4	29.8	70	4.11
7/17/2023	32	28.6	30.1	69	5.65
7/18/2023	32.5	27.2	29.9	71	4.63
7/19/2023	31.7	28	29.7	73	4.63
7/20/2023	32.1	26.1	28.9	71	4.63
7/21/2023	30.2	25.6	27.4	81	4.11
7/22/2023	31.5	27.8	29.5	72	4.11
7/23/2023	31.8	28.2	29.8	68	4.63
7/24/2023	32.5	28.5	30.1	71	3.60
7/25/2023	33.2	29	30.6	70	3.08
7/26/2023	32.9	28.4	30.6	72	3.08
7/27/2023	32.6	26.2	30.1	72	2.57
7/28/2023	32.4	24.8	29.4	69	2.06
7/29/2023	31.2	24.5	28.5	75	6.68
7/30/2023	31.6	27.2	29.4	73	4.11
7/31/2023	32.1	28.5	30.1	70	3.60
8/1/2023	32.2	28.6	30.2	70	4.63
8/2/2023	32.3	28.4	30.2	68	3.08
8/3/2023	32.1	27.8	30.1	66	3.08
8/4/2023	32.4	25.5	29.8	70	3.60
8/5/2023	32.1	25.9	29.6	69	5.14
8/6/2023	31.2	27.5	29.6	71	5.14
8/7/2023	31.6	25.4	29.7	70	5.65
8/8/2023	32.2	27.5	29.7	68	5.14
8/9/2023	31.7	24.9	29.1	70	5.65
8/10/2023	31	25.8	29	70	5.14
8/11/2023	32.4	28.4	29.8	71	4.63
8/12/2023	31.2	24.2	29.7	70	5.65
8/13/2023	30.9	28.2	29.6	67	4.63
8/14/2023	32	28.2	29.8	67	4.63
8/15/2023	31.6	27.7	29.8	62	3.60
8/16/2023	31.8	26.4	29.4	66	2.06
8/17/2023	32.4	28	29.8	66	4.11
8/18/2023	32.5	26.5	30.1	67	5.65

Date	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Mean Humidity (%)	Mean Wind Speed (m/s)
8/19/2023	31.9	28.2	30	63	6.17
8/20/2023	31.7	28.3	29.9	70	5.65
8/21/2023	31.6	28.1	29.7	68	4.63
8/22/2023	32	28.2	30	68	4.11
8/23/2023	31.9	27.5	29.9	69	4.11
8/24/2023	31.9	25.1	29.4	67	5.65
8/25/2023	32.6	27.3	30	67	4.11
8/26/2023	32.3	26.6	29.9	67	3.08
8/27/2023	32	27	29.6	66	3.60
8/28/2023	31.5	24.8	28.4	73	6.68
8/29/2023	30.7	27	28.4	72	6.68
8/30/2023	31.8	25.5	29.3	67	5.65
8/31/2023	30.6	26.2	28.7	76	5.65

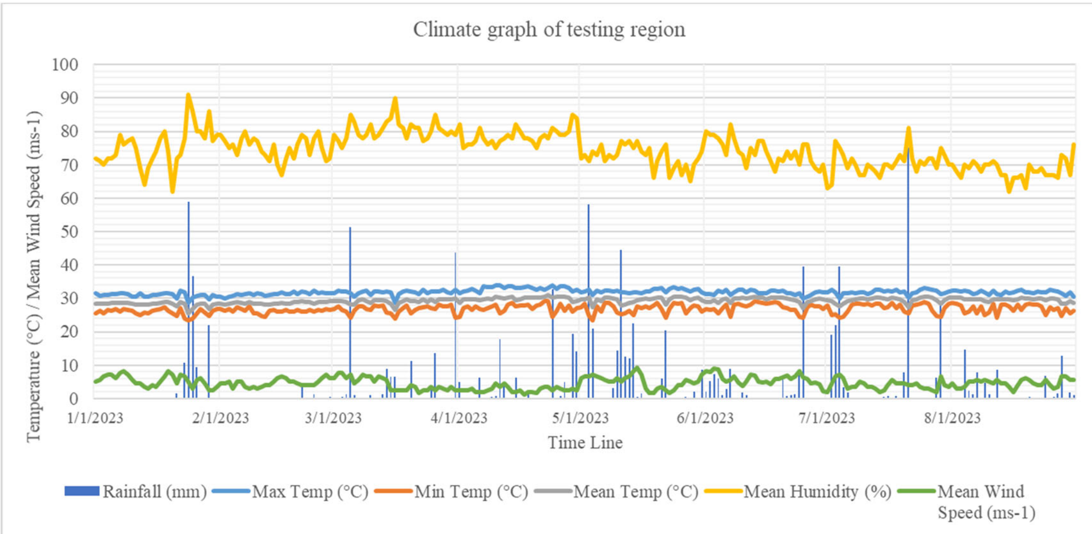

Figure D.1: Climate graph of testing region

Appendix E Measured Weather Conditions During the Experimental Study

Table E.1 – E.4 gives the ambient condition data records during the testing period.

Table E.1: Ambient condition during the testing period-Day 1

Date	Time	Ambient Temperature (°C)	Wind (ms^{-1})	Humidity (%)
8/13/2023	9.00 am	32.0	1.00	70.0
8/13/2023	9.19 am	33.1	0.50	65.0
8/13/2023	9.32 am	34.0	-	61.0
8/13/2023	9.48 am	32.1	1.50	67.6
8/13/2023	10.00 am	32.4	1.40	68.0
8/13/2023	10.18 am	32.5	1.96	68.9
8/13/2023	10.33 am	32.6	1.00	71.2
8/13/2023	10.50 am	34.5	1.10	72.4
8/13/2023	11.04 am	33.3		69.5
8/13/2023	11.18 am	32.1	0.14	71.0
8/13/2023	11.36 am	32.8	2.21	66.2
8/13/2023	11.46 am	32.9	-	63.6
8/13/2023	12.17 pm	33.0	2.04	65.1
8/13/2023	12.32 pm	32.6	1.14	
8/13/2023	1.23 pm		1.57	61.6
8/13/2023	1.47 pm	32.5	1.42	61.1
8/13/2023	2.11 pm	31.1	1.25	75.3
8/13/2023	2.20 pm	32.1		
8/13/2023	3.01 pm	30.5	1.42	62.6
8/13/2023	3.18 pm	31.7		
8/13/2023	3.26 pm	32.3	1.89	63.0
8/13/2023	3.34 pm	31.3	1.57	66.7
8/13/2023	3.50 pm	31.8		
8/13/2023	4.01 pm	32.0	1.92	70.7
8/13/2023	4.32 pm	30.7	1.10	82.9
8/13/2023	5.06 pm	30.3	1.42	81.6
8/13/2023	5.32 pm	28.3	1.96	86.5
8/13/2023	6.01 pm	26.2	1.96	93.2
8/13/2023	6.32 pm	28.3	1.07	76.9
8/13/2023	6.51 pm	28.0	1.25	79.8
8/13/2023	6.57 pm	28.1	1.75	86.7
8/13/2023	10.16 pm	25.5	-	99.8

Table E.2: Ambient condition during the testing period-Day 2

Date	Time	Ambient Temperature (°C)	Wind (ms^{-1})	Humidity (%)
8/14/2023	7.06 am	30.2	-	94.5
8/14/2023	7.17 am	28.4	-	87.6
8/14/2023	7.31 am	28.8	1.42	76.0
8/14/2023	7.45 am	30.7	-	68.5
8/14/2023	8.02 am	31.4	-	74.5
8/14/2023	8.19 am	30.9	0.85	72.2
8/14/2023	8.29 am	30.8	0.71	63.0
8/14/2023	8.48 am	30.9	-	79.2
8/14/2023	9.06 am	31.3	1.07	81.5
8/14/2023	9.41 am	31.0	0.21	65.9
8/14/2023	9.52 am	32.2	-	63.3
8/14/2023	9.59 am	32.8	-	62.4
8/14/2023	10.17 am	32.3	2.00	65.5
8/14/2023	10.39 am	31.8	0.92	60.4
8/14/2023	10.48 am	32.3	-	63.3
8/14/2023	10.55 am	32.7	1.78	55.4
8/14/2023	11.20 am	31.8		61.2
8/14/2023	11.31 am	32.8	-	55.4
8/14/2023	12.31 pm	33.8	1.25	68.7
8/14/2023	12.45 pm	32.4	1.46	62.0
8/14/2023	12.58 pm	32.1	2.00	67.9
8/14/2023	1.28 pm	32.5	1.96	63.3
8/14/2023	1.46 pm	34.2	1.25	61.2
8/14/2023	2.02 pm	34.1	0.64	58.6
8/14/2023	2.05 pm	34.1		
8/14/2023	2.29 pm	33.2	1.00	65.2
8/14/2023	2.46 pm	32.0	1.32	80.5
8/14/2023	3.02 pm	33.1	1.42	57.2
8/14/2023	3.17 pm	32.9	1.39	63.7
8/14/2023	3.30 pm	33.2	1.60	61.8
8/14/2023	3.46 pm	32.9	1.75	61.4
8/14/2023	4.05 pm	32.0	1.60	63.4
8/14/2023	4.15 pm	30.8	1.67	62.4
8/14/2023	4.31 pm	30.5	1.28	67.1
8/14/2023	5.00 pm	30.2	1.96	63.2
8/14/2023	5.28 pm	29.6	1.53	93.8
8/14/2023	6.36 pm	28.4	1.07	80.9

Table E.3: Ambient condition during the testing period-Day 3

Date	Time	Ambient Temperature (°C)	Wind (ms^{-1})	Humidity (%)
8/15/2023	7.57 am	30.8	-	83.2
8/15/2023	8.20 am	31.9	-	78.2
8/15/2023	8.33 am	30.8		79.7
8/15/2023	9.00 am	32.1	0.21	74.4
8/15/2023	9.13 am	30.4	0.85	67.9
8/15/2023	9.34 am	30.4		85.7
8/15/2023	9.45 am	32.3	1.14	66.3
8/15/2023	10.18 am	31.8		79.3
8/15/2023	10.31 am	33.1		55.8
8/15/2023	10.33 am	32.1		
8/15/2023	10.44 am	31.8	1.14	63.3
8/15/2023	11.12 am	32.8	1.46	53.9
8/15/2023	11.23 am	31.8	0.64	58.7
8/15/2023	11.32 am	34.3	2.32	50.4
8/15/2023	11.33 am	32.5		
8/15/2023	11.39 am	33.5		
8/15/2023	11.45 am	32.4		54.7
8/15/2023	12.02 pm	32.0	1.54	54.3
8/15/2023	12.16 pm	32.7		
8/15/2023	12.32 pm	32.3	0.78	50.1
8/15/2023	12.44 pm		0.50	54.5
8/15/2023	1.02 pm	33.5	0.14	58.3
8/15/2023	1.23 pm	32.0		64.6
8/15/2023	1.34 pm		1.02	45.8
8/15/2023	1.48 pm	32.2	1.67	
8/15/2023	2.01 pm	32.6	0.71	59.4
8/15/2023	2.21 pm	33.0	1.00	57.4
8/15/2023	2.33 pm	34.5	0.28	59.0
8/15/2023	2.48 pm	34.0	0.35	49.5
8/15/2023	2.59 pm	34.3		55.7
8/15/2023	3.17 pm	30.8	1.25	75.9
8/15/2023	3.29 pm	33.4	0.64	62.7
8/15/2023	3.48 pm	31.5	1.50	77.8
8/15/2023	4.01 pm	32.4		66.4
8/15/2023	4.16 pm	33.4		68.3
8/15/2023	4.29 pm	32.7		64.3
8/15/2023	5.04 pm	32.0		64.4
8/15/2023	5.37 pm	27.3	1.50	
8/15/2023	6.01 pm	27.4	1.50	90.8
8/15/2023	6.31 pm	25.4		94.9
8/15/2023	7.17 pm	28.0		83.6

Table E.4: Ambient condition during the testing period-Day 4

Date	Time	Ambient Temperature (°C)	Wind (ms^{-1})	Humidity (%)
8/16/2023	7.32 am	28.9	-	93.8
8/16/2023	7.48 am	31.8	-	79.2
8/16/2023	8.17 am	29.7	-	87.3
8/16/2023	8.32 am	30.7		71.5
8/16/2023	9.08 am	30.5	0.21	88.4
8/16/2023	9.29 am	32.2	0.57	60.9
8/16/2023	10.01 am	32.5	-	76.3
8/16/2023	10.17 am	32.1		65.9
8/16/2023	10.29 am	32.3		61.3
8/16/2023	10.49 am	32.6	1.17	62.2
8/16/2023	11.16 am	32.6		60.9
8/16/2023	11.23 am	31.4		63.5
8/16/2023	11.33 am	32.7	0.64	57.7
8/16/2023	11.57 am	31.4		61.5
8/16/2023	12.12 pm	31.5		59.5
8/16/2023	12.54 pm	30.8		
8/16/2023	12.58 pm	32.3		
8/16/2023	1.12 pm	32.1		57.9
8/16/2023	1.13 pm	32.4	0.35	58.7
8/16/2023	1.33 pm	32.6		62.3
8/16/2023	1.50 pm	34.1		58.0
8/16/2023	2.03 pm	35.0	0.21	55.7
8/16/2023	2.33 pm	32.1		
8/16/2023	2.46 pm	32.4		
8/16/2023	3.05 pm	31.4		76.1
8/16/2023	3.19 pm	31.4	1.57	80.7
8/16/2023	3.28 pm	33.9	1.25	64.7
8/16/2023	3.45 pm	29.7		76.7
8/16/2023	3.58 pm	32.5	0.54	6.6
8/16/2023	4.27 pm	30.0		66.5
8/16/2023	4.56 pm	32.2	0.85	61.8
8/16/2023	5.34 pm	31.5	0.28	63.4
8/16/2023	6.01 pm	29.9		68.2
8/16/2023	6.36 pm	29.1		

Appendix F Measured Data of Testing Concrete

Table F.1 -F.4 gives the data recorded on the concrete characteristics during testing period.

Table F.1: Field measurements on concrete characteristics - Day 1

Date	Time	Temp. of Concrete (°C)	Slump (mm)	Weight of the Sample to Measure the Evaporation (kg)
8/13/2023	12.34 pm	34.2	160.0	
8/13/2023	1.06 pm	36.1	135.0	16.688
8/13/2023	1.32 pm	38.6	95.0	
8/13/2023	1.33 pm			16.578
8/13/2023	2.03 pm	37.9	45.0	
8/13/2023	2.17 pm			16.472
8/13/2023	2.36 pm			16.442
8/13/2023	2.39 pm	37.0	30.0	
8/13/2023	2.50 pm			16.408
8/13/2023	3.18 pm			16.352
8/13/2023	3.34 pm			16.322
8/13/2023	3.50 pm			16.312
8/13/2023	4.01 pm			16.296
8/13/2023	4.32 pm			16.258
8/13/2023	5.06 pm			16.218
8/13/2023	5.32 pm			16.190
8/13/2023	6.01 pm			16.172
8/13/2023	6.32 pm			16.162
8/13/2023	7.00 pm			16.156
8/13/2023	7.28 pm			16.148

Table F.2: Field measurements on concrete characteristics - Day 2

Date	Time	Temp. of Concrete (°C)	Slump (mm)	Weight of the Sample to Measure the Evaporation (kg)
8/14/2023	11.02 am	32.7	160.0	
8/14/2023	11.20 am	34.3	155.0	
8/14/2023	11.31 am	35.6	145.0	
8/14/2023	12.01 am	36.0	110.0	16.768
8/14/2023	12.13 pm			16.662
8/14/2023	12.31 pm			16.594
8/14/2023	12.35 pm	35.8	50.0	
8/14/2023	12.45 pm			16.576
8/14/2023	12.58 pm			16.556
8/14/2023	1.01 pm	35.3	30.0	
8/14/2023	1.28 pm			16.492
8/14/2023	1.46 pm			16.398
8/14/2023	2.46 pm			16.312
8/14/2023	3.17 pm			16.258
8/14/2023	3.30 pm			16.236
8/14/2023	3.46 pm			16.234
8/14/2023	4.15 pm			16.228
8/14/2023	4.31 pm			16.216
8/14/2023	5.00 pm			16.198
8/14/2023	5.28 pm			16.168
8/14/2023	6.36 pm			16.146

Table F.3: Field measurements on concrete characteristics - Day 3

Date	Time	Temp. of Concrete (°C)	Slump (mm)	Weight of the Sample to Measure the Evaporation (kg)
8/15/2023	11.23 am	36.0	150.0	
8/15/2023	11.45 am	36.9	145.0	
8/15/2023	12.02 pm	37.7		
8/15/2023	12.09 pm			16.688
8/15/2023	12.16 pm	39.5		
8/15/2023	12.21 pm		100.0	
8/15/2023	12.32 pm			16.608
8/15/2023	12.44 pm			16.560
8/15/2023	12.50 pm	38.6	50.0	
8/15/2023	1.02 pm			16.504
8/15/2023	1.23 pm	37.6	25.0	16.384
8/15/2023	1.34 pm			16.390
8/15/2023	1.48 pm			16.376
8/15/2023	2.01 pm			16.370
8/15/2023	2.21 pm			16.274
8/15/2023	2.33 pm			16.242

8/15/2023	2.48 pm			16.218
8/15/2023	2.59 pm			16.192
8/15/2023	3.17 pm			16.146
8/15/2023	3.29 pm			16.132
8/15/2023	3.48 pm			16.100
8/15/2023	4.01 pm			16.078
8/15/2023	4.16 pm			16.072
8/15/2023	4.29 pm			16.058
8/15/2023	5.04 pm			16.038
8/15/2023	5.37 pm			16.030
8/15/2023	6.01 pm			16.008
8/15/2023	6.31 pm			16.018
8/15/2023	7.17 pm			16.004

Table F.4: Field measurements on concrete characteristics - Day 4

Date	Time	Temp. of Concrete (°C)	Slump (mm)	Weight of the Sample to Measure the Evaporation (kg)
8/16/2023	12.12 pm	30.1	165.0	
8/16/2023	12.51 pm	34.2		
8/16/2023	12.54 pm		155.0	16.454
8/16/2023	1.11 pm	35.5	125.0	
8/16/2023	1.13 pm			16.376
8/16/2023	1.33 pm			16.298
8/16/2023	1.46 pm	35.3	75.0	
8/16/2023	1.50 pm			16.254
8/16/2023	2.03 pm			16.198
8/16/2023	2.17 pm	34.8	50.0	
8/16/2023	2.19 pm			16.162
8/16/2023	2.33 pm			16.118
8/16/2023	2.46 pm			16.088
8/16/2023	3.05 pm			16.064
8/16/2023	3.19 pm			16.026
8/16/2023	3.28 pm			16.008
8/16/2023	3.45 pm			15.978
8/16/2023	3.58 pm			15.954
8/16/2023	4.27 pm			15.940
8/16/2023	4.56 pm			15.912
8/16/2023	5.34 pm			15.886
8/16/2023	6.01 pm			15.876
8/16/2023	6.36 pm			15.862

Appendix G Industry Data on Fresh Concrete Temperature and its Development

From the industry data, analysis was done to identify the temperature gap between the ambient temperature and the fresh concrete temperature for grades 25 and 30, where the temperature control is not done other than the shading for aggregates.

Table G.1 and Figure G.1 shows the probability of various temperature differences for Grade 25. In which it is clearly understood that there will be a 2 °C – 4 °C difference between ambient temperature and fresh concrete temperature.

Table G.1: Probability for various temperature differences for Grade 25

Ambient Temperature & Fresh Concrete Temperature Difference (°C)	Probability %
Below 0	1.88%
0-1	6.33%
1-2	15.91%
2-3	25.33%
3-4	25.56%
4-5	16.35%
5-6	6.63%
6-7	1.70%
Above 7	0.31%

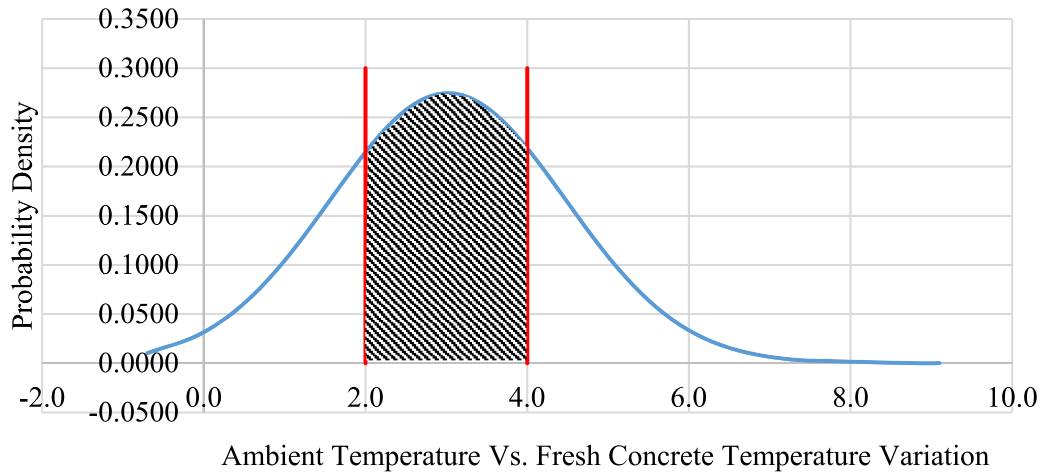

Figure G.1: Ambient temperature Vs. fresh concrete temperature variation distribution for Grade 25 concrete

Table G.2 and Figure G.2 shows the probability for various temperature differences for Grade 30. In which it is clearly understood that there will be 2 °C – 4 °C difference from ambient temperature and fresh concrete temperature.

Table G.2: Probability for various temperature differences for Grade 30

Ambient Temperature & Fresh Concrete Temperature Difference (°C)	**Probability %**
Below 0	3.31%
0-1	7.91%
1-2	16.44%
2-3	23.49%
3-4	23.09%
4-5	15.61%
5-6	7.25%
6-7	2.32%
Above 7	0.59%

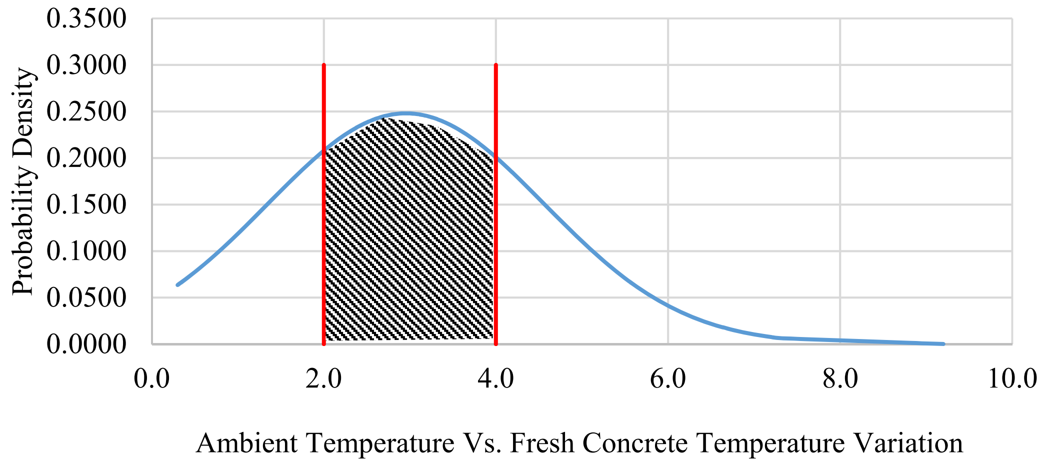

Figure G.2: Ambient temperature Vs. fresh concrete temperature variation distribution for Grade 30 concrete