REDUCING THE STRENGTH AND DURABILITY LOSS OF HIGH PERFORMANCE READY MIX AND ROLLER COMPACTED CONCRETE DUE TO EARLY AGE HIGH TEMPERATURE CURING

BY

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This thesis reports the findings of a study conducted on the effects of mixing and curing high performance concrete at elevated temperature. The purpose of the study was to find solutions to ameliorate the strength and durability loss resulting from high temperature environments. This investigation is broken down into two distinct phases. Phase I consists of a preliminary mortar investigation followed by Phase IIa which was conducted on ready mix concrete and Phase IIb which studied roller compacted concrete. Phase IIa investigated the ability of supplementary cementing materials and chemical admixtures to mitigate the deleterious effects of curing at high temperature. In contrast, Phase IIb investigated the ability of supplementary cementing materials to reduce the deleterious effects. It was found that supplementary cementing materials were moderately effective at ameliorating strength loss, and performed well in reducing durability loss. The chemical admixtures only performed well in ameliorating strength loss.

Acknowledgements

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ACI	American Concrete Institute
C2S	Dicalcium Silicate
C3S	Tricalcium Silicate
C3A	Tricalcium Aluminate
C4AF	Tetracalcium Aluminoferrite
CH	Calcium Hydroxide
CSA	Canadian Standards Association
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
HRWR	High Range Water Reducer
ITZ	Interfacial Transition Zone
J	Joule
PC	Portland Cement
PCA	Portland Cement Association
RCC	Roller Compacted Concrete
RCPT	Rapid Chloride Permeability Test
RH	Relative Humidity
RMC	Ready Mix Concrete
SCM	Supplementary Cementing Materials
SEM	Scanning Electron Microscope
W/C	Water Cement Ratio
WR-Ret. Adm.	Water Reducing Retarding Admixture

Chapter 1
Introduction and Objective

1.1 - Introduction

The problems associated with mixing, transporting, and placing normal ready mix concrete in hot weather environments have been widely documented [1-6]. There is however, a lack of information on the effects of hot weather and methods to prevent strength and durability loss of high performance high slump and low slump concrete. Also, there is a lack of information on the impact of adverse temperature on the compared effects of these concretes batched and cured in the same environment.

As the developing world continues to build larger and more advanced infrastructures, a huge dependence is being put on concrete based structures. Concrete structures are being designed to withstand larger stresses and to survive in more adverse conditions then ever before. The economic restraints and logistics of these projects often entails that they are batched and cast in hot, humid and arid environments. As such, this program will focus on methods of ameliorating the strength and durability loss of high performance high and low slump concrete due to early age high temperature batching and curing.

The average ambient temperatures in Mexico, the Middle East and the Far East are typically in the range of 20 - 30°C and the maximum daily temperature can be as high as 35 - 55°C. Using hot cement and heat generated from the hydration of Portland cement can raise the internal temperature of freshly placed structural members and roller compacted projects in excess of 40°C. Exposure of concrete to elevated temperatures in the first 2-24 hours can cause significant reductions in compressive strength and durability at later ages. Also, it is often necessary to increase the water content of concrete placed in hot environments to minimize the loss of consistency caused by accelerated hydration. If water is not added to combat the loss of consistency, problems with consolidation and roller compaction will result. However, the addition of more batch water leads to lower compressive strengths and a less durable more permeable microstructure.

In this research program, supplementary cementing materials such as Class C and Class F fly ash will be investigated in depth to quantify their effect on compressive strength and durability at high curing temperatures. Also, a grade 80 ground granulated blast furnace slag will be investigated alone and in ternary blends with Class C fly ash. With the cement substitution of these constituents the water demand of mixes will be adjusted accordingly in order to maintain the principle of constant consistency for both high and low slump concrete.

Retarding and water reducing admixtures will also be investigated in depth in this program. They are used extensively in hot weather concreting to reduce water demand, extend open time and improve compressive strength. By slowing cement hydration, retarders allow the formation of a more uniform and finer microstructure which increases strength. As mentioned above, when cement temperatures are high, the demand for water increases in order to maintain the same consistency. The use of retarders should increase later age strengths and therefore permit a reduction in the cement content necessary to achieve prescribed strengths. A secondary benefit will be an increase in the holding time in concrete trucks and batch mixers which will result in an extended delivery period, increasing efficiency.

The principles established for hot weather normal ready mixed concreting also apply to high performance high and low slump concrete. As a result of this relation, and the availability of a broad range of sources, this investigation would not be complete without an in depth exploration of previous works pertaining to hot weather batched normal ready mixed concrete. A literature review of the aforementioned subject is presented in the following chapter.

1.2 – Objective

This investigation can be broken down into two distinct phases; Phase I, Phase IIa and Phase IIb. Phase I consists of a preliminary investigation into the effectiveness of three common elementary ingredients of retarders and water reducers; sucrose, corn syrup and sodium gluconate. This phase consisted of testing mortar with a range of addition rates of the aforementioned admixtures. Mixes were batched and cured at 23, 35 and 50°C while maintaining a constant water content. The only variable analyzed was the effect of the individual admixture on compressive strength. This was done in an effort to narrow down the secondary concrete investigation of Phase IIa.

The objective of Phase IIa was to investigate the ability of Class C and F fly ash as well as GGBFS as a sole constituent as well as in ternary blends to ameliorate the deleterious effects of high initial temperature curing on compressive strength and durability of high performance high slump concrete. Raw and proprietary retarders and water reducers were also investigated. The program was conducted on the premise of constant consistency and water contents were adjusted accordingly to maintain a slump of 100+/-10 mm at 23, 35 and 50°C.

Similarly to Phase IIa, the objective of Phase IIb was to investigate the ability of Class C fly ash as well as GGBFS in both mono and ternary blends to reduce the effects of high initial temperature curing. However, Phase IIb focused on the effects incurred on high performance roller compacted concrete. This portion of the program was also conducted on the premise of constant consistency and a modified VeBe test method was developed to test the consistency of the RCC.

Chapter 2
Literature Review

Many of the principles established for hot weather normal performance ready mix concrete also apply to high performance concrete. As a result of this relation, and the availability of a broad range of sources, this investigation would not be complete without an in depth exploration of previous works pertaining to hot weather and ready mixed concrete. A literature review of the aforementioned subject is presented next. It should be noted that the principles established by this literature review in reference to ready mix concrete also apply to batching roller compacted concrete in high temperature environments. However, due to the existence of very little published literature on roller compacted concrete only minor information has been added where possible.

When batching ready mix concrete (RMC) in hot adverse climatic environments, many regions rely on guidance from documents for concrete production such as, ACI 305, ACI 306 and CIRIA/Concrete Society Guide. All of these documents take into account the effects of wind velocity, solar radiation, relative humidity and temperature on RMC. ACI 305 defines hot weather as, "any combination of high air temperature, low relative humidity, and wind velocity tending to impair the quality of fresh or hardened concrete or otherwise resulting in abnormal properties" [1]. These documents are good guidelines to follow however, a more in depth investigation into the effects of these elements is necessary to fully understand how to prevent their negative effects.

2.1 - Slump Loss

The most visible effect of hot weather on RMC in the early stages of production is the development of slump loss (or loss of workability) during batching and delivery. The rate of slump loss is dependent on many factors including but not limited to: the increased hydration rate of concrete in high temperatures, cement composition, w/c ratio, increased evaporation, and the use of chemical admixtures and supplementary cementing materials [1-3]. The hydration of Portland Cement is an exothermic reaction that continues to accelerate with increases in specific heat. A well known axiom of physical chemistry is that for a 10°C increase in concrete temperature the hydration reaction of cement will double in speed [2]. The acceleration of hydration leads to the liberation of more energy and a rapidly stiffening paste structure causing a loss in workability. As can be seen in Figure 2.1, rapid hydration with increasing temperature also leads to

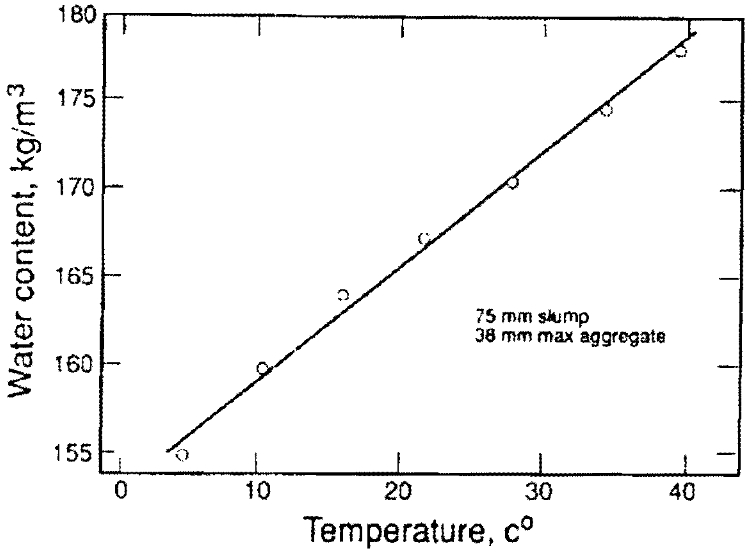


Figure 2.1. Effect of temperature increase on the water requirement of concrete. (1)

an increase in water demand to maintain a specified slump [4]. At RMC plants and on the job site, the loss of workability often leads to the use of an increased w/c ratio resulting in a lower compressive strength and reduced durability [1].

Abdulaziz et al. studied the impact of extremely hot weather and mixing method on the changes in properties of RMC during delivery [5]. The summer temperatures in the Arabian Gulf region can often reach 45°C with a RH of 15%. It should be noted that the Portland Cement Association (PCA) defines hot weather as a range of temperature of 24°C to 34°C [6]. Abdulaziz et al. found that during the summer period RMC batched using chilled water showed temperature increases of 1.1°C and lost 37% of their initial slump value during an average delivery time of 52 minutes [5]. It was also shown that a longer travel time between the batch plant and job site increased slump loss. Figure 2.2 illustrates the ratio of the slump at the batch plant to the slump measured on site [5]. As can be seen from the graph, an increase in slump at the batch plant translated into an increased slump loss at the job site. Also, truck mixing of ingredients compared to central batch mixing had little effect on slump loss [5].

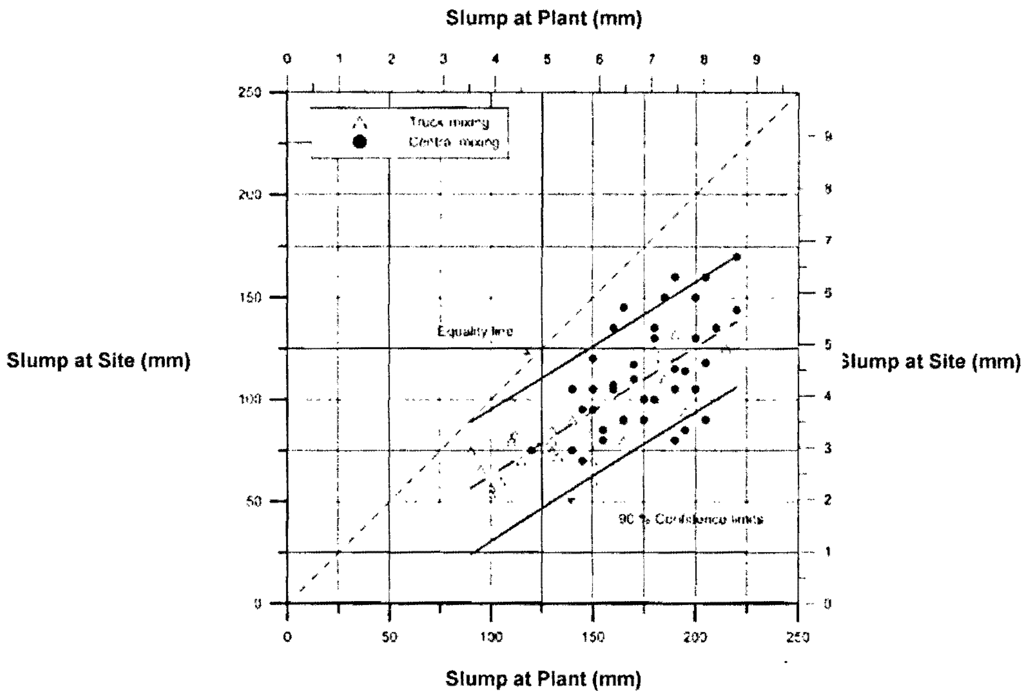


Figure 2.2. Slump at site versus slump at batch plant [5].

There are certain precautions that can be taken at RMC batch plants to lower concrete temperatures and prevent or limit slump loss. They include, cooling the concrete ingredients such as the aggregates or water, batching with ice as part of the mix and the addition of liquid nitrogen to fresh concrete mixes [7]. An empirical study conducted by Mahboub et al. with over 1000 sets of concrete cylinders collected in the Kentucky area produced a model that correlated the combined effects of mix temperature and mix duration on compressive strength [7]. They theorized that long mixing times have been shown to decrease the air content at approximately 2% per hour as well as increase the temperature of concrete by 3.3°C per hour when transported in 32°C ambient temperatures. A concrete mix that is batched at a lower initial temperature will allow for more time in transit before exceeding the 32°C maximum concrete temperature before placement, allowed by the CSA and other concrete regulatory bodies around the world [1].

It should be noted that the principle of slump loss exhibited by ready mix concrete batched in hot weather environments also applies to roller compacted concrete. A paper written by Qasrawi et al. demonstrated the necessity of increasing the water content of roller compacted concrete in order to maintain a required consistency for concrete batched in hot weather environments. It also touched on the necessity of increasing the cement content of a mix in order to achieve a required compressive or tensile strength that could have only been recorded with a lower cement content when batched at a lower temperature. However, an increase in cement content would not come without other added problems and cost to the producer [38].

2.2 - Evaporation

An important factor to consider when batching RMC in hot weather environments is the effect of evaporation on concrete properties. Evaporation of water from RMC during mixing and delivery can lead to a lowered w/c ratio and an increased loss of workability. Evaporation after RMC placement and consolidation can also lead to plastic shrinkage and cracking [2]. When trying to counteract the effects of evaporation by the addition of more water to the mix it is very important to take into account the affects of an increased w/c ratio. An increase in the water-cement ratio will decrease the strength, durability, water tightness, increase the drying shrinkage and have a detrimental effect on other

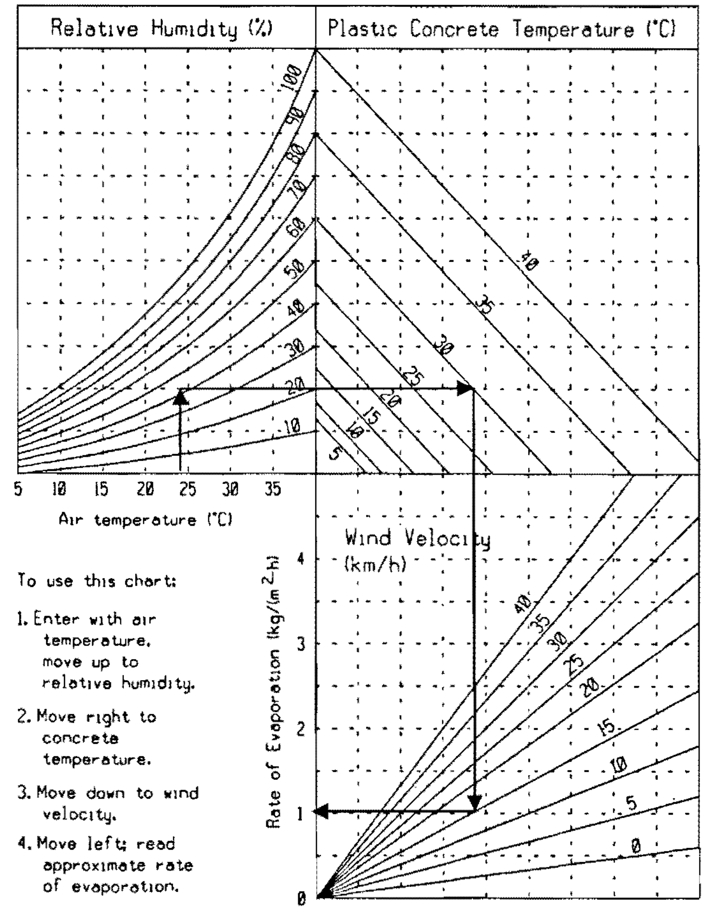


Figure 2.3. Effect of concrete and air temperatures, relative humidity (RH), and wind velocity on the rate of evaporation of surface moisture from concrete.(1)

related properties [1]. As a result, plasticizers are often incorporated in RMC in order to maintain a given slump without the addition of more mix water.

After RMC has been placed and consolidated at the job site, the evaporation rate of the ambient surroundings must be monitored. When the evaporation rate of concrete is expected to reach 1.0 kg/m/hr (0.2 lb/ft/hr), precautions should be taken to ensure adequate and effective curing [1]. Evaporation is caused by a combination of solar radiation, wind velocity, low relative humidity, high ambient temperature and a high concrete temperature [1]. If all the previous listed factors are known the evaporation rate can be predicted using Figure 2.3. This is done by simply drawing a straight line from quadrant to quadrant until a rate of evaporation is determined on the lower y-axis. It should be noted that a small increase in any of the five factors above will cause a substantial increase in evaporation. In order for proper hydration and strength development to occur the internal RH of concrete must be maintained at a minimum of 80% [8].

An increased evaporation rate leads to problems with finishing and drying shrinkage [1]. There have been extensive studies done to determine the most effective ways to cure RMC in adverse hot weather conditions. If proper curing is not undertaken excessive plastic shrinkage and cracking, reduction in strength and an increase in the rate of carbonation, chloride and sulphate ingress are possible [9].

An extensive literature review as well as an experimental program conducted by Alsayed et al. concluded that burlap rewet three times a day produced the highest increases in compressive strength and decreases in permeability when compared to other forms of curing in in-situ hot weather environments [9]. Alsayed et al. also discovered that curing concrete with the use of impermeable membranes, such as vapor barriers, were often detrimental to the curing process as a result of acting as an insulator for the heat generated by hydration and solar radiation [9]. However, as long as the internal RH is kept above 80% and the concrete temperature is minimized, there are other effective methods to cure RMC in hot weather environments, such as fogging in combination with sun and wind sheltering [10].

2.3 - Cement & Heat of Hydration

As mentioned earlier, increases in concrete temperature result in an increased rate of hydration. This occurs partly as a result of the exothermic reaction that takes place when cement is combined with water in the mixing process. The hydration of cement can produce up to 500 joules of energy per gram. However, in concrete the exact production of heat differs for different cement types and contents as well as the temperature at which hydration occurs. Table 2.1 illustrates the differences in hydration heat generated for three different types of cement. As can be seen from the table, the temperature at which hydration takes place greatly influences the rate of heat development. If the

Table 2.1: Heat of hydration developed after 72 hours at varying temperatures [11].

Heat of hydration developed at-

Cement Type	4°C (40°F) J/g	4°C (40°F) cal/g	24°C (75°F) J/g	24°C (75°F) cal/g	32°C (90°F) J/g	32°C (90°F) cal/g	41°C (105°F) J/g	41°C (105°F) cal/g
I	154.0	36.9	285.0	68.0	309.0	73.9	335.0	80.0
III	221.0	52.9	348.0	83.2	357.0	85.3	390.0	93.2
IV	108.0	25.7	195.0	46.6	192.0	45.8	214.0	51.2

temperature of concrete is allowed to rapidly increase, not only will a rapid loss of workability be evident but many other problems such as loss in compressive strength and durability will occur. When batching in hot climates the type of cement used is a very important factor when trying to minimize heat generation and accelerated hydration.

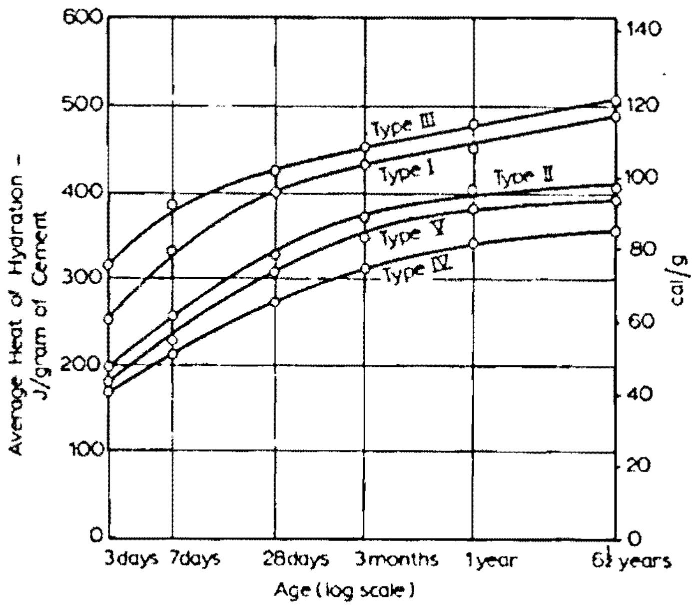


Figure 2.4. Development of heat of hydration of different cements cured at 21°C with a w/c ratio of 0.40 [3].

Figure 2.4 illustrates the average heat of hydration for five common cement types. As can be seen from the graph, the cement type used in a batch plays a very important role in the amount of heat generated and thus the temperature of the concrete mix [11].

In general, when concreting in hot weather environments many things have to be taken into consideration when selecting a cement. Cement consists primarily of four main molecules in varying quantities depending on the cement type; tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF). The cement molecules of C_3A and C_3S hydrate at a much faster rate then C_2S and C_4AF and as a result release heat at a much faster pace. C_3A and C_3S have a heat of hydration of 867 and 502 J/g respectively, as compared to C_2S and C_4AF with heats of hydration of 260 and 419 J/g [11]. The effect that varying heats of hydration of different cement compositions has on the overall concrete temperature has to be known and controlled in hot climates.

When pouring or roller compacting large mass concrete projects or in areas with large diurnal tendencies, it is important that the temperatures developed during hydration are limited to ensure that the temperature stresses developed in the concrete do not exceed its tensile strength, resulting in thermal cracking [12]. Also, it is essential to control the concrete temperature in order to achieve thorough homogenous hydration of the cement paste [13]. Supplementary cementing materials (SCM) as well as chemical admixtures are often considered for use in hot weather environments to aid in slowing down the hydration reaction and thus limiting the heat liberation [3,11,13]. The effects of the above mentioned constituents and their effect on concrete strength, pore structure and volume stability will be examined in further detail in the following sections.

2.4 - Compressive Strength

It is no secret in the construction industry that concrete cast in hot weather conditions requires more attention to curing if the full strength gain of the material is to be achieved. ACI 305 reports that a strength loss of 10 to 15% can occur if a fresh RMC molded test cylinder is exposed to 38°C for the first 24 hours of curing when compared to curing at 23°C. Similarly to controlling workability, the effects of cement type, w/c, mixing duration, mixing temperature, curing procedures, SCMs, chemical admixtures etc. all play an important role in determining the compressive strength of concrete produced in hot weather environments [3,7,11,13]. Also, if high early strengths need to be achieved, extra care must be taken to ensure that the later age strengths are not affected by poorly crystallized hydration products [14].

Mahboub et al. created a strength index representing a comparison of the effects of mix duration and mix temperature on the compressive strength of RMC. The square encapsulated index numbers presented in Figure 2.5 below represent the percentage of compressive strength achieved by field cured samples compared to their lab cured (24°C, 100% RH) counter parts. The graph illustrates that both the mix duration and temperature play a huge role in determining the actual strength of RMC in the field. Longer mix durations combined with increased hydration temperatures contribute to lower compressive strengths [7].

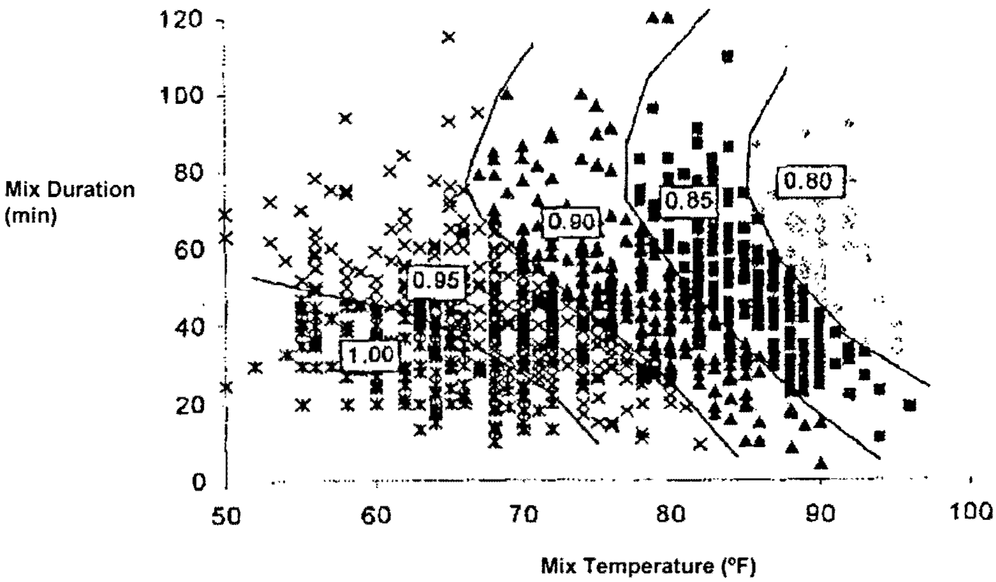


Figure 2.5. Concrete strength index zones [7].

High initial curing temperatures for concrete generally produce high initial compressive and tensile strengths when compared to low temperature curing. This is due to the stiffening effects caused by the increased rate of hydration. These affects are advantageous when working in cold weather environments, where proper curing temperatures are difficult to control, but are avoided when dealing with hot environments.

High initial temperatures can create a reduction in later life compressive and tensile strength as well as elastic modulus due to poor uneven hydration of the microstructure and an increased permeability [3,14,15]. The effect of increased curing temperatures on compressive strength is illustrated in the figure below.

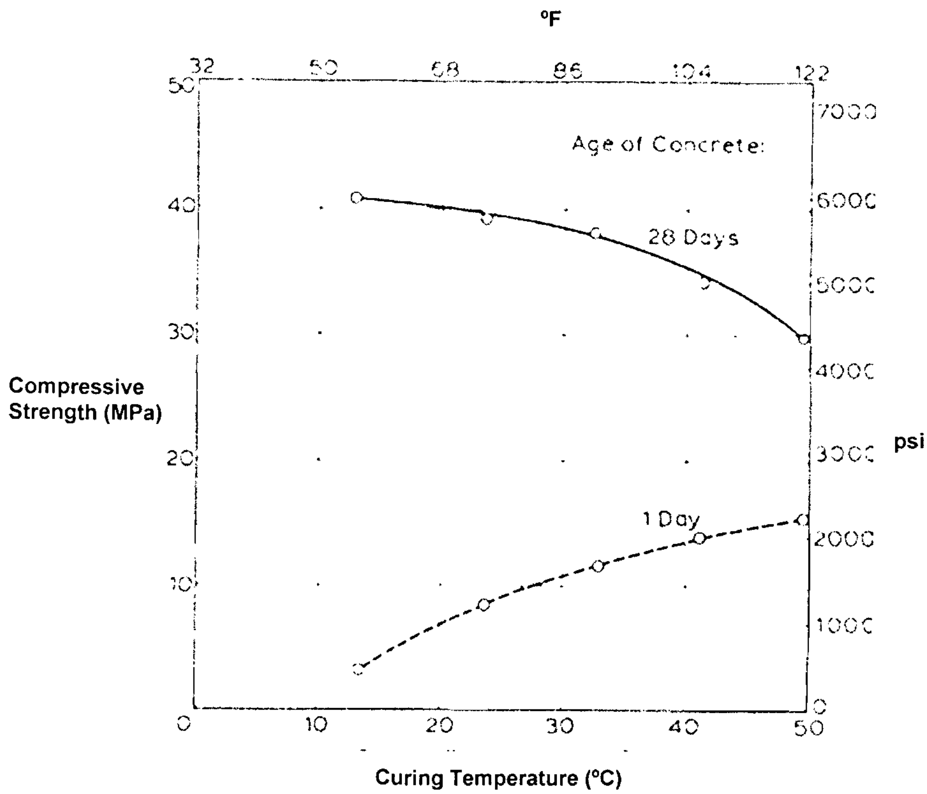


Figure 2.6. Influence of curing temperature on compressive strength at 1 and 28 days [1].

Reductions in compressive strength cannot be fully explained without an investigation into the microstructure of the hydration products of hot weather cured concrete. The importance of maintaining a controlled w/c ratio is essential to maintaining a high compressive strength [16]. If the water content is increased in an effort to achieve a higher workability the concrete will have a higher porosity leading to a lower compressive strength [4]. Through a SEM study of concretes batched with an increased water content to counteract the slump loss of 50 °C ambient temperature, Mouret et al. showed that an increase in water quantity produced an increase in the calcium hydroxide (CH) content in the aggregate-paste interfacial transition zone (ITZ). The presence of well developed CH crystals at the ITZ were the result of the sustained hydration of the calcium silicate phases, made possible by the excess of mix water. The small specific surface area as well as the laminar growth of these crystals were predicted to weaken the ITZ and thus lower the compressive strength of the concrete [16]. In another SEM study by Mouret et al. a large concentration of ettringite rods were also visible in the vicinity of the aggregates. It was predicted that the crystal growth was made possible due to the open microstructure formed at elevated curing temperatures [17].

A study by Ortiz J. et al. found that the most important factors affecting the compressive strength of RMC were the temperatures of the concrete, the ambient temperature and the difference between the two. It was concluded that when dealing with hot weather environments it is better to batch concrete at the end of the day in order to avoid thermal ramping of peak hydration temperatures. When cement is hydrated at a higher temperature, "a faster and non-uniform precipitation of the hydration products, makes the structure more disordered and microstructure development is more heterogeneous and less compact; reflected in minor strength increases over time "[18]. Furthermore, if during the early days of hydration the concrete temperature increases rapidly, thermal stresses can be created that exceed the tensile strength of the fresh concrete. If this occurs, micro-cracking of the hydration products can transpire leading to increased porosity, cracking and a reduction in compressive strength [18]. However, it has been proven that temperature increases at ages later then 3 to 7 days have little effect on the ultimate later age strength of RMC [19].

An important fact that should be taken into account when designing a concrete mix for a hot environment is that the maturity method does not always produce accurate early and later age strengths. The maturity concept proposed by Saul and later put forth as a function based on the Arrhenius equation by Freisesleben and Pederson, was designed to work with concrete cured in an isotherm environment [20,21]. A study put forth by Kim J. et al. showed that concrete samples cured for a 28 day period at 20°C but exposed to a 1 day 40 °C cure at varying times for each sample produced different compressive strength results [19]. Although all samples had the same theoretical strength result when calculated using the maturity function, the varying time at which a high temperature cure was applied had a anecdotal effect on the compressive strengths.

2.5 - Supplementary Cementing Materials

SCMs are widely used in the construction industry today. Fly ash (FA) and ground granulated blast furnace slag (GGBFS) will be tested in this program with their effects on hot weather concreting investigated. A review of each of their performances in hot weather concreting will be presented.

2.5.1 - Fly Ash

When used in conjunction with Portland cement (PC), fly ash can have both beneficial and detrimental affects on the properties of concrete cured in hot weather. Its rate of hydration and hydration products have an effect on many concrete properties including; compressive strength, permeability and durability [3,11,13,22-24].

Blended cements containing FA are widely known to hydrate and develop strength much slower then pure Portland cement [11]. The slower hydration process results in a lower release of heat and the development of a more homogenous microstructure. This is mostly due to the pozzolanic reaction that FA ions undergo when in contact with PC [23]. As a result, curing must take place over a longer time period or the strength and durability will be diminished when compared to PC concrete. However, if ample curing is applied to fresh blended concrete, generally considered to be 7 days, strength and durability related properties can be greatly increased in hot weather environments [23]. Haque et al. conducted a study comparing pure PC mortar to a 0.3 ratio FA/PC blend. Specimens were moist cured at 23°C and 100% RH for 1, 7 and 28 days before being exposed to either 43°C, 20% RH or 23°C, 40% RH conditions for an extended period of time. Table 2.2 and 2.3 illustrates the compressive strengths of specimens developed after 1 and 7 day initial moist curing followed by exposure to hot weather conditions [37].

Table 2.2. Effect of a hot-dry environment (45°C + 20% RH) on the strength of fly ash-cement paste cubes (after 1 day of fog curing) [37].

	Strength, Mpa				Strength ratio, percent					
	Age				Specimen / Reference				Actual Curing/ fog curing	
	29 days		91 days							
Mix designation	1 + 27 days	28 + 0 days	1 + 90 days	91 + 0 days	1 + 27 days	28 + 0 days	1 + 90 days	91 + 0 days	28 days	91 days
PC	62 1	115 2	60 6	119 0	67	78	81	95	54 0	51 0
PC/FA	41 4	89 5	49 0	112 9					46 0	43 0

Table 2.3. Effect of a hot-dry environment (45°C + 20% RH) on the strength of fly ash-cement paste cubes (after 7 days of fog curing) [37].

	Strength, Mpa				Strength ratio, percent					
	Age				Specimen / Reference				Actual Curing/ fog curing	
	35 days		98 days							
Mix designation	7 + 28 days	35 + 0 days	7 + 91 days	98 + 0 days	7 + 28 days	35 + 0 days	7 + 91 days	98 + 0 days	35 days	98 days
PC	64 6	124 6	64 1	126 2	104	79	106	92	52 0	51 0
PC/FA	67 2	98 4	67 7	116 1					68 0	58 0

When samples were moist cured for 1 day followed by hot weather conditions degradations in strength were visible for both PC and FA-PC samples. The degradation was however, less prominent in the FA-PC specimens. When the specimens were moist cured for 7 days the FA-PC mortar specimens showed superior strength development to those of plain cement in both hot weather and temperate curing conditions. The results substantiate the need for adequate 7 day curing when batching using a FA blended cement. However, they also illustrate the strength improvements possible when concrete batched with FA is exposed to high temperature environments [37].

In hot environments or large mass concrete structures, FA is added to concrete to slow down the hydration reaction and to improve the microstructure of the hardened concrete. The heat evolved in PC concrete during hydration can be enough to cause plastic shrinkage cracking and thermal cracking. The addition of FA reduces the heat evolved during hydration, helping to prevent these detrimental effects and improve the paste microstructure as a result of grain and pore refinements [24].

FA's primary hydration reaction occurs when amorphous silica reacts with calcium hydroxide (CH) formed from the hydration of calcium silicates [24]. This reaction causes a net reduction in the quantity of CH in the pore solution and an increase of calcium silicate hydrate (CSH), leading to a more homogeneous less permeable microstructure as can be seen in Figure 2.7. Also, solutions rich in silica from the FA, hydrate with the CH layers formed around the aggregates to produce less permeable and stronger interfacial transition zones [3]. This reduction in porosity helps reduce diffusion of harmful molecules and ions through the concrete paste such as chlorides, sulphates and CO2. It also helps to increase later age compressive strengths.

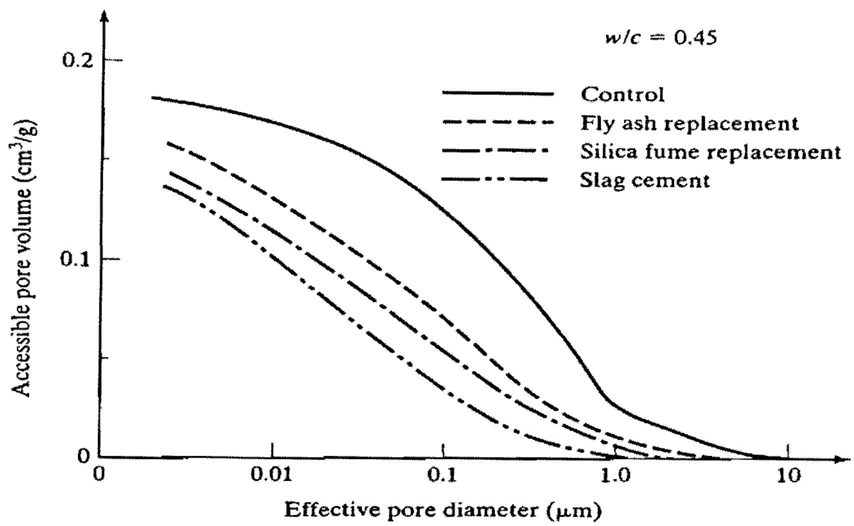


Figure 2.7. Effect of SCMs on properties of fresh concrete [5].

The addition of most FA's to RMC mixes allows for increased workability and a lower w/c ratio when compared to PC concrete. FA also has the ability to sustain this increased workability over a longer mix cycle in hot weather conditions then most chemical admixtures. This is partly due to the retarding effect it has on the hydration of cement through dilution and pozzolanic reactions as well as the round morphology of the FA particles. This is especially important for hot weather concreting where slump loss and increased addition of water is a common problem [3]. A study by Soroka et al. found that the use of FA blended cement out performed combinations of FA, water reducers and plasticizers in maintaining slump over a 180 minute mixing cycle at 32°C.

An ancillary benefit of using blended cement in RMC is the reduction of CH in solution leads to a reduction of expansion caused by alkali dependent attacks. Limiting the

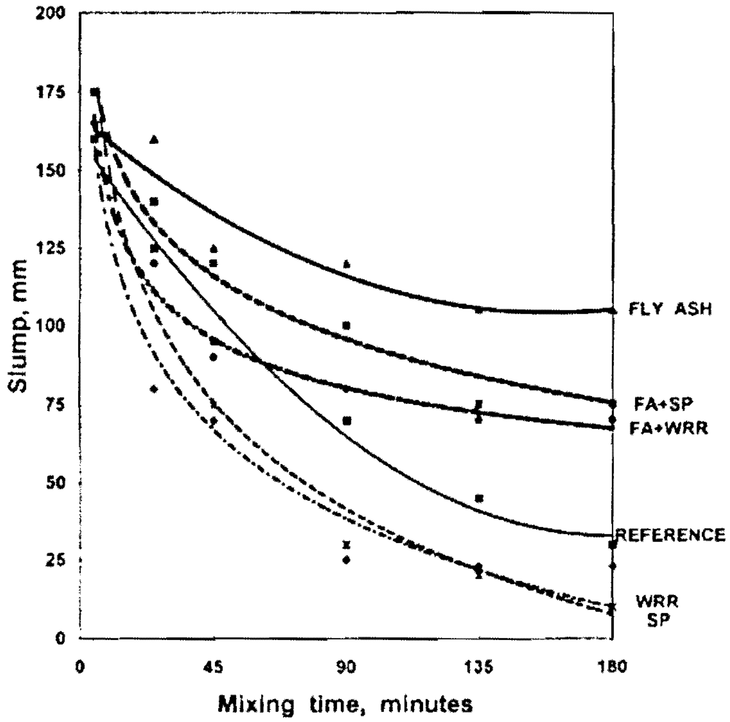


Figure 2.8. Slump loss of concrete with and without fly ash and with and without a water-reducing and retarding admixture or a superplasticizer after prolonged mixing at 32°C [31].

availability of alkalis in solution such as CH, limits the ability of silica and carbonate, from reactive aggregates, to form an expansive gel in the ITZ. ASR and ACR accelerate with the addition of heat, FA helps limit them by reducing the amount of heat that is produced during hydration as well as by limiting the reaction products available [3,11].

Sulphate attack is a prominent issue in many hot climatic regions around the world. Another ancillary benefit of using FA in concrete batched in hot environments is its increased resistance to sulphate attack. FA helps to control sulphate attack through a reduction in ettringite formation in a number of ways. The first method of control comes as a result of a reduction of permeability and porosity. This limits the ingress of harmful sulphate ions into the pore solution. The reduction of CH also helps to lower the formation of gypsum, necessary for ettringite formation, from soluble sulphates. Also, the use of FA reduces the C3A content, a necessary constituent of ettringite formation.

However, it should be noted that not all FA's help to prevent sulphate attack to the same extent. High calcium FA's don't consume as much CH in solution due to the availability of lime and some FA's are high in alumina contents and can lead to the formation of more ettringite [3].

2.5.2 - Ground Granulated Blast Furnace Slag

Similarly to fly ash, partial replacement of cement with ground granulated blast furnace slag (GGBFS) has the ability to produce stronger and more durable concrete in hot climates. However, a disadvantage of the use of GGBFS is that it also makes concrete mixes more sensitive to poor curing then ordinary PC concrete. If proper curing is not applied to a freshly placed concrete containing GGBFS, strength, permeability and durability can be seriously impaired. Although, it has also been concluded, that as long as adequate curing is provided an increase in temperature can benefit the formation of strength and durability [25].

GGBFS is produced as a by-product of metal smelting. It consists mainly of quenched amorphous glasses of lime, silica, alumina and magnesium. When pure 100% slag cement comes in contact with water it undergoes a slow hydraulic reaction that can take months to produce an equivalent 28 day strength to ordinary PC. However, when slag is blended with PC the alkaline compounds formed during PC hydration act as a catalyst drastically increasing the rate of hydration of GGBFS [3,11].

The hydration of slag blended cements depends on the formation of alkali compounds, specifically CH. GGBFS improves the microstructure of concrete exposed to high temperatures by slowing the hydration reaction of PC and transforming surplus alkalis into a mixture of CSH and hydrated alumina phases. The CSH formed by the hydration of slag has a lower calcium-silica (C/S) ratio then that formed by PC. As a result, it undergoes a pozzolanic reaction that slowly consumes the CH in solution until the C/S has reached a stable value between 1.5 and 2.0, leading to a further refinement of pore structure [11].

Slag blended cements have a lower heat of hydration then ordinary PC. The hydration rate is similar in energy released to the hydration of dicalcium silicate. The lower generation of energy and refinements in pore structure all contribute to increased strength and durability when blended slag cements are used in hot weather environments [3,11].

Similarly to FA, refinements in pore structure as well as the reduction of CH in the microstructure and pore solution leads to improved sulphate, carbonation and chloride resistance. Slag blended cements are also known to marginally reduce the susceptibility of aggregates to alkali silica and alkali carbonate reaction [3].

The extent to which GGBFS increases the strength of concrete is dependent on the slag activity index, the percentage used, the w/c ratio, the type of PC and the curing conditions [26]. A study by Gowripalan et al. found that a 70% blended GGBFS cement had a lower permeability when cured at 35°C then at 21°C [27]. Percentage replacements of PC up to 90% will produce varying pore structures in hydrated cement. Depending on the application, curing performed and concrete temperature, a proper mix has to be selected for varying conditions.

A study performed by Austin et al. tested the effect of five common curing methods on the performance of slag blended cement cured in simulated Algerian Sahara arid environment. Various percentages of GGBFS were used as a cement replacement in concrete to test their effects on strength and durability. Wet burlap curing produced the highest compressive strengths at 28 days for all specimens tested [25]. An example of a 50% GGBFS blended cement is presented in Table 2.4.

Table 2.4. Mean compressive strength for cubes and cores consisting of ordinary Portland cement (OPC) or 50% ground granulated blast furnace slag (GGBFS) blended cement [25].

Mix	*Curing method*	*Cube strength*						*Core*
		7 days compressive strength (N/mm²)	*Relative strength (%)**	*14 days compressive strength (N/mm²)*	*Relative strength (%)**	*28 days compressive strength (N/mm²)*	*Relative strength (%)**	*28 days compressive strength (N/mm²)*
Hot conditions								
OPC	Air	32·7	65	34·1	68	35·3	70	33·5
	Burlap	37·4	74	47·3	94	49·8	99	38·2
	Polythene	36·0	72	39·3	78	44·5	89	37·1
	Membrane	31·6	63	37·1	74	40·9	81	37·7
GGBFS	Air	22·9	46	24·5	49	26·0	52	29·9
	Burlap	35·8	72	43·5	87	53·0	106	40·1
	Polythene	33·5	67	41·3	83	47·2	97	40·5
	Membrane	32·7	66	40·4	81	44·4	89	38·0
Temperate conditions								
OPC	Air	31·4	62	34·7	68	36·5	72	35·1
	Burlap	32·9	65	45·4	89	51·6	102	41·6
	Polythene	30·5	60	36·1	71	43·7	86	—
	Membrane	29·1	57	34·9	69	41·0	81	—
GGBFS	Air	18·9	38	22·0	44	25·1	50	31·4
	Burlap	25·0	50	33·1	66	45·7	91	42·1
	Polythene	22·1	44	31·0	62	39·1	78	—
	Membrane	21·2	42	30·5	61	37·2	74	—

*Strength expressed as a percentage of the 28-day 20°C water-cured cube strength.

The program found that 50% replacement of PC with GGBFS, designed for equal workability produced the most improvements in simulated hot arid environments when proper curing was utilized. Improvements in strength, permeability and absorption were all seen when compared to a 100% PC concrete cured under the same conditions. However, it was also concluded that although slag blended cements produced the best results in hot curing environments, their slow rate of hydration at temperate temperatures failed to produce an improved concrete in comparison to PC concrete at lower temperatures. This fact is also evident in Table 2.4 [25].

A study by Roy et al. also made a similar conclusion about the use of slag in blended cements [28]. Mercury porosimetry and SEM testing of blended cements cured at temperatures above 30°C produced a finer pore structure, as well as a lower total cumulative pore volume. As can be seen in Figure 2.9 a 60% blended slag cement

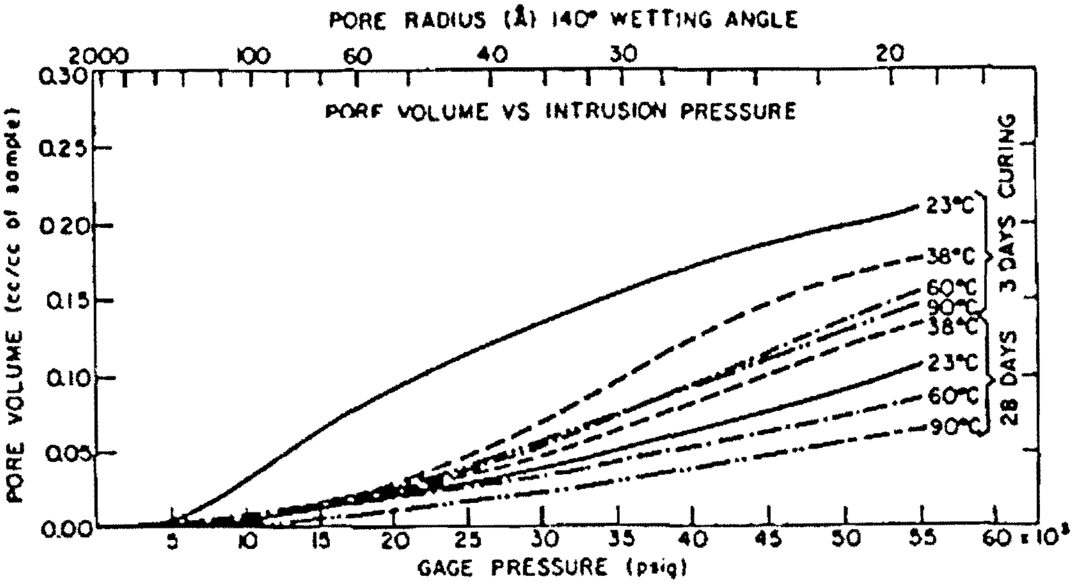


Figure 2.9. A comparison of differential pore radius for a pure Portland cement, a 60:40 weight proportion slag/cement mixture [28].

demonstrated reduced pore radius, and total pore volume for increases in curing temperature and time at elevated temperature. Notable increases in compressive strength were also observed for high percentage slag mixes cured at sustained elevated temperatures [28].

2.6 - Admixtures

There are countless chemical admixtures available for use in concrete today. However, the two forms of admixtures that are most commonly used in hot environments are set-controlling admixtures (ASTM C494) and plasticizing admixtures (ASTM C494 & C1017) [3]. A review of their behavior and mechanism will be presented in the following section.

Plasticizing admixtures can be separated into three categories; low-range water reducers, mid-range water reducers and superplasticizers (high-range water reducers). Low-range water reducing admixtures impart a 5-10% reduction in batch water to achieve the same slump of a reference mix. Mid-range water reducers function best in the slump range of 125-200mm and superplasticizers can achieve 12-30% water reductions. Superplasticizers are used frequently to produce high-strength concrete with very low w/c ratios [3]. They are also effectively used in high temperature concrete to maintain high slump levels without increases in water content.

Plasticizing admixtures are negatively charged organic molecules that absorb mostly at the solid-water interface. This imparts like charges on cement particles creating electrostatic repulsive forces in solution, aiding in the deflocculating of the mix. This repulsive force helps to maintain or increase the slump value of mixes even in hot weather conditions leading to their common use in high temperature environments [3].

Set controlling or retarding admixtures are used to offset the effects of high temperature curing and long delays between batching and placing that result in a decrease in setting time. They prolong the induction period during the initial set, allowing time for the development of a homogenous microstructure under high temperature conditions [3]. Retarders are thought to work in one of two ways; the absorption theory suggests that retarders absorb on the surface of anhydrous cement grains through ionic, hydrogen or dipole bonding and prevent water from reacting with the cement and the precipitation theory suggests that retardation occurs by the formation of an insoluble layer of calcium salts on the hydration products of cement [29,30,31].

There are approximately five main categories of chemical admixtures used in hot climates. They include[32]:

- Lignosulphonates
- Hydroxycarboxylic acid
- Phosphate/ Hydroxycarboxylic blend
- Naphthalene sulphonate formaldehyde polymer
- Melamine sulphonate formaldehyde polymer

Each admixture has its own advantages and disadvantages in its ability to increase plasticity and prolong set which will be described below [32].

- Lignosulphonates:

  Can impart effective plasticizing action in combination with water reduction creating increased workability. This is achieved by the polar ends of the lignosulphonate molecules being absorbed on the cement particle resulting in electrostatic repulsion of cement particles.

- Hydroxycarboxylic acid

  Give marginally greater increases in workability at fixed water contents then lignosulphonates, however, they do not provide good workability retention. They have also been shown to retard the setting time of concrete mixtures. Consist of organic chemicals which have both hydroxyl and carboxyl groups in their molecules. Generally in the form of sodium, ammonium or triethanolamine salts.

- Phosphate/ Hydroxycarboxylic blend

  When used in concrete cast in hot environments high dosage levels have to be used to achieve the required workability and degree of workability retention. The high dosage rates used increases the set retardation in a non-linear relationship. They consist of a blend of both hydroxycarboxylic acids and phosphates and are generally used in hot climates where set retardation is more important then increased workability.

- Naphthalene sulphonate formaldehyde polymer

  Used in admixtures to produce products known as superplasticizers. They are added to concrete mixes to encourage large increases in workability and large reductions in w/c ratios without having a retarding effect. They are commonly used in high temperature environments where an increased rate of hydration results in a high level of slump loss.

- Melamine sulphonate formaldehyde polymer

  Also used to form superplasticizing admixtures however, can also be blended with hydroxycarboxylic acids or lignosulphonates to impart water reducing and retarding qualities to a concrete mix. When used on its own, it has very little retarding qualities however, can impart increased slump loss when used at high temperatures in comparison to naphthalene based admixtures.

The practical considerations that determine the usefulness of a plasticizer or a retarder depend on its efficiency at minimum dosage in achieving the required increased workability or set retardation. It also depends on the dosage range of each that can be used without adversely affecting the retardation, physical and chemical durability aspects of concrete and that can be easily dispensed and used economically [33]. When casting concrete in hot weather environments the ambient temperature and concrete temperature have to be taken into account when selecting the appropriate plasticizer or retarder for use. This is a result of all retarders extending the induction period at varying dosages and temperatures to different extents.

A study by Ramachandran et al. investigated the use of eleven potential retarders in combination with mortar having a w/c ratio of 0.5. A calorimetric study of the hydration of mortar samples at room temperature over 72 hours demonstrated the varying effects retarders had on the induction period. All retarders were found to increase the induction period by 4 to 55 hours at dosages generally less then 0.15%. This large range in the extension of the induction period illustrates the need to properly select a retarder for use in hot weather environments. If too powerful a retarder or too high a dosage is used the set of concrete can be delayed for an extensive period leading to plastic shrinkage cracking and other durability issues or set can be prevented altogether [33].

Although there can be some side effects with the use of retarders, overall when used in a controlled manner they have a positive effect on the compressive strength of concrete cast in hot environments. A study conducted by the Research and Development

Laboratory of ShawCor Limited demonstrated that the retarders, sodium gluconate and sucrose batched in a standard ASTM C109 mortar at 0.05 and 0.1%, produced compressive strength increases of 10% on average when cured at 100% RH and 35ºC. Similarly, the same dosages of retarders also produced significant strength gains in mortar when cured at 55ºC [36]. The compressive strength results of mortar tests cured at 35 ºC are presented below.

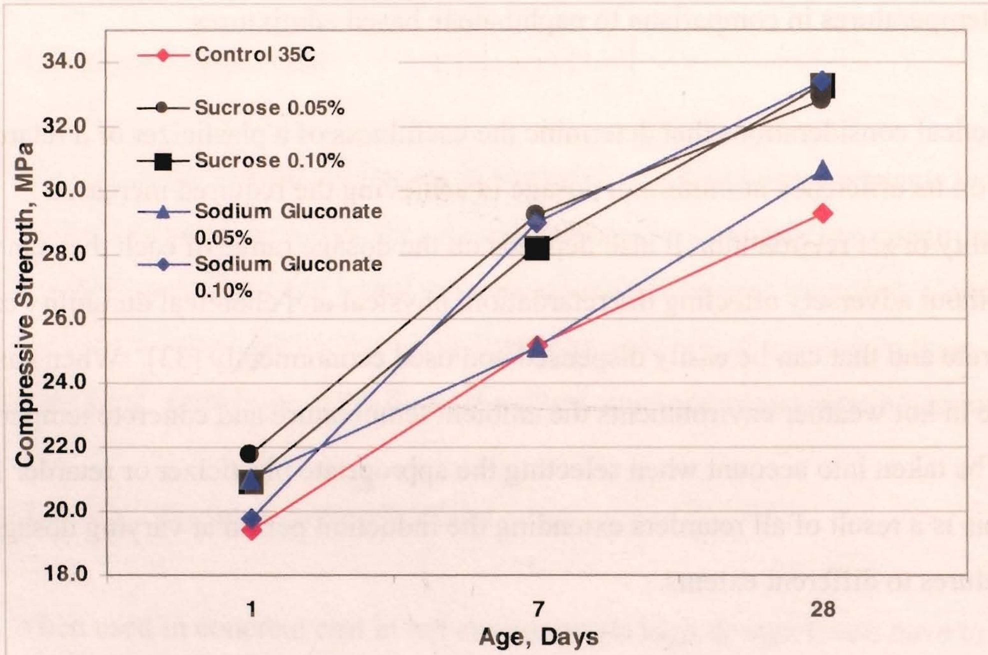


Figure 2.10. Effect of sodium gluconate and sucrose on the compressive strength of mortar cured at 35ºC & 100% RH [36].

Another concern that should be considered when using chemical admixtures in hot environments is the phenomenon of increased slump loss. Slump loss in the early stages of batching is thought to mainly occur as a result of the interaction of calcium sulphate with the aluminate phases of cement. The use of a chemical admixture can upset the balance between the tricalcium aluminate and soluble sulphate phases of PC resulting in mild or severe flash setting. This causes rapid loss in workability, or slump loss. Increased contents of gypsum can be used to offset some of these qualities however, the use of more gypsum raises the potential for long term expansion associated with sulphate attack [34].

A study by Soroka et al. found that the use of water reducing retarders actually increased slump loss rather then decrease it when the concrete mix was constantly agitated [31]. ASTM type D and G admixtures were both shown to increase slump loss in hot environments as can be seen in Figure 2.11. All three type D admixtures used

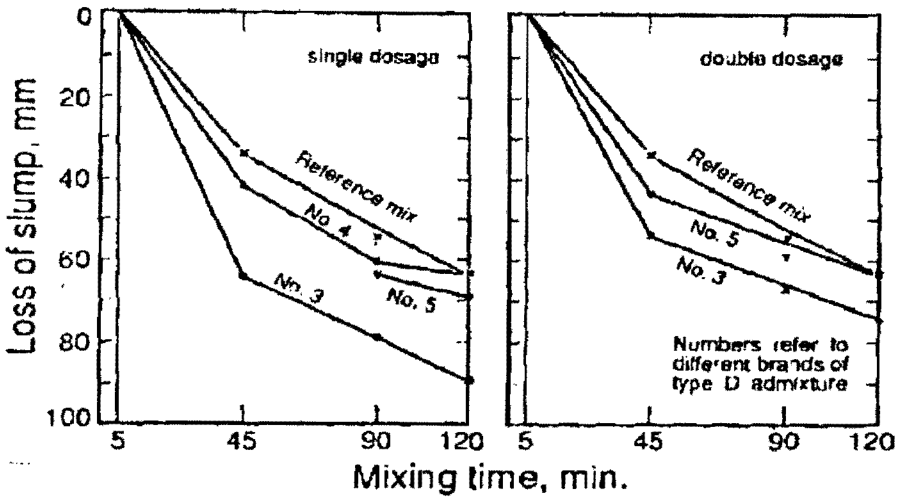
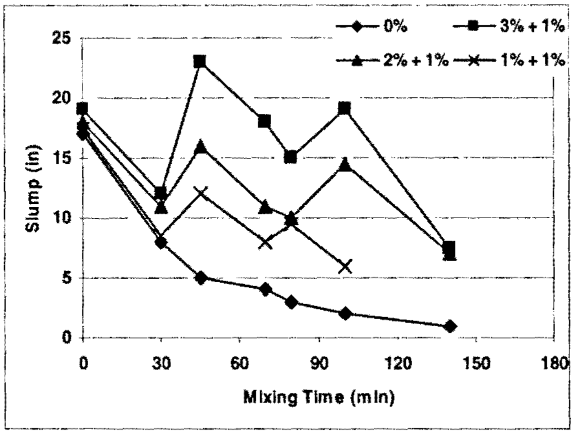


Figure 2.11. Effect of type D admixtures on slump loss. (Initial slump 95-115mm, temperature 30°C. (31)

increased the rate of slump loss over sustained agitation at 30°C. It is hypothesized that when concrete is kept continually agitated the insoluble layer of calcium salts of the retarder are slowly warn away allowing hydration to continue. Since the admixture imparts a reduced water content in the mix, the cement particles have a smaller solids spacing factor and thus hydration products are likely to more rapidly bridge between cement particles leading to lost workability. Retarders were also shown to increase the rate of plastic shrinkage cracking in most specimens cured at high temperatures. This was a result of increased evaporation at the surface coupled with a slower development of tensile strength [31].

Plasticizers can be used to retemper concrete mixtures that have lost a substantial level of workability over their delivery time [30]. A study by Ravina and Mor demonstrated that increased dosages of plasticizers, exceeding the manufacturers recommendations, should be used when long delivery times (<30 minutes) are to be expected [35]. They also found that incorporating the plasticizers either initially on site or retempering with more on site produced substantial gains in slump that were able to over come losses in workability due to long mixing times and increased mixing temperatures. Figures 2.12 & 2.13 illustrate the slump gains possible when plasticizers are added initially and then used to retemper at varying times over the mix cycle [35].



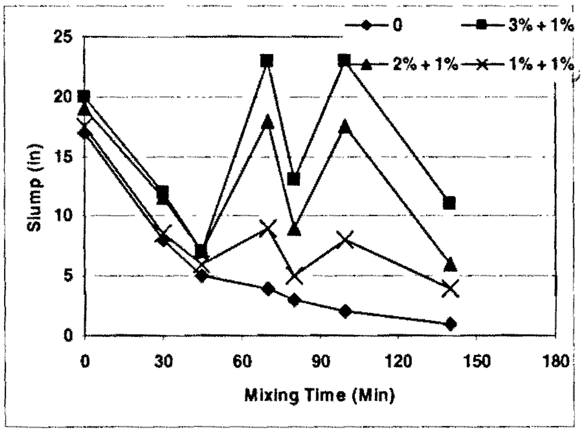


Figure 2.12. Slump pattern with repeated additions at 30 & 70mins. Figure 2.13. Slump pattern with repeated additions at 50 & 90 mins.

The study was able to conclude that prolonged mixing at high temperatures intensifies the formation of hydration products, such that a plasticizer will have little affect below a certain dosage. However, secondary additions of small doses do have a large effect on slump when batches are first mixed with medium to high dosages of plasticizers [35].

Retarders and plasticizers have been used extensively in the concrete construction industry for many years. However, the above brief review illustrates that there are many factors that have to be considered before selecting the proper admixture, dosage, time of dosage and method of dosage. These concerns also apply to manufacturing high performance ready mix concrete, and an extensive lab test program must be carried out to evaluate the use of any admixture before it is put into routine service.

2.7 - Conclusion

As can be seen from the above literature review on concrete principles batched and cast in hot climates, a lot of information is in existence on how to mitigate strength and durability loss of RMC as a result of high temperatures. This literature review was used to design a comprehensive test program for ameliorating the strength and durability losses of high performance RMC and RCC cast in hot weather environments. Proper curing practices, mineral and chemical admixture selections and dosage rates were all selected based on influences from previous research. The results of a test program performed on high temperature, low and high slump, concrete will be presented in the following sections.

Chapter 3
Experimental Details and Materials

3.1 - Phase I: Experimental Procedures, Mortar

3.1.1 – Objectives

To investigate the efficacy of using various raw cement hydration retarders at elevated temperatures at early curing ages. As an ancillary benefit, it was also investigated whether the three retarders tested could reduce the water demand and high cement contents that would otherwise be necessary to achieve target compressive strengths in hot and humid environments.

All testing was performed using a Type I/II moderate sulphate resisting Portland cement acquired from Lafarge North America. This cement was selected as a result of its wide use in arid and tropical climates around the world. The chemical composition for the cement can be viewed in Section 3.5.1.

Testing of mortar cubes was performed prior to large scale concrete batching in order to narrow the scope of the retarder type and dosage selection. Sucrose, Sodium Gluconate and Corn Syrup were selected for mortar testing based on their simple defined structure. These three chemicals are common ingredients in many proprietary retarders and water reducers. It was hoped that by testing these in their pure form it would give an indication of which direction should be taken for larger concrete batching. Testing the compressive strength of the mortar cubes consisted of several steps that will be explained next.

3.1.2 - Preparation of Retarder Solutions

Prior to preparing 20% solutions of the retarders, the solids content of each was measured according to the procedure in Appendix D. Solutions of Sucrose, Sodium Gluconate and Corn Syrup were prepared according to Table 3.1. 20% solutions were chosen to obtain good solubility of the admixtures.

Table 3.1. Preparation of retarder solutions.

Compound	Concentration (% Solids)	Preparation Method
Sucrose	20%	(50 grams/solids content*) were dissolved in 250 mls of distilled water.
Sodium Gluconate	20%	(50 grams/solids content*) were dissolved in 250 mls of distilled water.
Corn Syrup	20%	(50 grams/solids content*) were dissolved in 250 mls of distilled water.

*The raw materials contained some water. Only the solids were considered when preparing the solutions.

3.1.3 - Preparation of Batching Equipment

Curing was performed at temperatures of 23, 35 and 50°C at 100% RH (According to the schedule presented in Table 3.2). For tests above room temperature, all materials required for the batch (ie. cement, water and sand) had to be weighed and conditioned for several hours prior to testing in suitable air tight containers contained within an oven. The mixing bowl, mixing paddle and moulds were also conditioned at the same temperature as the materials.

1. When testing was set to begin, one set of materials was removed from the oven and temporarily placed in a foam lined container followed by the mixing bowl and paddle.
2. All materials were covered and transferred to the batching area.

3. Just prior to commencing batching, the bowl and mixing paddle were removed from the foam container and installed on the small Hobart mixer.

3.1.4 - Batching Procedure

Mixing was conducted according to ASTM C109 and mortar sufficient to mould nine 50 mm cubes was mixed during each batch. The mortar was batched with a cement to sand ratio of 1:2.75 and the mixing procedure utilized is presented next.

1. After the mixing bowl and paddle were installed on the mixer, water followed by the appropriate amount of retarder was added to the bowl with a 5 ml syringe.
2. The mixer was then switch on at a slow speed for 10 seconds to disperse the retarder.
3. The standard mixing procedure of ASTM C305 was then followed for all remaining steps. With the one exception that all materials were stored in a insulated container until utilized in the mix.
4. Initially batches of mortar were mixed at 23°C without admixtures in order to establish the water demand for the reference mortar. The w/c ratio necessary was determined through the use of a flow table. Measurement of flow was conducted utilizing the procedure presented in the next section. The w/c ratio was modified in order to establish a flow of 100+/-10%. Once this w/c ratio was established it was maintained throughout testing in order to limit variables and make the results comparable.
5. Batches of mortar suitable were mixed according to the schedule presented in Table 3.2. After compressive strength testing had been completed, the optimum dosages of each admixture had their batches repeated.

Table 3.2. Batching and curing schedule for Phase I of the test program. Each X represents one batch of 9, 50 mm mortar cubes.

Retarder	Dosage % w/w*	Initial 24 Hour Curing Temperature			
		23°C	35°C	50°C	Comments
Control		X	X	X	Batches repeated twice.
Sucrose	0.05		X		Optimum dosage repeated twice
	0.1		X	X	
	0.15			X	
	0.2			X	
Sodium Gluconate	0.05		X		Optimum dosage repeated twice
	0.1		X	X	
	0.15			X	
	0.2			X	
Corn Syrup	0.05		X		Optimum dosage repeated twice
	0.1		X	X	
	0.15			X	
	0.2			X	

* additive solids relative cement

3.1.5 - Mortar Flow Measurement

1. A mortar flow table meeting the requirements of ASTM C230/C230M was utilized for all flow testing.
2. Prior to testing, the flow table was first wiped down with a wet rag and allowed to air dry.
3. The flow mould was placed in the middle of the table and mortar was added in two lifts and compacted 20 times for each lift.
4. Once the mould was filled, the mortar was cut to a plane surface by drawing a small triangular hand trowel down the centre of the mortar surface. This procedure was repeated with a sawing motion 3 to 4 times or until a smooth clean surface flush with the top of the mould was obtained.

5. The steel mould was then carefully removed and the table was dropped through a height of 12.5 mm, 25 times over a period of 15 seconds.
6. The diameter of the mortar was then measured in four locations using a standard mortar caliper and recorded on the batch summaries presented in Appendix A.
7. All mortar flow testing was completed according to the standard procedures of ASTM C1437.

3.1.6 - Specimen Moulding and Curing Procedures

1. All cube moulds were assembled and sprayed with a release agent prior to mortar moulding.
2. Each mix design required nine sample cubes; three moulds per mixture.
3. For each cube, two lifts of mortar were compacted with 32 tamps each according to the standard compaction procedure of ASTM C109.
4. When tamping was completed, the surface of the mortar extended slightly above the top surface of the moulds. A trowel was then drawn across the surface of the moulds in a sawing motion.
5. The excess mortar was scraped from the trowel and then drawn across the surface of the mould in the opposite direction.
6. This procedure was repeated 3 to 4 times or until a smooth surface, flush with the top of the moulds was established.
7. Care was taken to ensure that the cubes were not over finished and bleeding did not occur.
8. Immediately after the cubes were moulded and finished, they were placed in 6 mil polyethylene bags lined with a layer of water saturated rags.
9. The bags were then tightly closed via a zip lock and placed in an oven at the predetermined batch and cure temperature.
10. Care was taken to ensure damage to the bags did not occur so that they would remain air tight during the 24 hour high temperature curing period.
11. All specimens were cured for an initial period of 24 hours at either 23, 35 or 50°C and 100% RH according to the batch schedule presented in Table 3.2.

12. After the initial 24 hour curing period the cubes were removed from their moulds and placed in a curing room (maintained at 23+/-2°C and 100% RH) for their allotted curing time.
13. The compressive strength of three cubes from each batch were determined at 24 hours, 7 days and 28 days according to procedures outlined in ASTM C109.

The data summaries for all information relating to casting, measuring and testing the mortar test specimens can be found in Appendix A.

3.2 - Phase IIa & IIb Experimental Procedures

3.2.1 - Objectives

To investigate the efficacy of using chemical admixtures and various supplementary cementing materials at elevated temperatures. Specifically, the strength development of concrete having a slump of 100 mm was compared with dry mix concrete (roller compacted concrete) when the mixing and curing temperatures for the first 1 to 3 days were 23, 35 and 50°C. The objective was also to determine whether the two types of concretes differ in their susceptibility to the effects of high initial temperatures at early and later ages.

For Phase IIa, increases in batching temperature lead to increases in water content to maintain a constant consistency. As a result, it was investigated if the reduction of strength loss was solely dependent on the reduction of the increased water cement ratio at high temperature. In particular, a polycarboxylate-based high range water reducer (Commercial Material #1 or HRWR), an aqueous solution of lignosulfonate and compound carbohydrates, water reducer and retarder (Commercial Material #2 or WR-Ret. Adm.) as well as the retarder and water reducer Sodium Gluconate selected from the first portion of the study were tested in ready mix batches. The performance of concrete containing Class C and Class F fly ashes and ground granulated blast furnace slag was also investigated.

For Phase IIb of this program, the performance of the SCMs mentioned in the previous paragraph were evaluated exclusively in roller compacted concrete mixes. The same early high temperature ranges were utilized so that the results could be compared.

All testing was performed using a Type I/II moderate sulphate resisting Portland cement acquired from Lafarge North America. The chemical composition for the cement can be viewed in Section 3.5.1, along with the chemical composition of all SCM's utilized. Also, the technical data sheets for the raw chemical admixtures can be found in Appendix J.

3.3 - Phase IIa: Experimental Procedures, Ready Mix Concrete

3.3.1 - Material Testing

Prior to batching, all materials had their physical properties determined.

The concrete sand and Dundas limestone (14 to 5 mm) had their saturated surface dry densities and absorptions determined according to ASTM C127 and C128. Also, they had their gradations determined according to the standard procedure of ASTM C136 and the bulk densities of both materials were determined according to the procedure of ASTM C29. The physical data of all raw materials utilized in the concrete batches can be found in Section 3.5.2 and 3.5.3.

It should be noted that all mix designs were developed according to the PCA volumetric mix design procedure. This mix design process was developed into an excel spread sheet which automatically calculated mix proportions for a one cubic meter yield. An example of this program can be viewed in Appendix G. Prior to mixing, all aggregates had their water content established according to the procedure listed in Appendix E unless otherwise noted. Also, moisture contents of all aggregates were measured according to the procedure listed in Appendix F.

3.3.2 - Testing the Fresh Mix

At the conclusion of batching each mix, the slump was tested to ensure that it was within the 100 +/- 10 mm limits before 100 x 200 mm cylinders were cast if applicable. The slump of each ready mix batch was measured according to the standard equipment and method listed in ASTM C143. The air content of each ready mix batch was also tested according to the standard pressure method listed in ASTM C231. Prior to batching, the air content of each mix was assumed to be a theoretical value of 2%. Once the actual air content had been measured this value was used to recalculate the actual mix proportions of all ingredients. These results are reported in the mix design summaries in Appendix B.

For mixes batched at temperatures above 23°C the concrete mix temperatures were measured via a calibrated dial thermometer at the conclusion of the mixing cycle. When slump and/or air content tests were being performed, the remaining quantity of concrete from the corresponding batch was left in the heated mixer to maintain temperature before being cast into cylinders if applicable or discarded if outside of the design specifications.

All slump, air content and temperature results are reported in the mix design summaries located in Appendix B.

3.3.3 - Mix Design Development

For this portion of the program, a cement content of 450 kg/m^3 was maintained for preliminary batching to establish the water demand of the ready mix batches at 23°C. A high cement content of 450 kg/m^3 was selected for testing due to the high strength, high performance concrete that was desired to be produced. Concrete sand and limestone conforming to ASTM C33 were utilized for all batches of ready mix and roller compacted concrete. All batching was performed according to the procedure listed in Table 3.3.

Table 3.3. Concrete batching procedure.

	Description	Mixer (On/Off)	Speed (rpm)	Initial Time (Minutes)	Time Interval (Minutes)	Elapsed Time (Minutes)
	Mixer should be moist with no free water					
1	Introduce Limestone	Off				
2	Introduce Concrete Sand	Off				
3	Mix	On	20 rpm	0	0.5	0.5
4	Introduce 90-95% of the mix water	On	20 rpm	0.5	0.5	1
5	Stop mixer - Introduce cement and/or supplementary cementing material(s)	Off		1	0.25	1.25
6	Start mixer	On	20 rpm	0	0.5	0.5
7	Add plasticizer (over 5 s, distributed), if applicable	On	20 rpm	0.5	0.5	1
8	Add water, if necessary	On	20 rpm	1	2	3
9	Stop mixer - scrape walls of mixing bowl or pan	Off		3	3	6
10	Start mixer	On	20 rpm	6	2	8
11	Stop mixer, start testing	Off		8	5	13

Note: Method developed by Philip Zacarias of ShawCor Ltd.

Initially, 15 kg trial batches containing 65% limestone to 35% sand by aggregate volume and varying water cement (w/c) ratios were mixed using a 20 Liter, Hobart HL200 mixer (pictured in Figure 3.1. below). This was done in an effort to establish the w/c ratio necessary to achieve a slump of 100 +/- 10 mm. The first batch was mixed at a w/c ratio of 0.40, producing a slump of 60 mm. The initial w/c ratio of 0.40 was selected as a starting point from information gathered from the literature review. Due to the low slump, the next batch was mixed with a w/c ratio of 0.45 and produced a slump of 110 mm. Since this was at the upper end of the confidence interval for consistency, the mix was again repeated with a w/c ratio of 0.445. This batch produced a slump of 105 mm and was selected as the final water cement ratio. However, over the course of these batches, it was noted that the mix had a very sandy consistency, leading the author to believe that the sand content of the mix was too high. As a result, the limestone content of the aggregate blend was increased from 65% to 70% by aggregate volume and more trial batching was conducted.

Figure 3.1. The Hobart HL200 Paddle Mixer used for all ready mix preliminary batching.

A batch containing 70% limestone by aggregate volume and a w/c ratio of 0.445 was mixed next This batch produced a concrete that was qualitatively determined to contain a proper sand content and a slump of 100 mm. Having satisfied all the requirements of the reference mix, this batch was repeated a further two times to ensure that the results were accurate. Slumps of 100 and 95 mm were achieved on subsequent batches. As a result, this mix design was selected as the 23°C reference.

The mix proportions of all trial batches tested can be found in Appendix B.1

3.3.4 - Mix Design – Cement Content

Following the establishment of the water cement ratio and aggregate proportions for the reference batch, a series of 65 kg mixes were batched at 450, 500 and 550 kg/m^3 cement content using a Sicoma Lab pan mixer. 12 cylinders were cast for each batch and cured in a curing room maintained at 23+/-2°C and 100% relative humidity. Three cylinders were tested at 1, 3, 7 and 28 days for compressive strength. This was done in an effort to ensure a cement content of 450 kg/m³ was the maximum amount of cement necessary to produce a maximum compressive strength for this high performance ready mix, mix design.

It should be noted that the 550 kg/m³ batch had its w/c ratio reduced to 0.395 in order to have its paste content and consistency maintained. This represented a reduction in the w/c ratio of approximately 11%. Similarly, the 500 kg/m³ batch had its w/c ratio reduced to 0.420, representing a 5% reduction in water cement ratio. The limestone, concrete sand ratio was maintained in order to make results comparable. The mix proportions, densities and compressive strengths for the 450, 500 and 550 kg/m³ cement content batches can be found in Appendix B.2.

3.3.5 - Establishing the Water Content for Reference Batches at 35 and 50°C

Once the 23°C reference mix design had been established, it was necessary to establish the reference mix designs for 35 and 50°C. In order to make these batches comparable, the mix designs were established based on the principle of constant consistency. Trial batching was performed with materials preconditioned at 35 and 50 °C in a preheated pan mixer.

The preconditioning of materials prior to batching was done according to the blending procedure presented next.

1. 24 hours before batching was set to begin, enough aggregate necessary to finish the following day's mixes was shoveled onto a polyurethane coated 4x8 sheet of plywood on the floor.
2. The aggregate was misted with water so that it would have a total water content greater than its absorption value (i.e., water content when the aggregate is saturated surface dry).
3. The aggregate was then blended by turning the pile over several times.

4. This was accomplished by having two technicians with shovels positioned opposite to each other, digging into the base of the pile and dumping the aggregate on top of the pile. The technicians moved one step clockwise or anticlockwise after each shovelful, and repeated until they had made four to six revolutions.
5. After the aggregate was thoroughly mixed, it was then placed into a series of 20 liter pails and sealed with air tight lids.
6. The pails were placed into a large lab oven programmed to maintain either 35 or 50°C.
7. The aggregate pails were allowed to condition at the elevated temperature for 24 hours before being removed for batching.
8. This procedure was repeated for both the limestone and concrete sand separately.
9. Similarly, enough cement, SCM(s) and water necessary to complete the following days batching was also sealed in 20 liter pails and placed in the ovens to condition over night.
10. Before being removed the following day, a thermometer and infra-red temperature gun were used to double check that the reference batch temperature had been achieved in all materials.
11. On the morning of batching, the Sicoma Lab pan mixer had its heating elements set to the necessary batch temperature. The elements consist of two 300 mm x 300 mm resistive heating pads adhered to the bottom of the pan of the Sicoma mixer. The temperature was controlled via a thermo couple mounted on the bottom of the pan mixer. Pictures of the mixer and heating elements can be found in Figure 3.2a and 3.2b below.
12. The pan of the mixer was allowed to preheat for as long as was necessary to achieve a constant temperature of 35 or 50°C throughout its base and side walls. This was confirmed through the use of an infra-red temperature gun.
13. Once the mixer had reached its batch temperature, the materials were removed from the ovens, quickly weighed according to a pre-established mix design and the mixing procedure displayed in Table 3.3 was utilized to complete a mix.

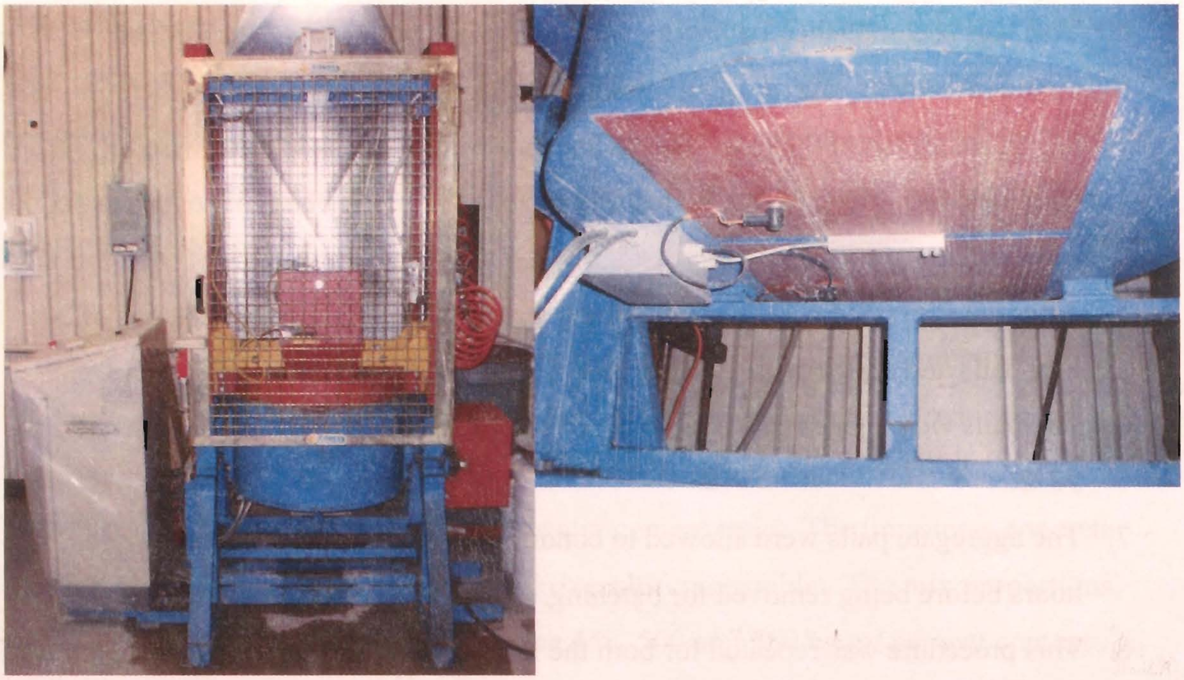


Figure 3.2a&3.2b. Pictured in Figure 3.2a is the Sicoma Lab Pan Mixer used for all large batch ready mix batching. Pictured in Figure 3.2b is the bottom of the mixing pan with heating elements and thermal couple used to control the temperature of the mixing pan.

Once all materials and equipment were preconditioned at 35 or 50ºC, 30 kg trial batches were mixed using the Sicoma heated pan mixer. A series of mixes were conducted over which the w/c ratio was gradually increased incrementally until the water demand at both 35 and 50 ºC could be established for a consistency of 100 +/- 10 mm. All trial mixes were discarded after slump measurements were performed. At the conclusion of this process it was determined that a water cement ratio of 0.465 for 35 ºC and 0.496 for 50ºC were necessary to maintain a 100 +/- 10 mm consistency.

After the mix designs for 35 and 50ºC were established, a series of four 65 kg batches for each temperature were cast. For each batch, 12 cylinders were cast and cured according to the procedure presented next.

3.3.6 - Casting and Curing 100x200 mm Cylinders

For each of the four 65 kg batches mixed in the Sicoma mixer at 35 and 50ºC, 12 cylinders were cast. All ready mix cylinders in this program were moulded and finished according to the consolidation procedure outlined in ASTM C192. All moulding of cylinders was completed within 30 minutes of the beginning of batching to minimize the heat loss of the concrete. The first three batches of concrete at both 35 and 50 °C had their cylinders cured at elevated temperature according to the schedule presented in Table 3.4. Prior to being placed in ovens at elevated temperature, the cylinders

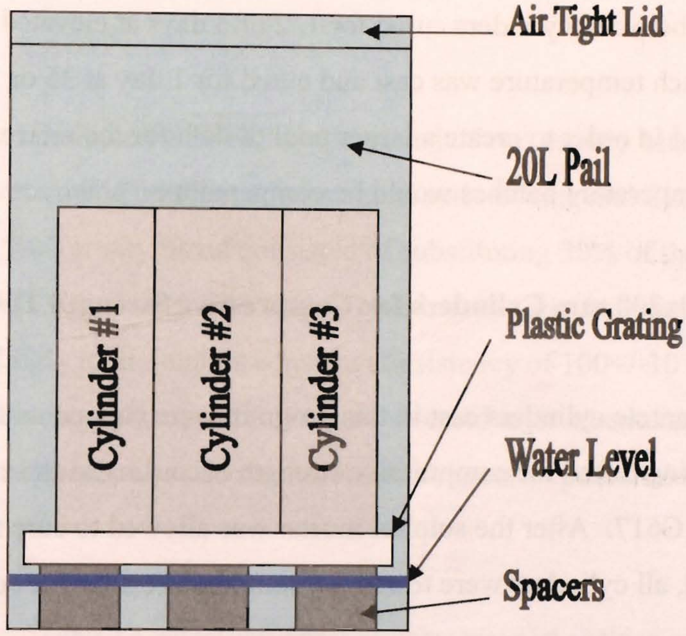


Figure 3.4. Diagram of 20 liter pails used for curing cylinders at elevated temperature.

were placed into 20 liter pails on top of 25 mm's of plastic grating. Below the grating was approximately 500 mls of water. The 20 liter pails were sealed with air tight lids to ensure that 95-100% relative humidity was maintained in the pails throughout the curing process. A diagram of the curing pails utilized can be seen in Figure 3.4.

Table 3.4. Elevated temperature curing schedule.

Batch Temperature (ºC)	35	35	35	50	50	50
Curing Temperature (ºC)	35	35	35	50	50	50
Batch Number	1	2	3	1	2	3
Oven Cure Duration (days)	1	2	3	1	2	3

Each of the first three batches were cured for either 1, 2 or 3 days to determine the necessary length of the high temperature curing period that produced the greatest reduction in compressive strength. At the conclusion of the high temperature curing period, all cylinders were demoulded and either tested for 1 or 3 day strength or placed in a 23+/-2°C curing room maintained at 100% relative humidity for the remainder of their curing period. After it was determined that there was a negligible difference in compressive strength between cylinders cured for 1, 2 or 3 days at elevated temperature, the fourth batch for each temperature was cast and cured for 1 day at 35 or 50°C. These results were duplicated in order to create a larger pool of data for the reference mixes that the rest of the high temperature batches would be compared to.

3.3.7 - Preparing 100x200 mm Cylinders for Compressive Strength Testing

All 100 x 200 mm concrete cylinders cast in this program were capped with sulphur compound prior to being tested for compressive strength according to the standard procedures of ASTM C617. After the sulphur mortar was allowed to cure for the necessary time period, all cylinders were tested for compressive strength according to ASTM C39.

3.3.8 - Supplementary Cementing Materials

Once the reference mix designs and high temperature curing period had been established, batches utilizing SCM's were mixed. 75 kg batches were mixed for all SCM addition rates presented in Table 3.5 at all three temperature levels. For all 75 kg batches, 15 cylinders were moulded and cured. At this stage, an extra three cylinders were moulded for rapid chloride permeability testing at 56 days of age. This testing will be further explained in a following section.

A Grade 80, ground granulated blast furnace slag from Lafarge, Stoney Creek was utilized at cement replacement rates of 25 and 40%. The same w/c ratios as the reference mixes were maintain for all temperature levels. This was done because very little change in consistency from the reference batches at all temperatures was noted.

A Class F Hatfield and a Class C Edgewater fly ash from Lafarge were also utilized at this stage of the program. To maintain a constant consistency, each batch had its water content reduced accordingly. Reductions in water content varied according to the type of fly ash and the cement replacement rate. Initial water reductions were estimated from the literature review and mixes were discarded and repeated if consistency was out of specification.

The final mixes conducted with SCM's consisted of two ternary blends. The ternary blends tested were made up of an equal volume ratio of slag and Class C fly ash. For example; the 15% Ternary blend consisted of substituting 30% of the Portland cement by volume with 15% fly ash and 15% slag. These batches also had their water contents reduced accordingly to maintain a constant consistency of 100+/-10 mm. It should be noted that all cement replacement rates were selected after an extensive literature review. These replacement rates were deemed to have the greatest potential for positive effect on the concrete.

Table 3.5. Supplementary cementing material addition rates.

Supplementary Cementing Materials		
	Cement Replacement Rate (%)	
	Batch #1	Batch #2
Blast Furnace Slag	25	40
Class F Fly Ash	15	25
Class C Fly Ash	20	30
Ternary Blends (50/50, Slag & Class C Fly Ash)	15	20

3.3.9 - Chemical Admixtures

For this portion of the study, ready mix concrete batches were mixed with the addition of chemical admixture. As was previously mentioned, three admixtures were investigated.

1. Commercial Material #1 (HRWR)
2. Commercial Material #2 (WR-Ret. Adm.)
3. Sodium Gluconate

For the 23°C reference batches with HRWR, dosages that would provide a 5 and 10% water reduction were selected for testing. For the retarders utilized, dosages were selected that provided a good balance between water reduction (2.5 and 5.0%) and retardation.

In order to establish what dosage rates would be necessary to produce the reductions in water demand desired, 10 kg trial batching was performed using the Hobart mixer. The same cement and aggregate contents were utilized as previous mixes, however in this case the water reductions were established before the batches were mixed. The water reductions were selected from either a review of available technical literature or for the case of Sodium Gluconate, from its performance in Phase I of the test program. Batches were repeated while gradually increasing the dosages of admixtures until the optimum dosage necessary to achieve the set water reductions were established. The dosages utilized in the program can be seen in Table 3.6.

Table 3.6. Addition rates for chemical admixtures.

Chemical Admixtures		
	Addition Rate (% mass relative to cement)	
	Mix #1	Mix #2
Commercial Material #1	0.05	0.12
Commercial Material #2	0.08	0.17
Sodium Gluconate	0.1	0.2

After the dosage rates of each admixture were established these addition rates were utilized for batches mixed at 35 and 50°C. All water cement ratios, dosages and consistency results for the above mentioned batches can be seen in Sections B.3 to B.5 of Appendix B.

3.3.10 - Rapid Chloride Permeability Testing (RCPT)

For all 75 kg batches, three cylinders were cast for durability testing. These cylinders were cured for 56 days until being prepared and tested for RCPT according to ASTM C1202.

The 100 x 200 mm cylinders were saw cut into 100 x 51 mm sections via a Target PAS 2HP-1HP WET diamond concrete saw pictured in Figure 3.5. One 51 mm section was cut from each of the three cylinders and labeled accordingly. For RCPT testing two of the three sections were randomly selected from each set of three. Two sections from all 75 kg batches of concrete, at all three temperature levels, were tested with the exception of a few of the non optimum admixture addition rates. These results can be seen reported in the results chapters.

Figure 3.5. Target concrete saw used for preparing cylinders for RCPT.

3.4 - Phase IIb: Experimental Procedures, Roller Compacted Concrete

For Phase IIb of the program the same raw materials used in Phase IIa were also utilized. However, roller compacted concrete (RCC) mixes were only batched with the addition of SCM's, and not chemical admixtures. Water reducing and retarding admixtures have had only limited use in RCC. Both have been shown to produce possible benefits in producing additional compactibility and extended setting time. (ACI 325) However, the scope of this study was limited to focus solely on ameliorating the reduction in compressive strength and durability through the use of SCM's.

The RCC mix designs were proportioned based on the same principle of constant consistency as in the ready mix program with the exception that a different consistency and consistency test method were utilized. The mix design, moulding and specimen testing procedures will be presented next.

3.4.1 - Mix Design

The procedures outlined in ACI 325 were followed to proportion the mix design for the reference RCC concrete batch. Mixture proportioning was conducted using both the principle of consistency testing, utilizing a modified VeBe apparatus, and establishing optimum water contents and fine aggregate contents through the use of soil cement methods. The establishment of coarse and fine aggregate and water contents will be explained first.

3.4.2 - Soil Compaction Method

In order to produce high performance, high strength RCC, a cement content of 350 kg/m^3 was selected for testing. This is at the upper range of potential cement contents recommended in ACI 325 (208 to 356 kg/m^3) and was selected to ensure a maximum deleterious effect on durability and compressive strength would be exhibited through the effect of high initial temperature on the hydration rate and products of the cement paste. Once the cement content of the mix was established, is was next necessary to establish the coarse/fine aggregate ratio and the water content necessary to produce a RCC mix with optimal consistency, density and compactibility with minimal permeability. This was done through batching and casting Proctors (an example of the mould and compaction hammer is illustrated in Figure 3.6 below) over a range of water contents and coarse/fine aggregate levels. The finished proctors were then assessed based on the criteria mentioned above. Moulding Proctors in this manner is commonly referred to as producing moisture density curves and is often used to determine the optimum moisture content necessary to achieve maximum compacted density for granular layers of road bases.

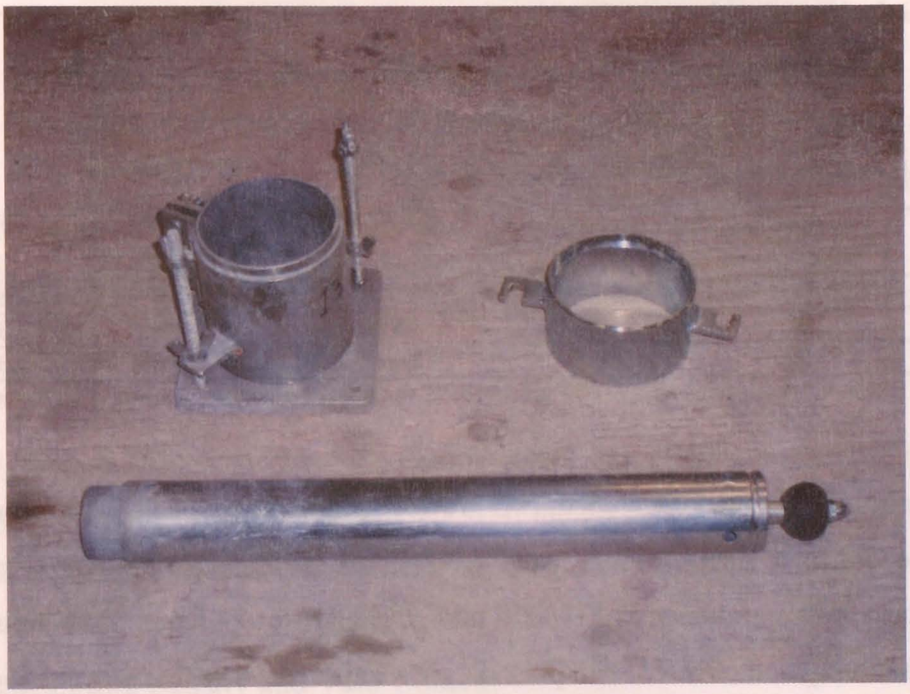


Figure 3.6. Proctor Mould, Filling Collar and Compaction Hammer.

3.4.3 - Preparing Materials, Mixing, Moulding and Curing at Room Temperature

Prior to mixing batches of RCC, all aggregates were blended according to the procedure of Appendix E, except where noted for batches above room temperature. After the aggregates were blended and sealed in 20 liter pails, a sample of aggregate from each pail (resealed after sampling) was acquired for moisture determination. The moisture content of all aggregates was determined according to the standard procedure outlined in Appendix F.

Next, mix ingredients sufficient to mix 10 kg batches were proportioned according to Table 3.7. Mixes containing 35, 40 and 45% fine aggregate by total aggregate volume were selected for testing as advised by ACI 325. A void content of 5% was assumed for all theoretical mixes. All mix designs were proportioned utilizing the same volumetric mix design spread sheet developed in Phase IIa and shown in Appendix G. Mix proportions for each batch can be seen in Appendix C. For each individual batch, empty pails were tarred on a scale and the required quantity of aggregate, cement and water was weighed into separate pails and sealed until batching. The mixing procedure presented in Section 3.3.3 was utilized for all RCC batches, with the exception that the Hobart HL200 mixer was used for the preliminary moisture density work only.

Table 3.7. Mix proportions for RCC moisture density curves.

Series	Number of Batches	Cement Content (kg/m^3)	Coarse/Fine Aggregate Ratio	Theoretical Void Content (%)	W/C Ratio Range
1	5	350	55/45	5	0.30 to 0.38
2	5	350	60/40	5	0.30 to 0.38
3	5	350	65/35	5	0.30 to 0.38

Note: W/C ratios were increased by 0.02 increments for each subsequent batch in a series.

Once the mixing cycle had concluded, two Proctor specimens for each batch were moulded according to the procedure listed in Appendix H. Finished proctors were cured in a moisture room maintained at 23+/-2°C and 100% RH for 24 hours. The moulds were placed on shelving and covered with plastic sheets to prevent any free water dripping onto the exposed concrete. Proctors were demoulded at 24 hours and returned to the moisture room under plastic sheets to cure for 28 days.

3.4.4 - Testing Proctors

After 28 days of curing, the Proctor cylinders were removed from the moisture room and patted dry with a rag for a sufficient time such that their surfaces attained the saturated surface dry condition. The Proctors were then capped with sulphur compound according to ASTM C617, with the exception that a modified capping jig was utilized. The standard capping jig utilized for 100 x 200 mm concrete cylinders had to be modified to have a vertical V block that was short enough to allow a Proctor to be capped on both sides. A picture of the modified V block can be seen in Figure 3.7.

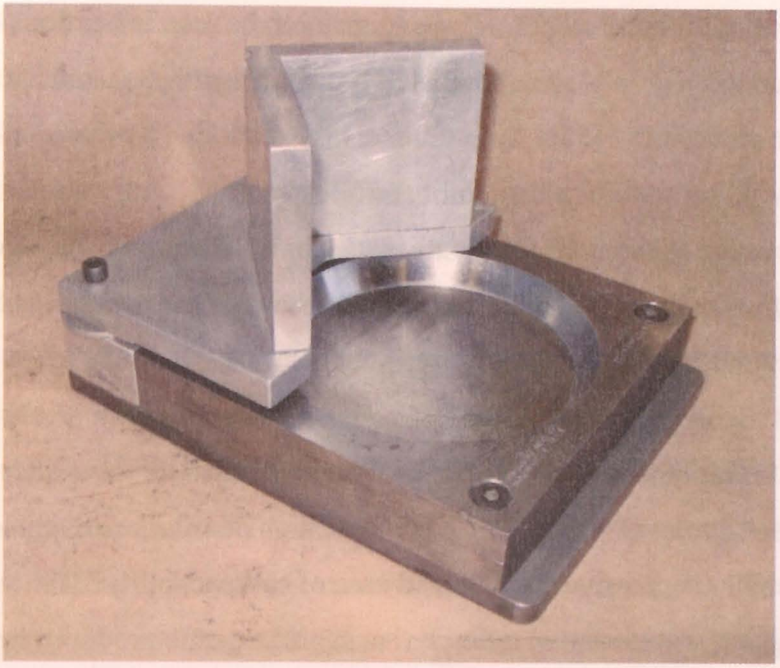


Figure 3.7. Modified Capping Jig.

After the Proctors were capped and the sulphur mortar was allowed to cure for the necessary time period prescribed in ASTM C617, the Proctors were tested for compressive strength according to ASTM C39.

3.4.5 - Calculating Density and Void Content

The weights taken for each proctor after finishing (according to the procedure of Appendix H) were used to calculate the wet density of each mix design. This density was calculated using the following equation:

$$\frac{\text{Mass of Wet Proctor (g)}}{\text{Volume of Proctor Mould (ml)}} = \text{Density (kg/m}^3\text{)}$$

These densities were then used to calculate the actual void content and mix proportions that are presented in Appendix C.1. Also, these calculated densities were used to form the moisture density curves for each fine/coarse ratio of aggregates; i.e. the water cement ratio of each batch was graphed vs. the average density of the two Proctors moulded at that water content. Also, the compressive strength and void content were graphed against the water cement ratio for all mixes. These graphs can be seen in Sections 4.6.4, 4.6.5 and 4.6.6. When these graphs were compared based on aggregate content, the optimum performing fine/coarse ratio (55% limestone to 45% sand) that produced a high density and minimum void content (or permeability) while also producing a strong compressive strength was selected as the final fine/coarse ratio for the reference mix. However, the consistency of the batches also had to be taken into consideration before a final reference mix could be established.

A water cement ratio of 0.36 was selected as the reference water level after the data was reviewed. This water level was selected due to its high density, relatively low permeability, high compressive strength and ease of compactibility. It should be noted that although higher water cement ratios at this aggregate ratio produced lower void contents, the consistency of the mix was considered to be too fluid for RCC. As noted in ACI 325, the consistency of a fresh RCC mix must be such that it can be efficiently compacted by a vibrating roller. It must also be able to support the weight of a vibrating roller without significant rutting after compaction.

3.4.6 – Measuring the Consistency of the Reference Mix Design

Once it had been determined that the 55% coarse to 45% fine aggregate ratio at a water cement ratio of 0.36 produced the optimum results for the RCC mix in terms of strength, density and void content, the next step was to quantitatively measure the consistency of this reference mix. This was performed by batching a series of identical concrete mixes in triplicate and testing for consistency. The consistency test was performed utilizing a modified VeBe device. The tester used for testing will be explained next.

In order to test the consistency of the roller compacted concrete, a modified VeBe apparatus was constructed at a reduced scale of the apparatus outlined in ASTM C1170. The size of the device was reduced for two main reasons. The first is that in order to batch, test and mould specimens at high temperature, it is necessary to perform all tasks at an accelerated rate. This is to ensure that the temperature of the concrete is not allowed to fall more than a few degrees below the allotted 35 or 50°C batch temperature before being placed in the ovens for curing. As a result, a device that contained a smaller mould as well as surcharge allowed the test to be performed faster. The second reason this was performed was to conserve materials. The VeBe apparatus outlined in ASTM C1170 specifies testing 13.4 +/- 0.7 kgs of material per test. When batching RCC, especially at high temperature, it is not possible to test a batch for consistency and then return the tested specimen to the mixer for a modification to the water cement ratio if the consistency is out of spec. The elevated temperature causes a significantly increased rate of hydration and remixing a batch with increased water content would not have produced accurate results. Instead, all batches were either discarded or moulded and retained if within specifications, immediately following the modified VeBe test. In order to minimize the use of material, smaller batches of concrete were tested. Drawings as well as measurements of the modified VeBe tester utilized can be seen in the Figures below. It should be noted that although the modified VeBe apparatus had the mould and surcharge mass and dimensions reduced, a constant amount of surface pressure relative to the actual VeBe tester was maintained in design.

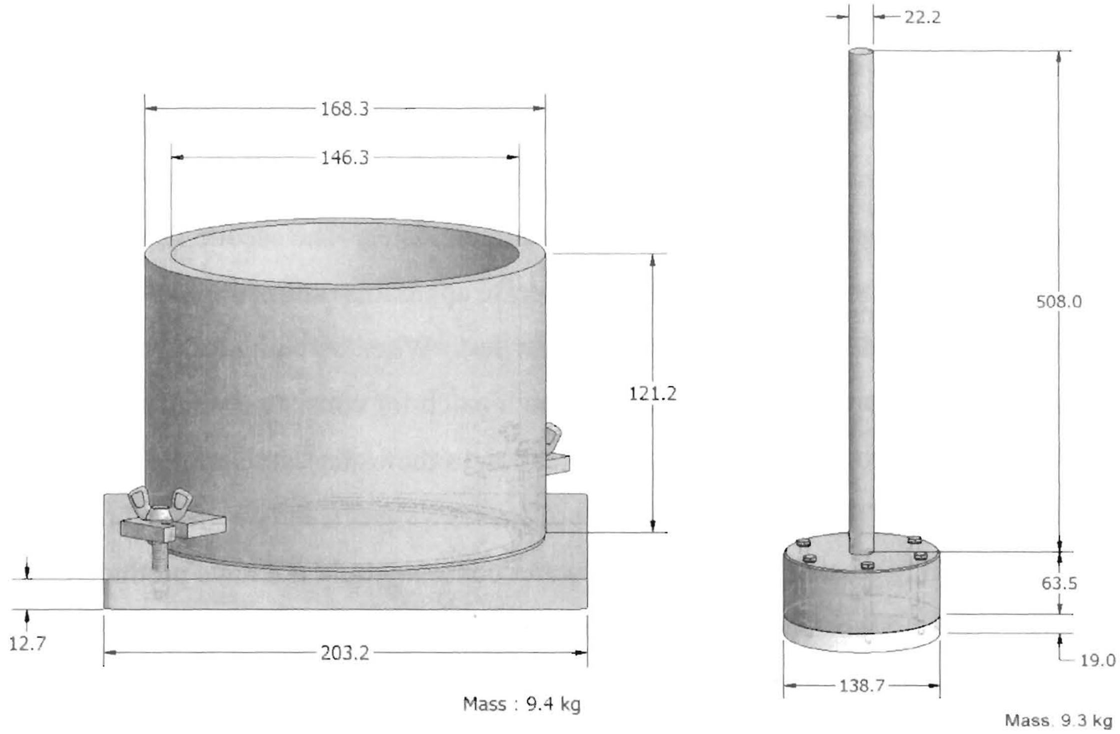


Figure 3.8. & 3.9. On the left Figure 3.8 displays the dimensions and total mass of the Modified VeBe mould. On the right Figure 3.9 displays the dimensions and mass of the surcharge. Drawings are not to scale. All dimensions are in mm.

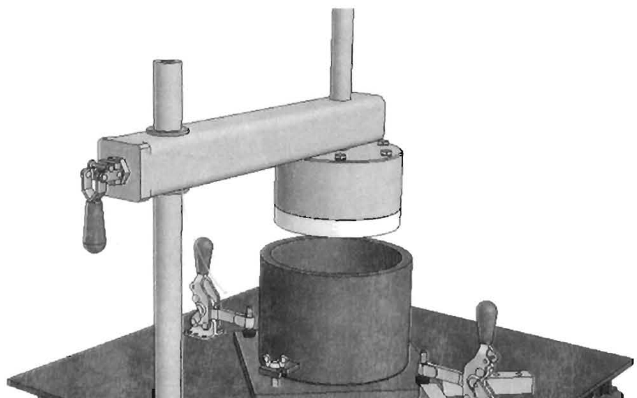


Figure 3.10. A rendered drawing of the modified VeBe apparatus. Drawing includes; Syntron vibrating table, surcharge suspension arm, surcharge, mould and clamps.

15 kg batches of RCC were mixed at the previously mentioned cement, aggregate and water content. After each batch finished its final mixing cycle according to the schedule presented in Section 3.3.3, the concrete was then immediately transferred to the modified VeBe apparatus and tested for VeBe time according to test Method A, outlined in ASTM C1170. This method was followed directly with a few exceptions. The first is that a sample of concrete weighing 3.3 +/- 0.2 kg was used to fill the mould and the second was the modified dimensions of the apparatus previously mentioned. It should also be noted that the mould was secured to the vibrating table via two large over centre clamps during operation.

If ASTM C1170 is followed directly, the VeBe time (or time to total compaction) is recorded as the amount of time it takes to form a mortar ring in the annular gap between the mould wall and the base of the surcharge. Once this ring is formed, the time is recorded and the sample is further vibrated for a total of two minutes and then density measurements are conducted. If a sample does not produce a mortar ring in under two minutes the test is aborted and the RCC is considered of too stiff a consistency. For the VeBe measurements performed in this study, VeBe time was measured as the time to total compaction (or the time in which no further vibration caused a decrease in volume and thus an increase in density of the concrete specimen contained in the mould under the surcharge). This measurement was performed using an electronic caliper. The distance between the supporting cross beam of the surcharge and the top surface of the surcharge was measured at four second intervals. The sample was considered fully compacted when no further movement of the surcharge weight was recorded during successive vibration. If a sample reached its fully compacted position in less then 35 seconds the mix was considered too stiff and the water content was increased. This number was set as the limit after reviewing the results of repeated VeBe tests of the reference mix at 0.36 w/c ratio. The mix that contained a w/c ratio of 0.36 was previously determined to have the best balance of consistency, density, permeability and compressive strength. As a result, the only step necessary was to determine the quantitative consistency of the mix so that it could be duplicated with other mix designs. The results of three identical repeated batches are presented in Table 3.8.

Table 3.8. Modified VeBe test results for the reference RCC mix.

Date	12-Jul-09	12-Jul-09	12-Jul-09
Trial	1	2	3
W/C	0.36	0.36	0.36
Test Time	10:00	11:00	12:00
VeBe Time (sec)	36	40	40
Density (kg/m³)	2026.7	2041.1	2034.3

It should be noted that the procedure for measurement of VeBe time found in ASTM C1170 was modified for this program because the published ASTM method is based on qualitative not quantitative observations. For this program, a more accurate quantitative measurement procedure was utilized.

3.4.7 - Batching with SCM's

Once the reference mix design for the RCC program had been established, it was next necessary to create the mix designs for all other batches. The RCC mix program involved casting five different mix designs at three temperature levels. The only mix ingredient that was changed between temperature levels was the amount of water (or w/c ratio). For subsequent increases in batch temperature, the water level had to be increased to maintain constant consistency. The water demand for all batches was determined using the modified VeBe apparatus. Small 15 kg trial batches were utilized when necessary to establish the reference water contents at 35 and 50°C. Once the water cement ratios had been established for the reference mix at all three temperature levels (23, 35 and 50°C), water reductions were made to maintain constant consistency with the addition of SCM's. 60 kg batches were mixed and moulded according to the schedule presented in Table 3.9. The complete mix proportions of all RCC batches can be found in Appendix C.2.1, C.2.2 and C.2.3. The batching and moulding procedures are presented next.

Table 3.9. Theoretical mix proportions of all final RCC batches.

Mix Temperature	Batch #	Cement Content (kg/m³)	SCM Replacement Rate (%)	Limestone/ Sand Volume Ratio	Water Cement Ratio	Theoretical Void Content (%)
23ºC	1	350	-	55/45	0.360	5
	2	350	40 - GGBFS	55/45	0.360	5
	3	350	30 - Class C FA	55/45	0.353	5
	4	350	15 - Ternary Blend	55/45	0.355	5
	5	350	20 - Ternary Blend	55/45	0.356	5
35ºC	6	350	-	55/45	0.376	5
	7	350	40 - GGBFS	55/45	0.376	5
	8	350	30 - Class C FA	55/45	0.361	5
	9	350	15 - Ternary Blend	55/45	0.368	5
	10	350	20 - Ternary Blend	55/45	0.365	5
50ºC	11	350	-	55/45	0.396	5
	12	350	40 - GGBFS	55/45	0.396	5
	13	350	30 - Class C FA	55/45	0.380	5
	14	350	15 - Ternary Blend	55/45	0.388	5
	15	350	20 - Ternary Blend	55/45	0.384	5

3.4.8 - Batching RCC Cylinders

Prior to mixing 60 kg batches of RCC at room temperature, all aggregates were blended according to the procedure of Appendix E. However, for aggregates intended for batches at 35 or 50°C, the aggregates were blended and preconditioned at elevated temperature according to the procedure presented in Section 3.3.5. Prior to batching, the moisture content of all aggregates was determined according to the standard procedure outlined in Appendix F.

Next, mix designs sufficient to mix 60 kg batches were proportioned according to Table 3.9. A theoretical void content of 5% was assumed for all mixes in order to achieve a 1m³ yield. All mix designs were proportioned utilizing the same volumetric mix spread sheet developed in Phase IIa and shown in Appendix G. For each individual batch, empty pails were tarred on a scale and the required quantity of aggregate, cement and water was weighed into separate pails and sealed until batching. The mixing procedure presented in Section 3.3.3 and the Sicoma pan mixer, were utilized for all RCC batches. For batches mixed at elevated temperature, care was taken to ensure a minimal amount of heat was lost from all mix constituents during weighing.

3.4.9 - Moulding RCC Cylinders

At the conclusion of the mixing cycle for each 60 kg batch, consistency measurements were conducted with the modified VeBe tester according to the method outlined in Section 3.4.6. If it was deemed that the batch was within the previously established consistency limits, twelve 100 x 200 mm cylinders were cast for each batch. The concrete cylinders were prepared according to ASTM C1435 with the exception that 100 x 200 mm cylinders were used instead of 150 x 300 mm cylinders and compaction with an impact hammer was stopped when no further downward vertical movement of the tamping plate was observed. A picture of the impact hammer, tamping plate, mould sleeve and finishing tools can be seen pictured in Figure 3.11. Also, the exact moulding procedure followed can be found in detail in Appendix I.

Figure 3.11. Impact hammer, tamping plate, mould sleeve with filling collar and finishing tools.

After filling, compaction and finishing, the cylindrical concrete specimens were immediately placed in either a moist room maintained at 23°C and 100% RH or in sealed 20 litre pails suspended above water (diagram pictured in Figure 3.3.4) in an oven maintained at 35 or 50°C. All specimens were demoulded at the age of ~23 hours and one set of 3 cylinders was tested for compressive strength at 24 hours after being capped with sulfur compound according to ASTM C39; the remaining cylinders were cured at 23°C in the moisture room until the time of testing at 7 and 28 days. Three cylinders were tested at each of the 1, 7 and 28 day test periods. The remaining three cylinders were cured for 56 days in the moisture room and then removed and tested for rapid chloride permeability according to ASTM C1202.

3.4.10 – Testing for Rapid Chloride Permeability

Just as in Phase IIa of the test program, the three 56 day 100 x 200 mm cylinders were saw cut into 100 x 51 mm sections via a Target PAS 2HP-1HP WET diamond concrete saw. One 51 mm section was cut from each of the three cylinders and labeled accordingly. For RCPT testing, two of the three sections were randomly selected from each set of three. Two sections from all 60 kg batches of concrete, at all three temperature levels, were tested. All results from the RCC testing can be found reported in Section 4.6, 4.7 and 4.8 and Appendix C.

3.5 – Material Properties

3.5.1 – Cement and Supplementary Cementing Materials

Table 3.10. Chemical analysis of cement and supplementary cementing materials.

Note: Lithium Tetraborate Fusion - ICP, % Weight Major and Minor Oxides

Analyte	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total	S
Type I/II Portland Cement, Lafarge	21.14	4.67	2.81	0.17	2.67	63.64	0.21	0.76	0.232	0.15	2.28	98.74	1.32
Grade 80 GGBFS, Stoney Creek, Lafarge	37.5	10.77	0.49	0.758	12.98	36.38	0.5	0.64	0.534	< 0.01	0.18	100.7	1.42
Class C FA, Edge Water, Lafarge	39.57	19.99	5.89	0.026	4.58	24.13	1.68	0.52	1.549	1.11	0.95	100	0.52
Class F FA, Hatfield, Lafarge	48.16	22.39	13.64	0.03	1.43	5.94	0.86	1.73	1.167	0.37	2.53	98.26	0.5

3.5.2 – Chemical Admixtures

Table 3.11. List of chemical admixtures.

	Chemical Admixture	Supplier
Phase I	Sodium Gluconate	Canada Chemicals
	Corn Syrup	Casco
	Sucrose	Casco
Phase IIa	Sodium Gluconate	Canada Chemicals
	Water Reducing Admixture	Commercial Material #1
	Retarding Admixture	Commercial Material #2

Note: All Technical Data Sheets and information for all chemical admixtures used in this program can be found in Appendix J.

3.5.3 – Concrete Sand

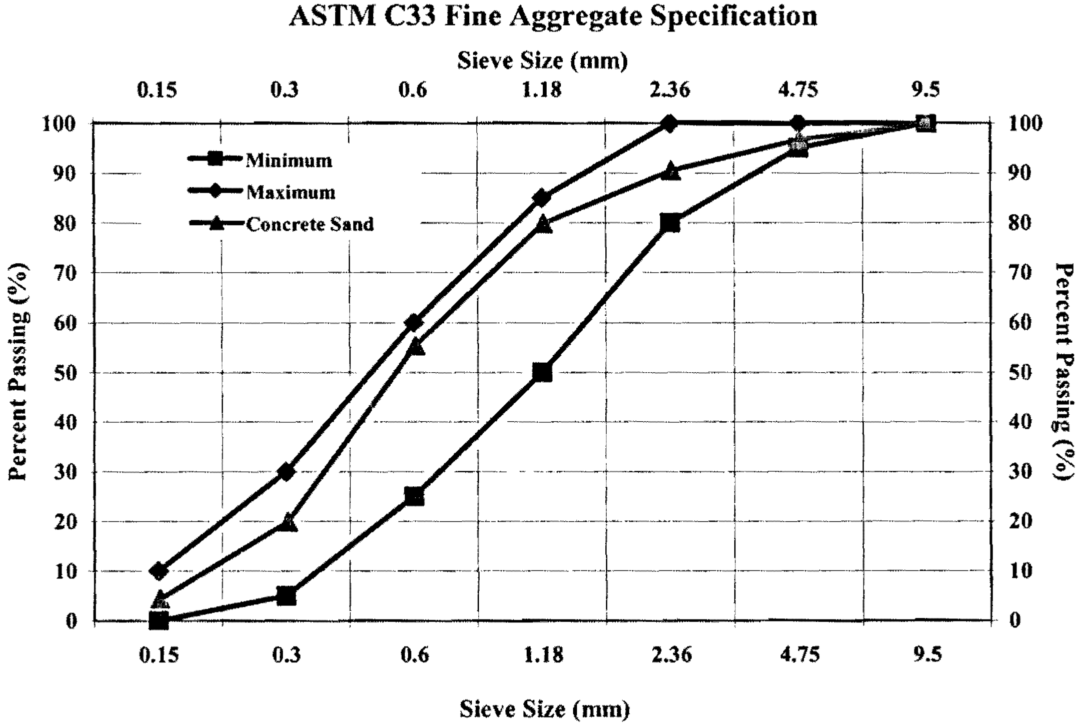
ASTM C33 Concrete Sand

Table 3.12. Aggregate Physical Properties

Loose Bulk Density (kg/m³)	1825.0
Saturated Surface Dry Density (kg/m³)	2.65
Apparent Density (kg/m³)	2.69
Absorption (%)	1.00

Table 3.13. Aggregate Gradation Specifications

Standard	Sieve Size (mm), Cummulative % Passing						
ASTM C33	0.15	0.3	0.6	1.18	2.36	4.75	9.5
Minimum	0	5	25	50	80	95	100
Maximum	10	30	60	85	100	100	100
Concrete Sand	4.4	20.0	55.4	79.9	90.5	96.6	100.0



3.5.4 – Limestone

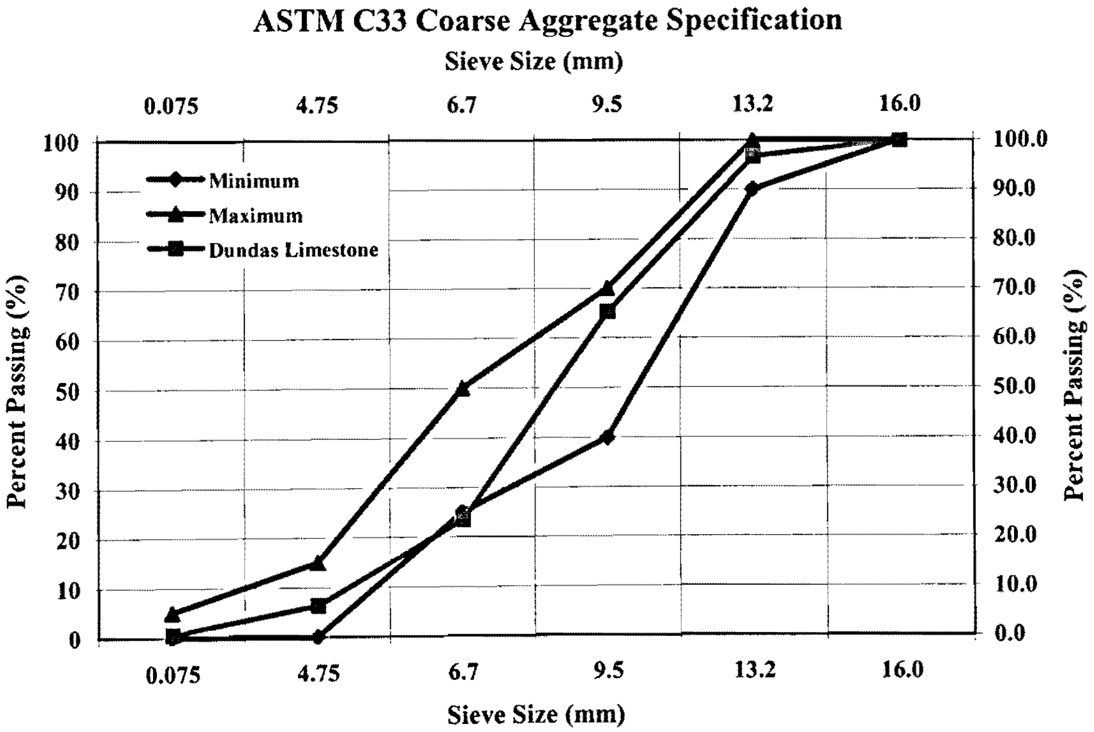
Dundas 14-5mm Limestone

Table 3.14. Aggregate Physical Properties

Dry Rod Bulk Density (kg/m³)	1628.8
Saturated Surface Dry Density (kg/m³)	2.78
Apparent Density (kg/m³)	2.79
Absorption (%)	0.18

Table 3.15. Aggregate Gradation Specifications

Standard	Sieve Size (mm), Cummulative % Passing					
ASTM C33	0.075	4.75	6.7	9.5	13.2	16.0
Minimum	0	0	25	40	90	100
Maximum	5	15	50	70	100	100
Limestone	0.6	6.3	23.5	65.3	96.6	100.0



Chapter 4
Phase I: Experimental Results and Analysis for Mortar

4.1 – Scope

For this portion of the study, three cement hydration retarders were investigated in a mortar program.

1. Sucrose
2. Sodium Gluconate
3. Corn Syrup

The compressive strength and water demand results of the mortar mixes will be presented next.

4.1.1 – Reference Mortar Results

Initially batches of mortar were cast according to the standard mix design outlined in ASTM C109. A water cement ratio of 0.519 was established as the reference water content after testing for flow according to ASTM C230. Once the final mix design was established, two batches, each consisting of nine 50 mm mortar cubes, were cast at 23, 35 and 50°C.

The average compressive strength results for 6 mortar cubes tested at 1, 7 and 28 days and cured at three different temperatures are presented in Figure 4.1. As predicted, the increased curing temperature produced higher 1 day compressive strengths. Curing at 35 and 50°C resulted in an 11.3% increase in compressive strength respectively at 1 day when compared to the 23°C results. However, this initial gain in strength was later negated at 7 days of age. At 7 days, the 23°C batches gained compressive strength at a much faster rate than the other high temperature batches. This is predicted to have occurred due to the development of a poorly hydrated microstructure in the higher temperature batches. When the 28 day results are analyzed a similar trend as the 7 day results is exhibited. The 23°C strengths continue to perform the best as expected, exceeding the 35 and 50°C results by 17.4% respectively. However, contrary to popular knowledge, the 35°C and 50°C samples produced compressive strengths identical in results at 28 days of age. This was an unexpected result due to the difference in strengths recorded at 7 days of age as well as the commonly reported idea that an increased curing temperature produces an increased deleterious effect on later age compressive strength results. It is not known conclusively why this relation occurred as all batches of mortar were identical in proportions and curing schedule with the exception of temperature. It is hypothesized that the 15°C difference in temperature gradient might not have been large enough to produce a significant effect on the microstructure of the mortar cubes. As well, the 27 day cure period at 23°C, after the initial high temperature cure, allowed enough time for the cubes to recover from the initial exposure to adverse temperature. However, the one conclusive result that can be drawn from this portion of the program is that temperature does have a significant effect on compressive strength at both early and later ages.

The average flow results for all reference batches can be seen in Table 4.1. Increasing the curing temperature from 23 to 35°C produced a moderate reduction in flow followed by a greater reduction when increased to 50°C. These results agree with practical knowledge of high temperature concreting whereby increases in batching temperature cause decreases in consistency.

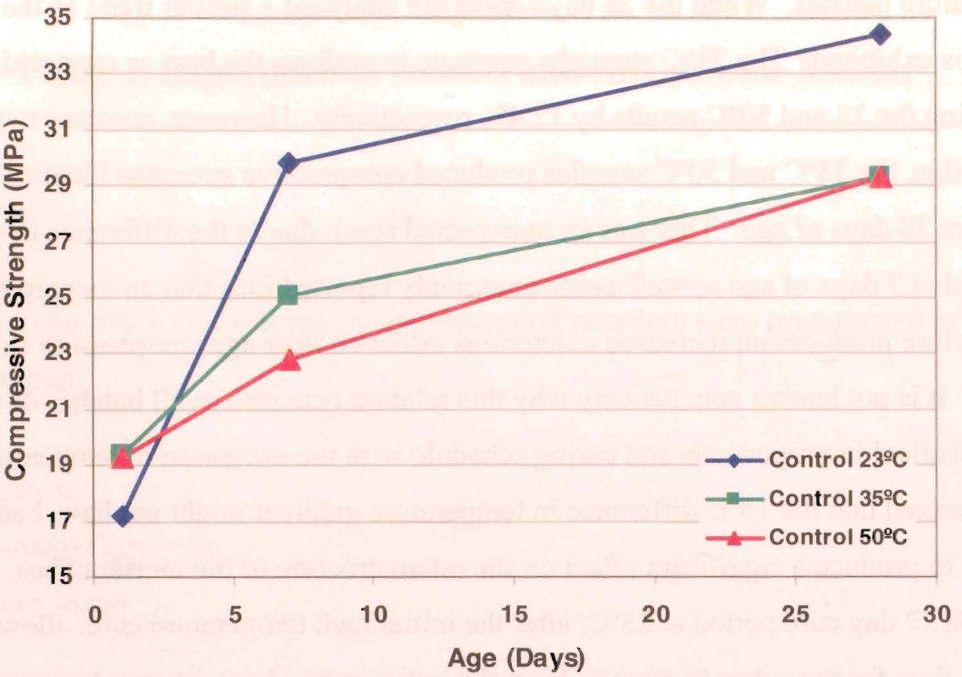


Figure 4.1. 1, 7 and 28 day compressive strength results for reference mortar batches.

Table 4.1. Average flow of reference mortar batches tested according to ASTM C230 at three temperature levels.

Average Flow of Reference Batches (%)		
23ºC	35ºC	50ºC
103.5	58.0	51.5

4.1.2 – Raw Retarders Tested at 35°C

For batches of mortar tested at 35°C, dosages of 0.025, 0.05 and 0.1% by solids weight relative to cement were utilized. This range in dosages was selected in an effort to try and establish the optimum level of retarder addition that produced the greatest positive impact on ameliorating the detrimental effects on compressive strength from curing at 35°C. Also, similarly to the previous section, impacts on the consistency of the batches was also measured and reported.

The 0.025% dosage rate for all retarders produced very little effect on compressive strengths at all ages, as can be seen in Figure 4.2. However, an initial reduction in the hydration rate and thus the early age compressive strength was observed. For the results at 28 days only the Sucrose produced a small gain in compressive strength of 2.2%.

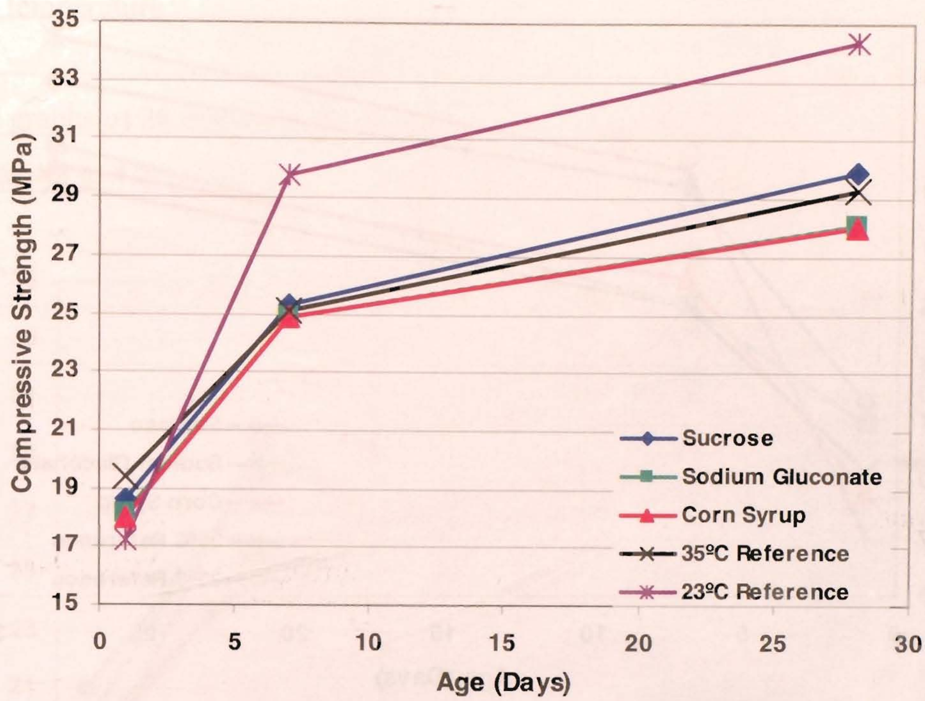


Figure 4.2. 1, 7 and 28 day compressive strength results for 0.025% retarder dosages cured at 35°C.

The next admixture addition rate tested was 0.05% solids by cement mass. At this dosage, both the Sucrose and Sodium Gluconate produced increases in compressive strength at 1 day of age in contrast to the reduction produced by the Corn Syrup. This was a common theme for the 0.05 and 0.10% dosage levels at 35°C. The Corn Syrup had a stronger retarding effect at early ages than both the other admixtures. The increases in compressive strength at 1 day created by the aforementioned retarders is thought to be due to their ability to moderately retard the concrete to allow a more uniform, consistent hydration to occur. However, it appears that the combination of high temperature and the use of retarders produced a beneficial synergistic effect at this test age as they not only negated any loss in strength but also produced a moderate positive effect.

When the mortar was tested at 28 days of age, the Sucrose continued to perform the best with a gain in strength of 12.1% compared to the next best, Sodium Gluconate with a 4.6% increase. The Sucrose produced only a minor increase in strength and was considered to be mostly ineffective. All three retarding admixtures had a significant effect on the water demand at this addition rate.

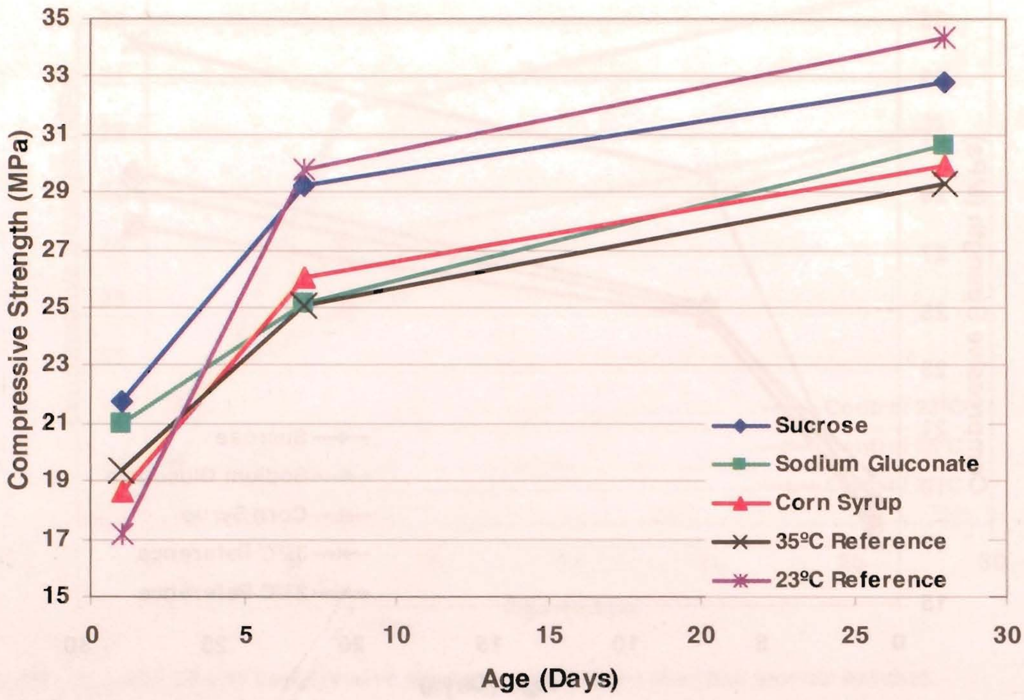


Figure 4.3. 1, 7 and 28 day compressive strength results for 0.05% retarder dosages cured at 35ºC.

The final dosage of retarder tested at this temperature level was 0.10%. The 1 day strength results recorded followed a similar pattern to those of the lower 0.05% dosage. However, the 7 day results produced a different pattern then the previously reviewed dosage. Sodium Gluconate produced the highest increase in strength from 1 to 7 days. This was followed by Sucrose and Corn Syrup. The 28 day results echoed this pattern with Sodium Gluconate producing the highest strength activity of 14.1%.

For this dosage level the Sodium Gluconate had the greatest improvement on flow with an increase of 36% followed by Sucrose and Corn Syrup when compared to the reference batch.

When all the 35ºC results are taken into perspective, the Sucrose had the most effect on compressive strength at the two lower dosage levels. However, Sodium Gluconate displayed the highest ability to ameliorate reductions in compressive strength at 35ºC when all dosages are reviewed. A dosage of 0.10% was able to produce 28 day strength results that were only 3.0% less then the reference mix cured at 23ºC. Also, Sucrose and

Sodium Gluconate displayed a very similar ability to reduce losses in consistency at elevated temperature.

Detailed graphs of 28 day strength activities for all batches at 35°C can be seen reported in Figures 4.5 to 4.7.

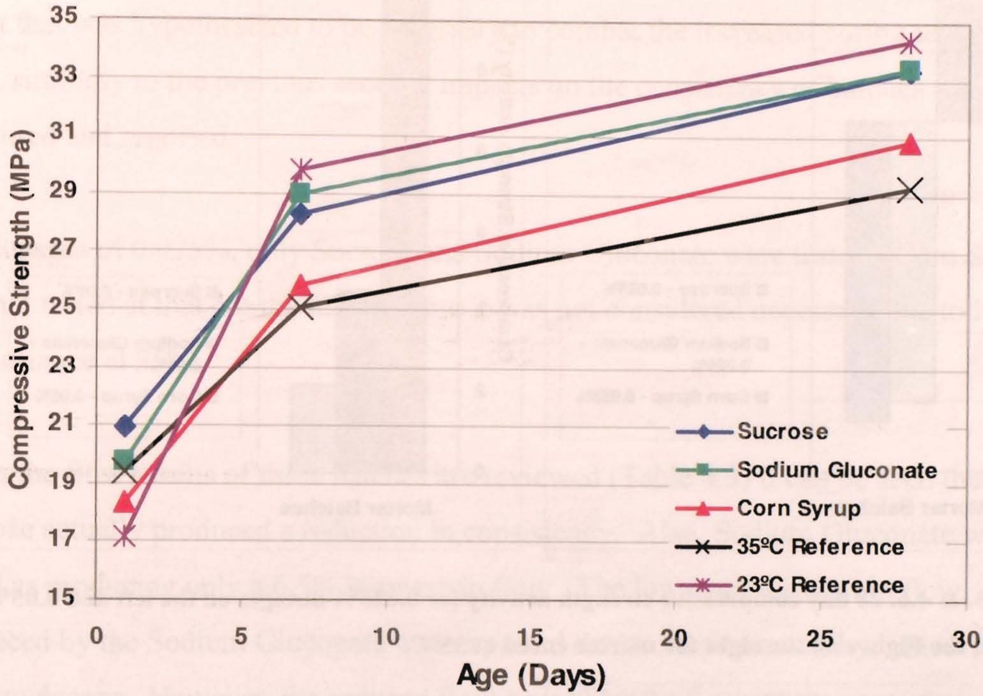


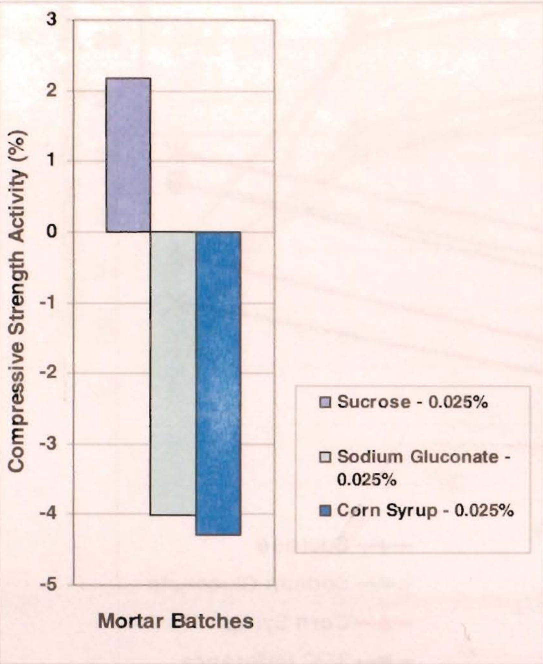
Figure 4.4. 1, 7 and 28 day compressive strength results for 0.10% retarder dosages cured at 35°C.

Table 4.2. Average flow of 35°C mortar batches tested according to ASTM C230.

	Average Flow at 35ºC (%)		
Dosage (%)	0.025	0.050	0.100
Sucrose	90.0	101.0	86.0
Sodium Gluconate	83.0	93.0	90.0
Corn Syrup	91.0	92.0	79.0
Reference	58.0		

4.1.3 – 28 Day Compressive Strength Activity Results for 35°C Results

All strength activities are reported as a percentage of the 28 day compressive strength achieved by the reference batch at 35°C.



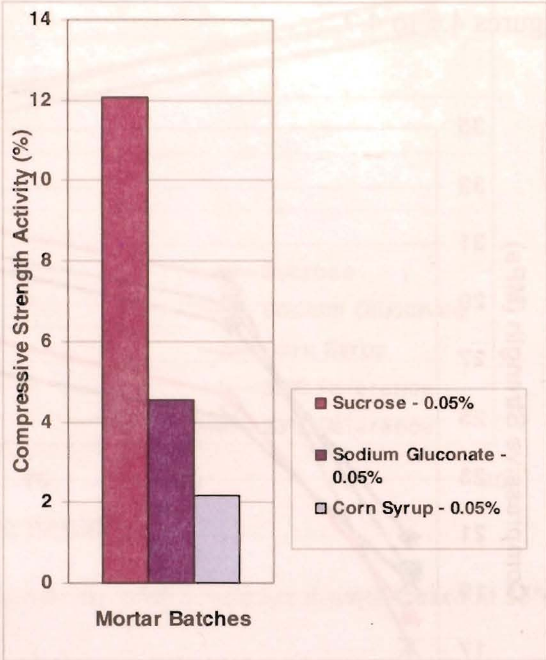


Figure 4.5. & 4.6. 28 day compressive strength activity for 0.025% dosages on the left and 0.05% dosages in the Figure on the right for mortar cured at 35°C.

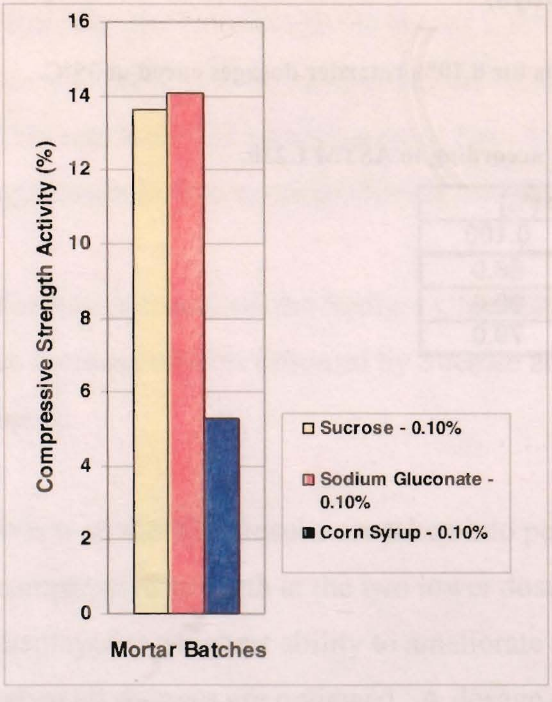


Figure 4.7. 28 day compressive strength activity for 0.10% dosages for mortar cured at 35°C.

4.1.4 – Raw Retarders Tested at 50°C

For batches of mortar tested at 50°C, dosages of 0.025, 0.05, 0.10, 0.15 and 0.20% by solids weight relative to cement were utilized. Similarly to the 35°C program, this range in dosages was selected in an effort to try and establish the optimum level of retarder addition. However, increased dosage rates were also tested due to the increased retarding effect that was hypothesized to be necessary to combat the increased curing temperature. Also, similarly to the previous section, impacts on the consistency of batches were also measured and reported.

For dosages of 0.025%, only Sucrose and Sodium Gluconate were tested. Corn Syrup was not tested at this dosage rate because it was not considered necessary due to its poor performance at 35°C.

When the flow results of these batches are reviewed (Table 4.3) it can be seen that the Sucrose actually produced a reduction in consistency. Also, Sodium Gluconate was noted as producing only a 6.5% increase in flow. The low improvement in flow produced by the Sodium Gluconate was expected due to the increased hydration rate and the low dosage. However, the reduced flow caused by the Sucrose was not expected. This illustrates the fact that a more complex relationship must be occurring between the hydration products of the cement and Sucrose. Also, the reduced consistency of the Sucrose batch could offer a possible explanation to the reduced compressive strengths achieved, due to this causing more difficulty with compaction, leading to a more permeable microstructure. However, this theory can not completely explain the reductions in strength due to Sodium Gluconate producing a small improvement in consistency while also producing a similar reduction in compressive strength.

Although the explanation of these results is inconclusive, the one conclusion that can be drawn is that a dosage of 0.025% was ineffective in ameliorating the compressive strength loss at 50°C.

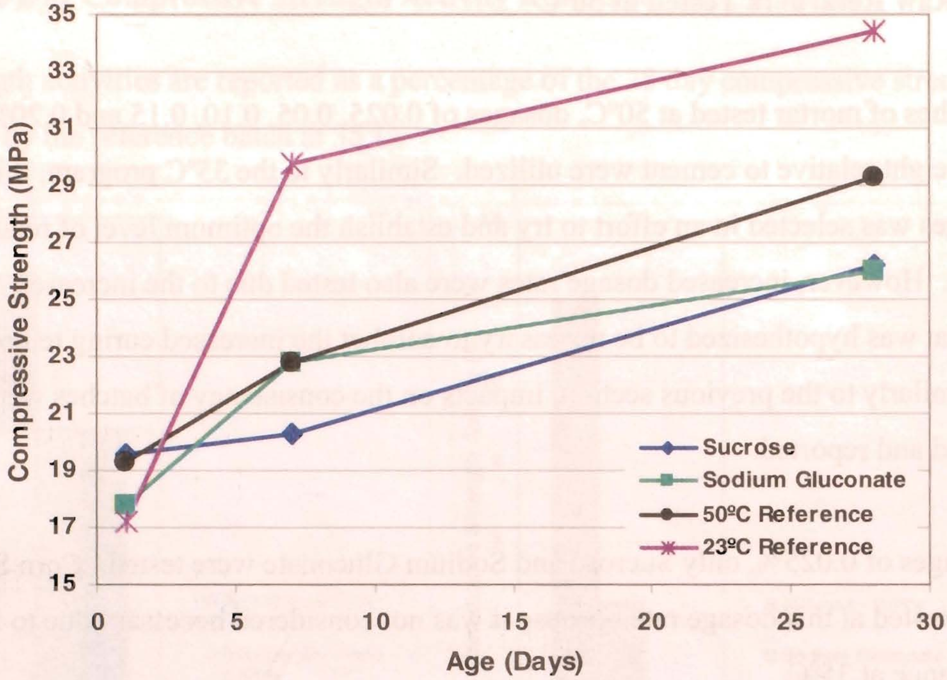


Figure 4.8. 1, 7 and 28 day compressive strength results for 0.025% retarder dosages cured at 50°C.

At s dosage of 0.05% the retarders had a more significant effect on the consistency of the mixes. Sucrose was able to maintain the flow of the reference batch and Sodium Gluconate and Corn Syrup were able to produce moderate increases in flow relative to the reference batch. This is thought to have occurred due to the stronger initial retarding effects of these admixtures. Compressive strength results can also be seen in Figure 4.9 below.

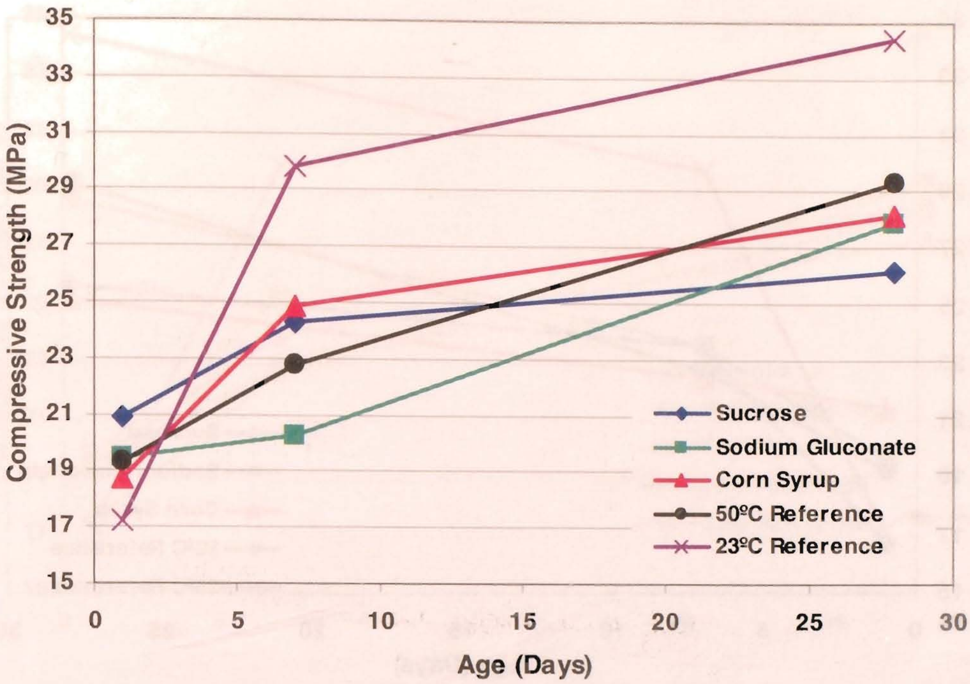


Figure 4.9. 1, 7 and 28 day compressive strength results for 0.05% retarder dosages cured at 50°C.

For the dosage of 0.10%, a change in the level of retardation at early ages was exhibited. Sucrose began to have more of a prominent retarding effect when compared to previous tests, including all samples cast at 35°C. Also the Corn Syrup began to have the least retarding effect at early ages which is the first time this behavior had been displayed. At 28 days of age, Sodium Gluconate was the only retarder that performed well. However, even this retarder still had a negative 28 day strength activity of 2.0% when compared to the reference batch.

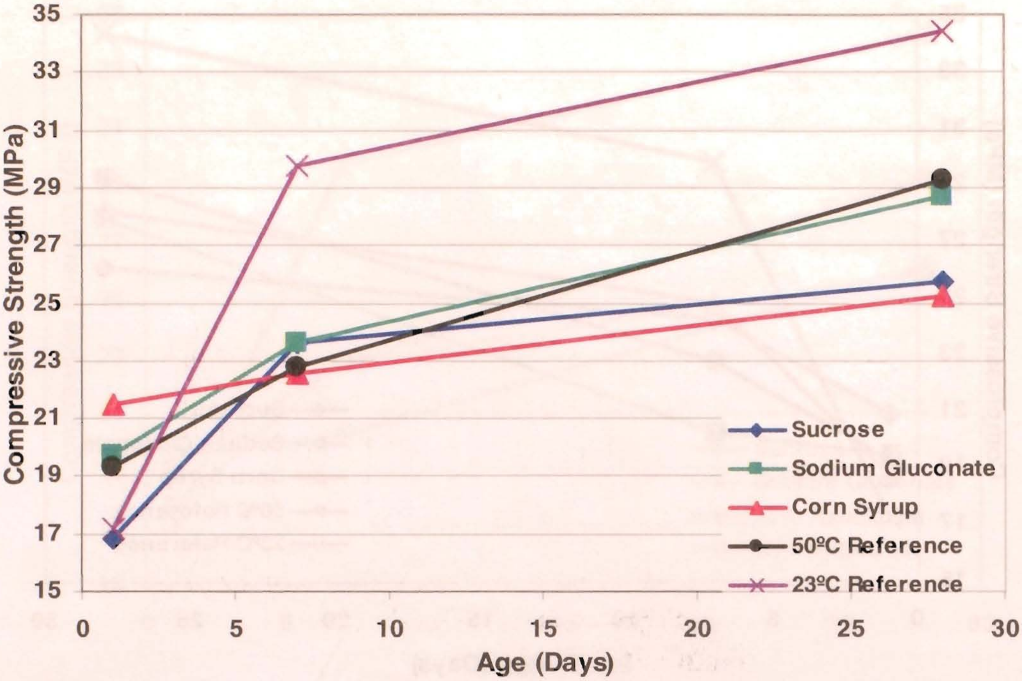


Figure 4.10. 1, 7 and 28 day compressive strength results for 0.10% retarder dosages cured at 50°C.

Next, mortar batches were mixed with a retarder dosage of 0.15%. At this dosage and the curing temperature of 50°C, all retarders failed to produce an increase in compressive strength at 28 days of age. Also, the Corn Syrup and Sucrose produced only moderate increases in flow.

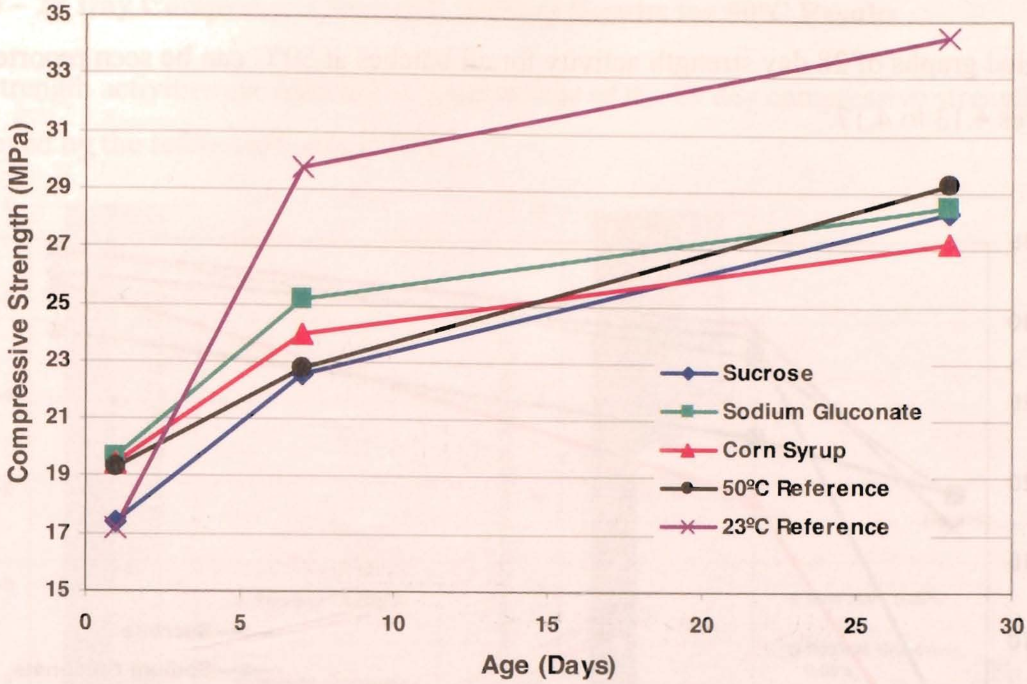


Figure 4.11. 1, 7 and 28 day compressive strength results for 0.15% retarder dosages cured at 50°C.

The final dosage rate tested with these three retarders was 0.20%. At this rate both the Corn Syrup and Sucrose caused extreme retardation of the mix at 1 day of age. This level of retardation exceeds accepted values and rules out this high dosage level for both retarders. In contrast to these two, the Sodium Gluconate produced 1 day strengths that were very similar to the reference batch. At the 50°C level of testing, the 0.20% dosage of Sodium Gluconate produced the most effective result in mitigating strength loss at 7 and 28 days. The 7 day strength of the mortar was only 7.3% below that of the 23°C reference and the 28 day result was equal to the 28 day 23°C results.

When the flow results are analyzed for the 0.20% Sodium Gluconate addition rate, only a 6.5% increase in flow was noted. As can be seen in Table 4.3, the Sodium Gluconate had only a limited water reducing effect at all dosage levels. However, when the flow results for all the batches cast at 50°C are compared based on their ability to provide a water reduction, it is apparent that no one retarder performed very well. As a result, the improvement in compressive strength provided by the Sodium Gluconate at elevated temperatures far exceeds any benefit achieved from water reduction of the other two retarders.

Detailed graphs of 28 day strength activity for all batches at 50ºC can be seen reported in Figures 4.13 to 4.17.

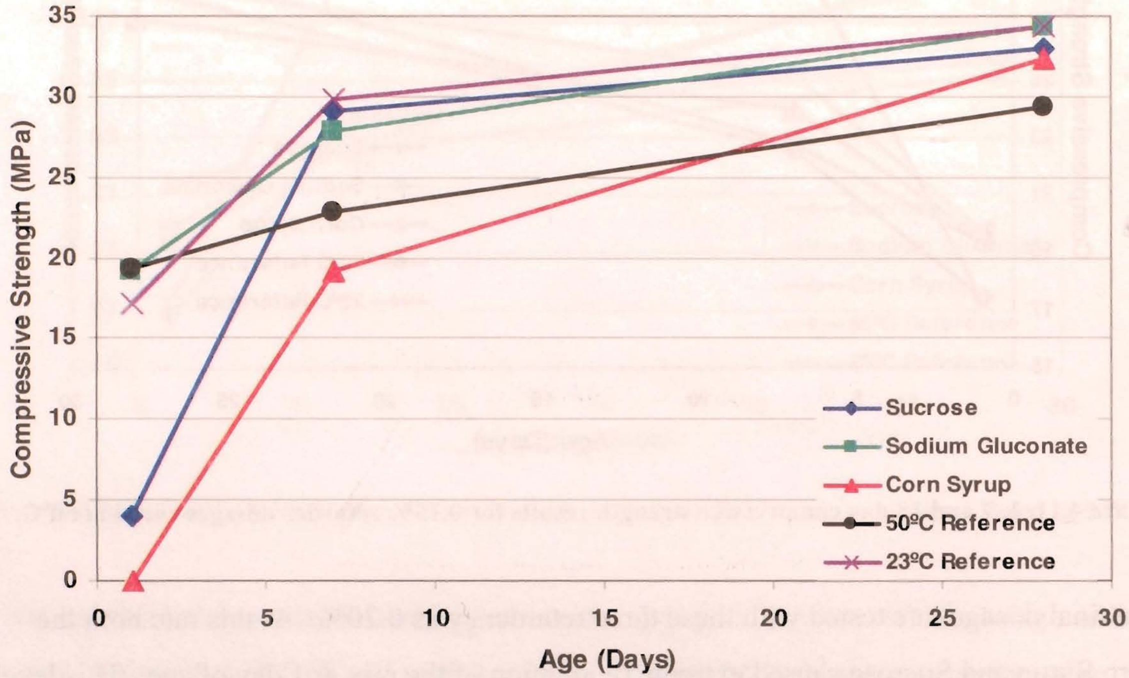


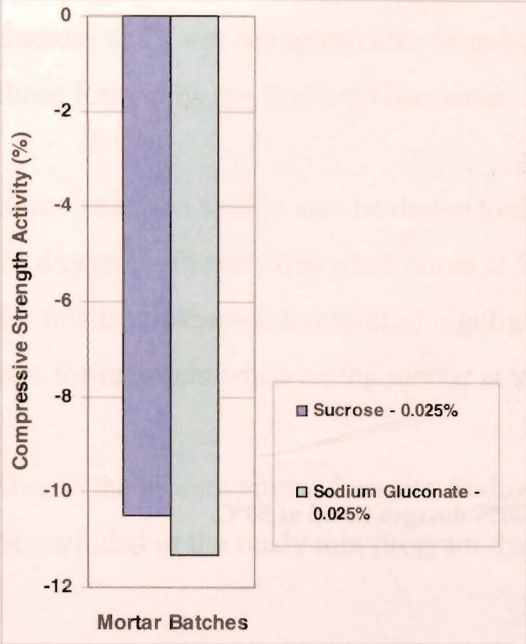
Figure 4.12. 1, 7 and 28 day compressive strength results for 0.20% retarder dosages cured at 50ºC.

Table 4.3. Average flow of 50ºC mortar batches tested according to ASTM C230.

	Average Flow at 50ºC (%)				
Dosage (%)	0.025	0.050	0.100	0.150	0.200
Sucrose	38.0	52.0	58.0	68.0	79.0
Sodium Gluconate	55.0	66.0	55.5	48.0	55.0
Corn Syrup	-	60.0	59.0	58.0	37.0
Reference	51.5				

4.1.5 – 28 Day Compressive Strength Activity Results for 50°C Results

All strength activities are reported as a percentage of the 28 day compressive strength achieved by the reference batch at 50°C.



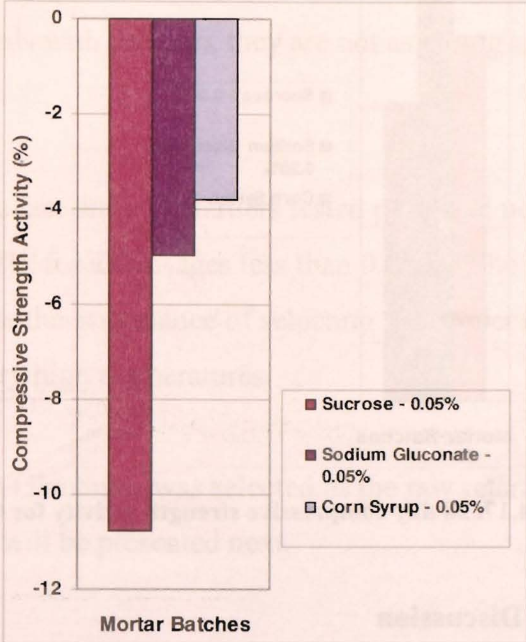
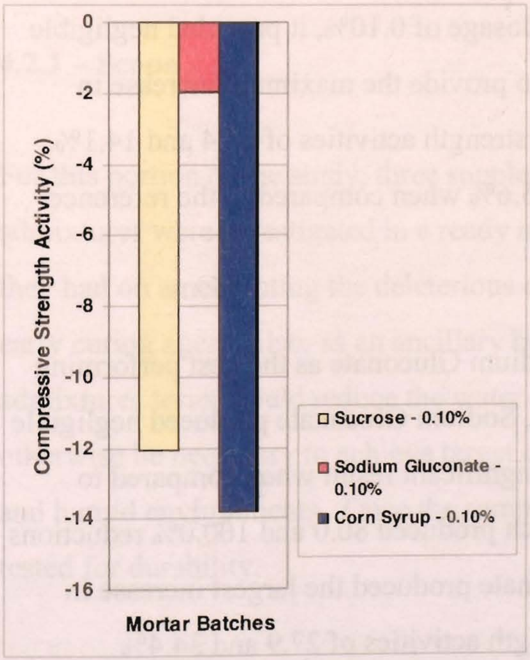


Figure 4.13. & 4.14. 28 day compressive strength activity for 0.025% dosages on the left and 0.05% dosages in the Figure on the right for mortar cured at 50°C.



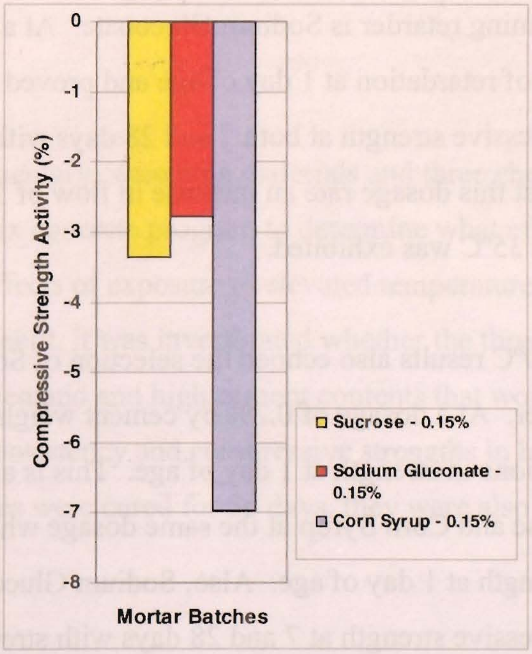


Figure 4.15. & 4.16. 28 day compressive strength activity for 0.10% dosages on the left and 0.15% dosages in the Figure on the right for mortar cured at 50°C.

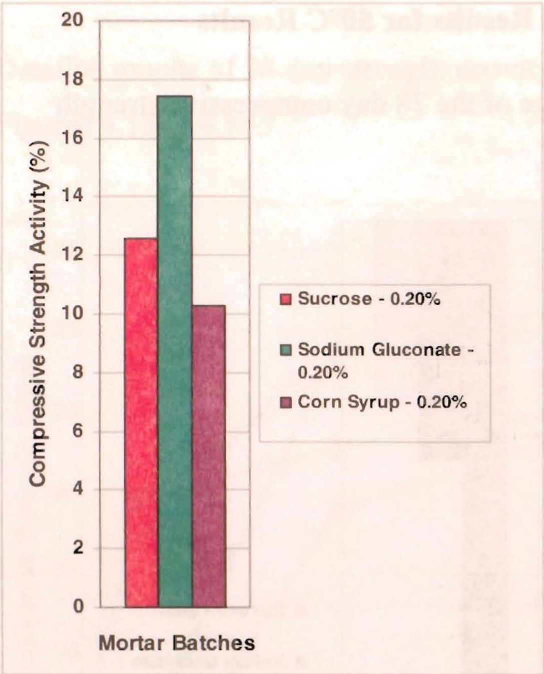


Figure 4.17. 28 day compressive strength activity for 0.20% dosages cured at 50°C.

4.1.6 - Discussion

When the 35°C results are analyzed in their entirety, it can be seen that the optimum performing retarder is Sodium Gluconate. At a dosage of 0.10%, it provided negligible levels of retardation at 1 day of age and proved to provide the maximum increase in compressive strength at both 7 and 28 days with strength activities of 15.4 and 14.1%. Also, at this dosage rate an increase in flow of 35.6% when compared to the reference mix at 35°C was exhibited.

The 50°C results also echoed the selection of Sodium Gluconate as the best performing retarder. At a dosage of 0.2% by cement weight, Sodium Gluconate produced negligible reductions in strength at 1 day of age. This is a significant result when compared to Sucrose and Corn Syrup at the same dosage which produced 80.0 and 100.0% reductions in strength at 1 day of age. Also, Sodium Gluconate produced the largest increase in compressive strength at 7 and 28 days with strength activities of 27.9 and 34.4% respectively.

It is hypothesized that Sodium Gluconate was able to perform more efficiently than both Sucrose and Corn Syrup because of its strong calcium chelating ability. Sodium Gluconate has the ability to form soluble, complex molecules with calcium ions, thus temporarily inactivating these ions and slowing down the hydration reaction. Although Sucrose and Corn Syrup can also form bonds with calcium, they are not as strong as those formed by the Sodium Gluconate.

Some attention should also be drawn to the fact that all retarders tested produced negative 28 day strength activities when cured at 50°C for all dosages less than 0.20%. The reason for this is not known, however, it highlights the importance of selecting the proper dosage rate for retarders when curing mortar at very high temperatures.

Due to the aforementioned results, Sodium Gluconate was selected as the raw retarder to be included in the ready mix program that will be presented next.

4.2 - Phase IIa: Experimental Results and Analysis for Ready Mix Concrete

4.2.1 – Scope

For this portion of the study, three supplementary cementing materials and three chemical admixtures were investigated in a ready mix concrete program to determine what effect they had on ameliorating the deleterious effects of exposure to elevated temperatures at early curing ages. Also, as an ancillary benefit, it was investigated whether the three admixtures tested could reduce the water demand and high cement contents that would otherwise be necessary to achieve target consistency and compressive strengths in hot and humid environments. Once the samples were cured for 56 days, they were also tested for durability.

Class C and F fly ash were selected for normal slump concrete testing based on their proven use in the concrete industry. They were also selected for their varying ability to influence the hydration of the cement paste through a pozzolanic reaction. Similarly, Grade 80 ground granulated blast furnace slag was selected for testing to help reduce the rate of cement hydration at increased temperatures.

After a review of Phase I of the research program, Sodium Gluconate was selected as the most effective raw admixture for cement mixtures cured at 35 and 50°C. It provided the greatest increase in compressive strength at 28 days without retarding the early age strength of mortar excessively. The other two chemical admixtures tested were proprietary admixtures. The first, HRWR, was a high range water reducer and the second, WR-Ret. Adm. was a retarding low range water reducer. There two admixtures were selected for testing based on their history of use in hot weather environments.

4.2.2 – Establishing the Target Cement Content

Once the aggregate and water contents had been established for the reference mix design, it was next necessary to ensure that the cement content used in preliminary testing was the optimum level for producing maximum compressive strengths. Initially mix calibration was performed utilizing a cement content of 450 kg/m³. This cement content was selected because it is at the upper suggested range for high performance concrete according to ACI. However, cement contents of 500 and 550 kg/m³ were also tested to ensure that 450 kg/m³ was appropriate for achieving maximum strength. The compressive strength results can be seen in Figure 4.18 below. It should be noted that the mixes presented below had their water cement ratios adjusted in order to maintain constant consistency.

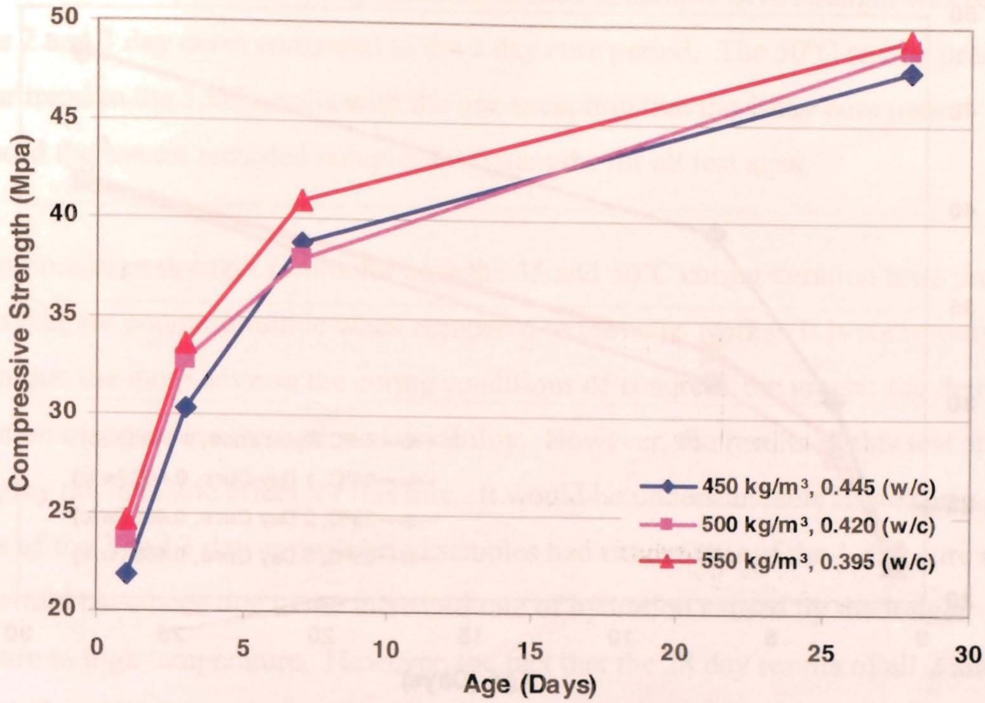


Figure 4.18. Compressive strength of ready mix concrete cured at 23°C with varying cement contents.

As a result of the limited improvement in compressive strength observed at 28 days of age, it was concluded that the 450 kg/m³ cement content was adequate and better represented real world application. Following this preliminary investigation, all further ready mix concrete was batched with a 450 kg/m³ cement content.

4.2.3 – Establishing the Duration of the High Temperature Cure Period

Once the final mix design had been established, it was next necessary to determine the duration of the high temperature curing period that would produce the most detrimental impact on compressive strength and by extension, durability. Batches of ready mix concrete were mixed and moulded in 100 x 200 mm cylinders according to the procedures outline in Section 3.4. The cylinders were all cured in the same manner with the exception that individual batches were cured for 1, 2 or 3 days at 35 and 50°C. The average compressive strength results of three cylinders tested at 1, 3, 7 and 28 days for the three curing durations can be seen in Figures 4.19 & 4.20 below.

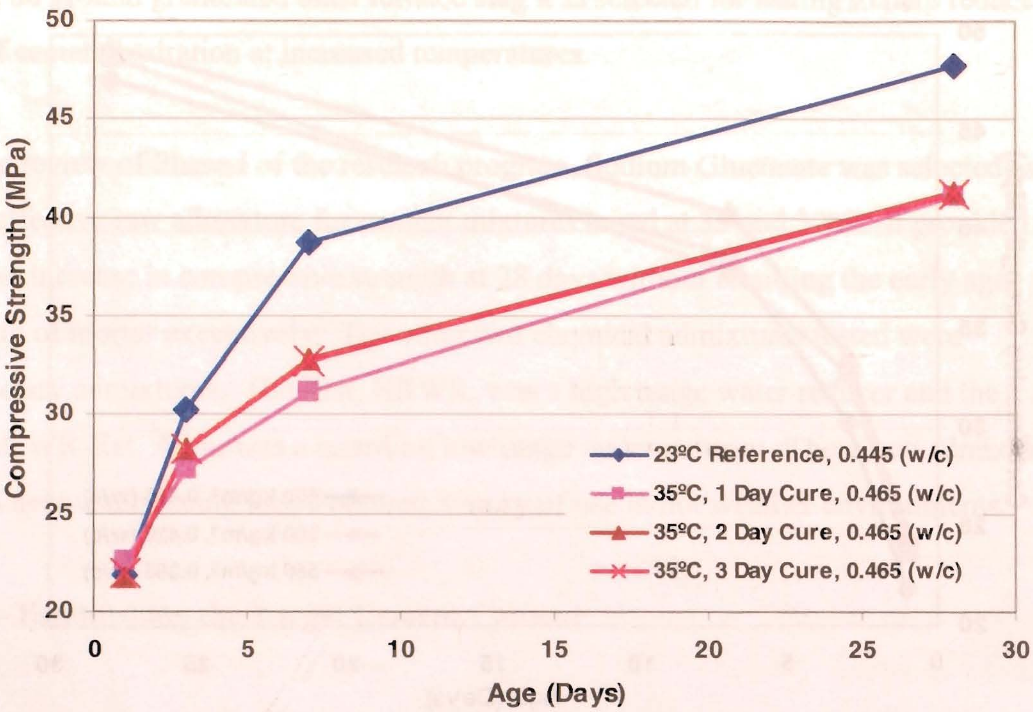


Figure 4.19. Compressive strength of ready mix concrete cured at 35°C for varying duration.

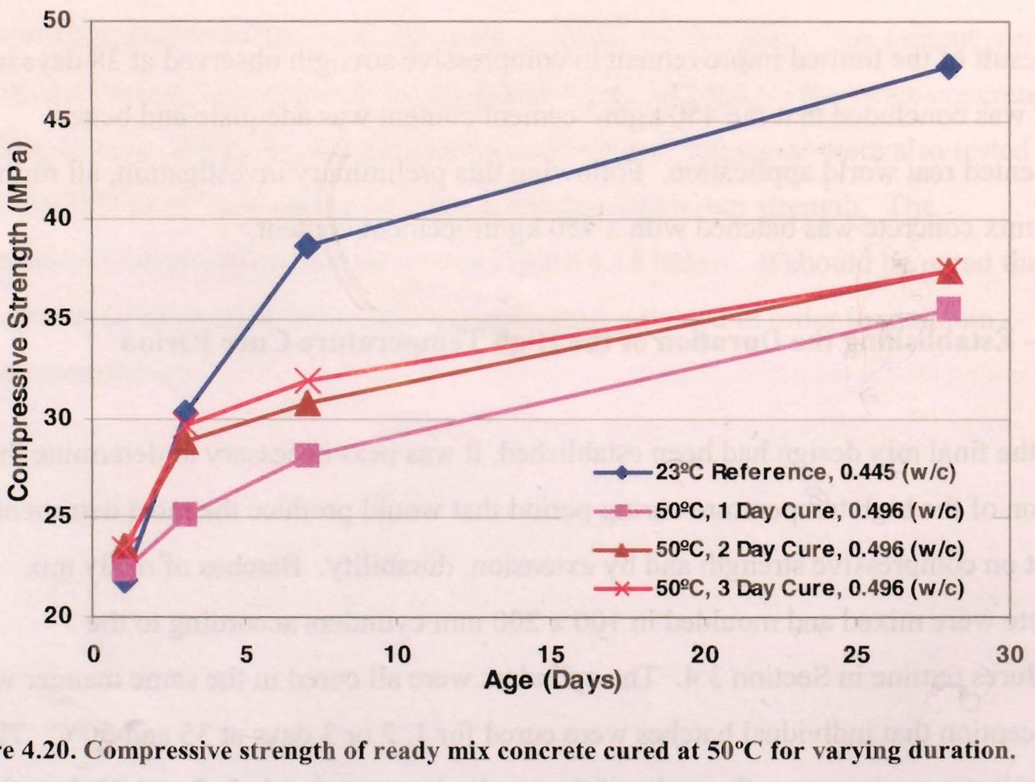


Figure 4.20. Compressive strength of ready mix concrete cured at 50°C for varying duration.

For the 35°C 28 day results, a negligible difference in compressive strength was recorded for the 2 and 3 day cures compared to the 1 day cure period. The 50°C results produced a similar trend to the 35°C results with the one exception that the 1 day cure period produced the lowest recorded compressive strengths for all test ages.

The compressive strength results for both the 35 and 50°C curing duration tests produced results that are counterintuitive when compared to previous works. It is commonly known that the more adverse the curing conditions of concrete, the greater the detrimental impact on compressive strength and durability. However, the results of this test appeared to display the opposite effect for this mix. It would be understandable if the early age results of the 2 and 3 day curing period samples had exceed that of the 1 day cure results. This would have been due to the increased rate of hydration caused by the longer exposure to high temperature. However, the fact that the 28 day results of all 2 and 3 day tests produced higher compressive strengths then the 1 day curing period was not expected. It is hypothesized that the sustained high temperature curing regime performed at in a controlled 100% RH environment helped produce a more completely hydrated microstructure. If the humidity had been reduced to simulate an arid environment it is thought that the longer curing period at high temperature would have produced a greater detrimental impact on compressive strength.

Although the results obtained in this portion of the study were not entirely expected, they all were uniform and gave a clear conclusion for the necessary high temperature curing, a period of 1 day (or 24 hours). Also, the effect that higher curing temperatures had on compressive strengths when compared to curing at 23°C, at constant consistency, was also very clear. As a result of this data, a high temperature curing period of 1 day was selected for all further testing.

4.3 – Ready Mix Concrete Cured at 23°C, Results and Analysis

4.3.1 – 25 and 40% GGBFS Cured at 23°C

Before batching at high temperature could be performed, it was first necessary to establish the impact of the SCMs and chemical admixtures utilized in this program on concrete batched and cured at 23°C. It should be noted that the concept of constant consistency was continued for this portion of the program. If added constituents produced an increase in consistency due to an intrinsic water reduction, the water content was adjusted accordingly to maintain a slump of 100+/-10mm.

The first SCM tested was Grade 80 ground granulated blast furnace slag (GGBFS). Cement substitution rates of 25 and 40% were selected and maintained throughout the entire program after an extensive literature review. These dosages were predicted to provide both a mid range impact on concrete properties with 25% addition and a maximum impact at 40% addition.

Although this SCM did not provide a water reduction at a 23°C batching temperature, it did produce an impact on compressive strength. As expected, the slag caused a reduction in compressive strength at the early test ages of 1, 3 and 7 days. This result was caused due to the slower hydrating rate of Grade 80 GGBFS in comparison to Portland cement. It is common knowledge that at room temperature the pozzolanic and hydraulic reaction rate of slag decreases early age strengths. However, when the 28 day compressive strength results are investigated, it can be seen that the 25% addition of slag produced an increase in strength activity of 7.3%. This result is indicative of published results whereby when slag mixes are allowed to cure for adequate amounts of time, increases in compressive strength when compared to Portland cement concrete are possible. It should be noted that the 40% addition rate of slag at this curing temperature produced a reduction in compressive strength at 28 days. The average compressive strength results of all cylinders tested with GGBFS at 23°C can be seen in Figure 4.21.

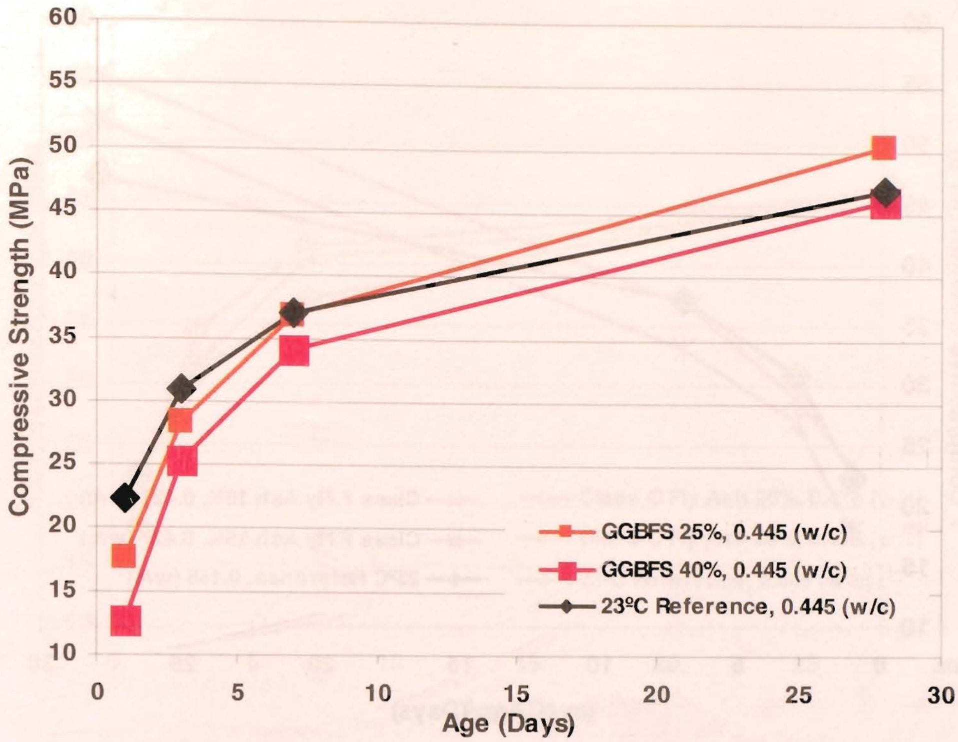


Figure 4.21. Compressive strength of ready mix concrete with GGBFS cured at 23°C.

4.3.2 – 15 and 25% Class F Fly Ash Cured at 23°C

Following the investigation of GGBFS, concrete containing cement substitution rates of 15 and 25% Class F fly ash were tested. These substitution rates were selected based on information gathered from the literature review. It was hypothesized that the 15% Class F fly ash would provide a mid range impact for improving compressive strength and 25% Class F fly ash would be at the upper end of the cement substitution limit based on the high reactive silica content.

For this SCM, the 15% addition rate produced an increase in compressive strength at 1 day of age. It should be noted that both addition rates produced a 4.0% water reduction at 23°C. It is hypothesized that the water reduction had a strong impact on the increase in strength of the 15% addition rate at 1 day of age. The 28 day results demonstrated the benefit of adding a pozzolanic material to Portland cement as strength increases of 17.8 and 9.9% were recorded for the two dosage rates. The results of all compressive strength tests for this SCM can be seen illustrated in Figure 4.22.

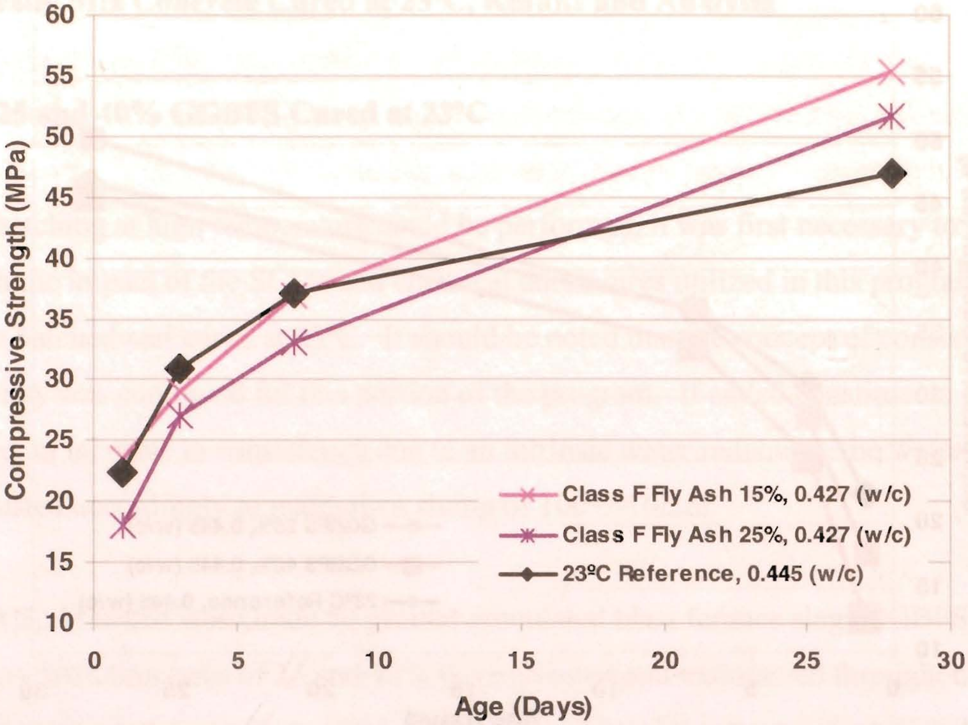


Figure 4.22. Compressive strength of ready mix concrete with Class F fly ash cured at 23°C.

4.3.3 – 20 and 30% Class C Fly Ash Cured at 23°C

When Class C fly ash was tested with cement replacement rates of 20 and 30% a similar relationship as exhibited by Class F fly ash above was recorded. Moderate strength reductions were recorded at the 1 day test age. However, it is predicted that these reductions in strength would have been even greater had it not been for a water reduction of 6.1%. The effects of the slower pozzolanic reaction can clearly be seen at this test age. At 28 days, reductions in strength activity were recorded. This result was unexpected and can be explained by the faster hydration rate of the Portland cement mix or the fact that high calcium fly ash may contain less reactive silica then the Class F ash. It is predicted that if these samples were allowed to cure for a more extended period of time the compressive strength of the Class C fly ash supplemented mixtures would exceed that of the Portland cement mix.

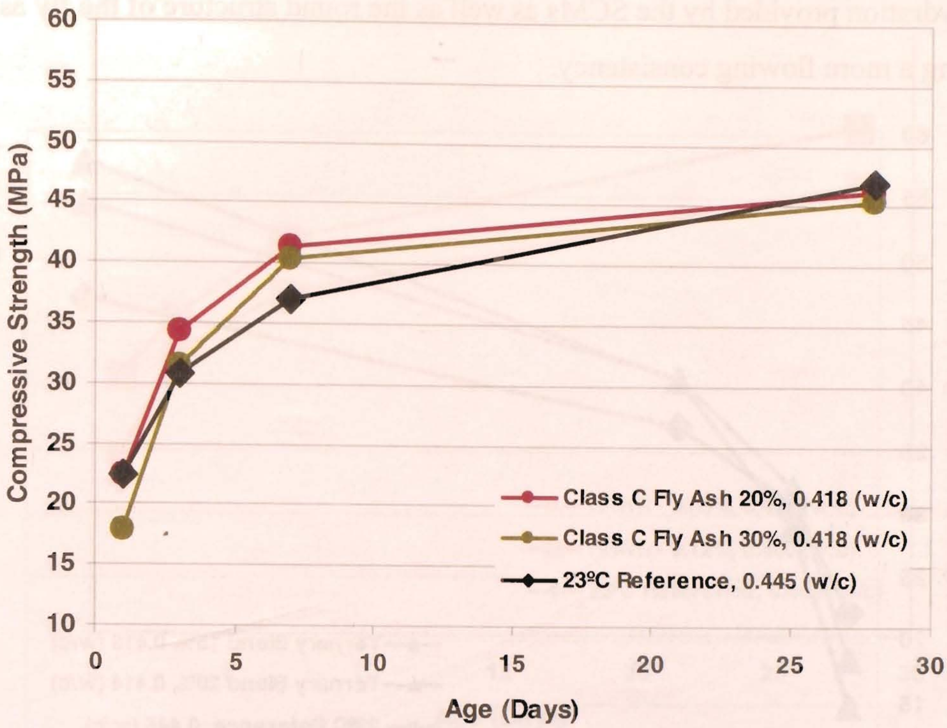


Figure 4.23. Compressive strength of ready mix concrete with Class C fly ash cured at 23°C.

4.3.4 – 15 and 20% Ternary Blends Cured at 23°C

The last supplementary cementing material tested was a combination of Class C fly ash and GGBFS. The early age strengths produced by these blends of SCM's were lower than the reference concrete, as was expected. The large dosage and slower reaction rate of the ternary blends caused a reduction in compressive strength at 1 day of age. However, the mixes experienced a substantial strength gain at 3 days of age. This rapid increase in strength from 1 to 3 days is thought to have occurred due to the combined hydraulic and pozzolanic reaction of the cement and SCM's. The strength results at 7 and 28 days demonstrated the ability of ternary blends to significantly increase the later age compressive strength of ready mix concrete. This is accomplished through a more uniformly hydrated microstructure. Strength activities of 15.9 and 22.7% were recorded for the 30 and 40% addition rates at 28 days of age. It should also be noted that a water reduction of 6.0 and 7.0% for the 30 and 40% additions also helped to contribute to increased strength activities. This water reduction was produced as a result of a slower rate of hydration provided by the SCMs as well as the round structure of the fly ash facilitating a more flowing consistency.

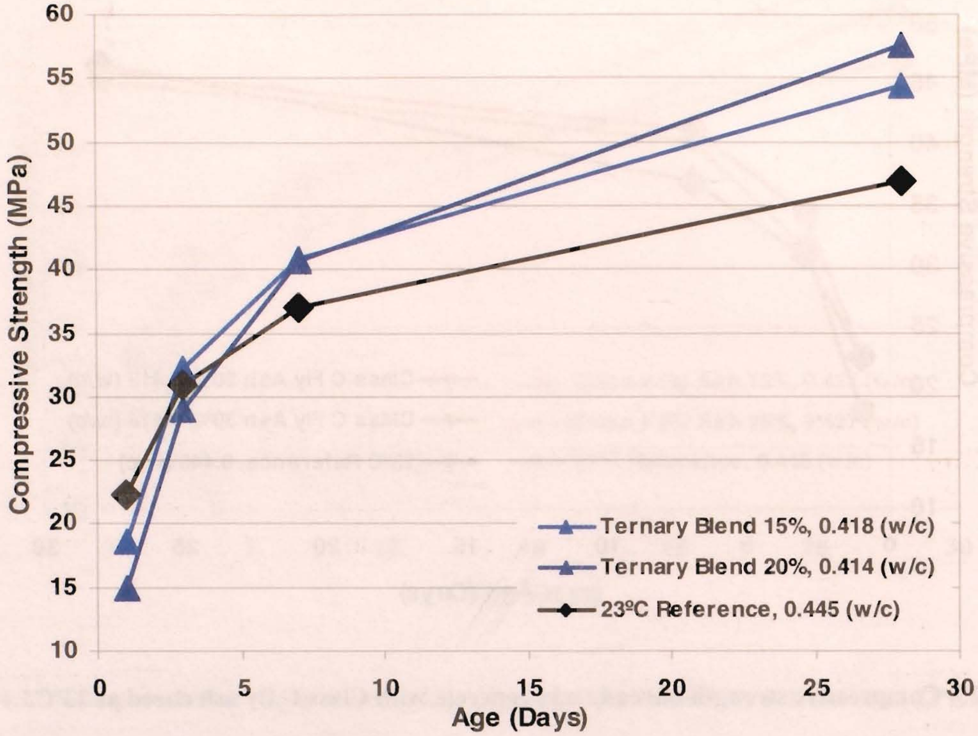


Figure 4.24. Compressive strength of ready mix concrete with a ternary blend of class C fly ash and GGBFS cured at 23ºC.

4.3.5 – 0.05 and 0.12% HRWR Cured at 23ºC

For batching at 23ºC, two dosages were selected that produced water reductions of 5.0 and 10.0% respectively. These dosages were 0.05% (or 140mls/100kg cement) and 0.12% (or 220mls/100kg cement). The water reductions were set based on the principle of constant consistency and it was hoped that by doing this the ability of water reduction to positively effect deleterious strength and durability activities could be investigated.

At 23ºC both dosages of the admixture had an immediate positive effect on compressive strength. Simply by reducing the water demand of the ready mix batches by 5 and 10% resulted in large gains in strength at 1 day of age. It should be noted that these water reductions also produced a large increase in durability which will be presented in a following section.

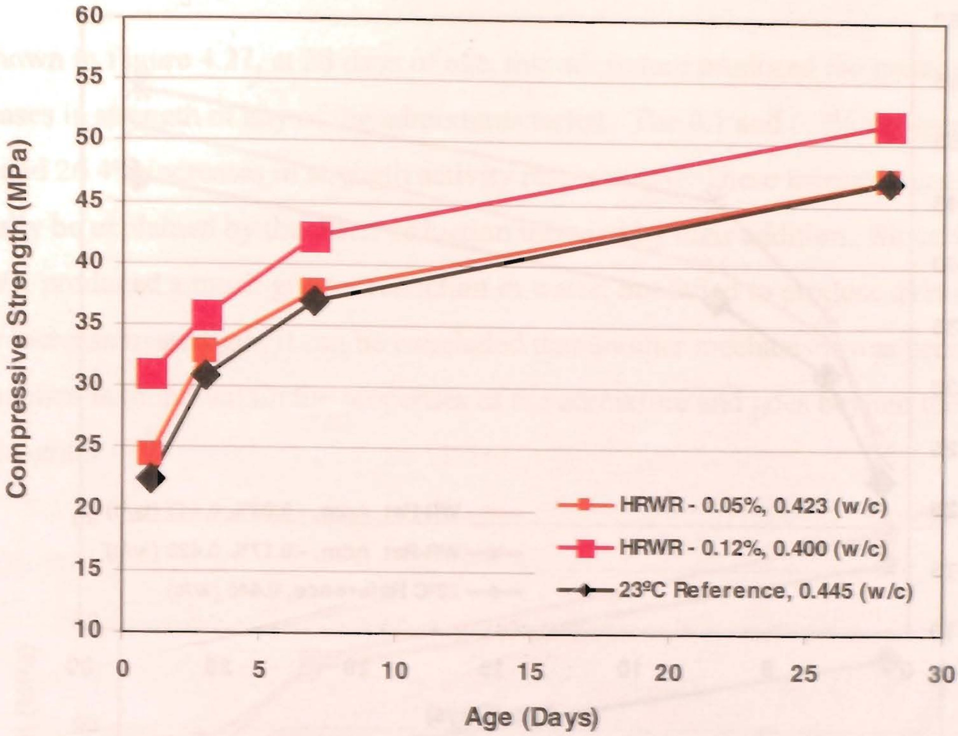


Figure 4.25. Compressive strength of ready mix concrete with HRWR cured at 23ºC.

4.3.6 – 0.08 and 0.17% WR-Ret. Adm. Cured at 23ºC

For this portion of the study, two dosages were selected for testing. The first, 0.08% (or 173.6mls/100kg of cement) was selected to illustrate only a retarding effect on compressive strength, while the higher 0.17% (or 347.2mls/100kg of cement) dosage was selected based on its ability to produce both a retarding effect and a low range, 5.0% water reduction. When samples were tested at 1 day of age, increases in strength were recorded. The strength activities of these two dosages at 1 day of age indicate that the higher dosage had more of a retarding effect then the lower dosage which was to be expected. The author has not been able to conclude exactly why this relationship occurred at this curing temperature. The partial explanation comes from the water reduction incurred by the higher dosage of admixture. However, further investigation is necessary to fully explain this phenomenon.

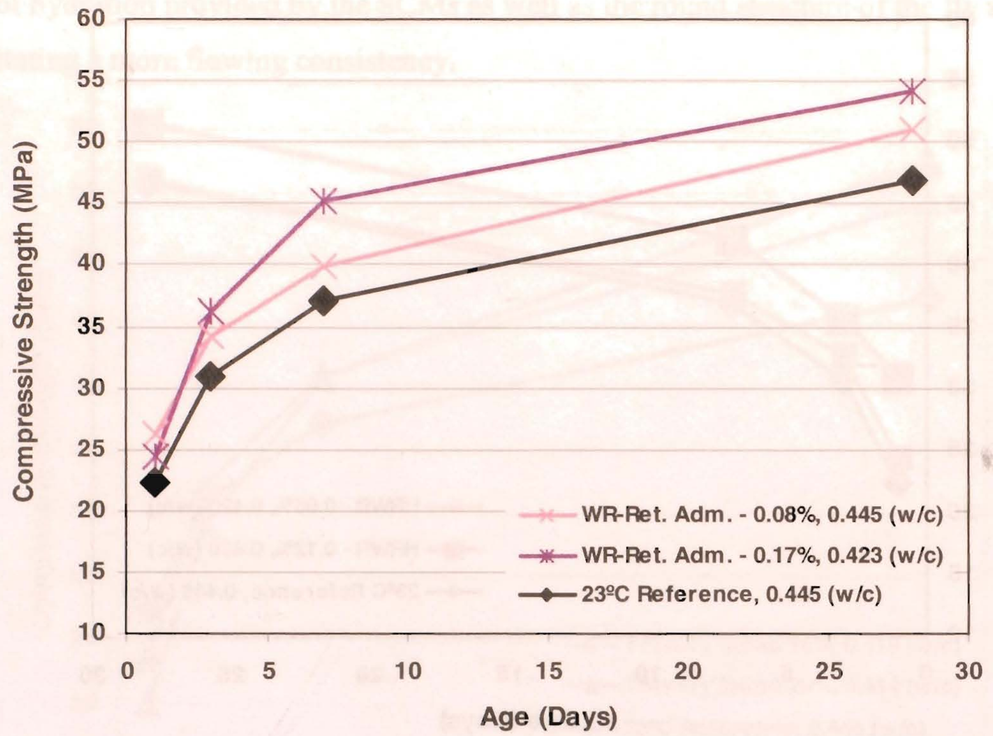


Figure 4.26. Compressive strength of ready mix concrete with WR-Ret. Adm. cured at 23°C.

4.3.7 – 0.1 and 0.2% Sodium Gluconate cured at 23°C

The final chemical admixture tested in this study was selected based on its performance in Phase I of the program. Similarly to the selection of dosages for the WR-Ret. Adm., dosages of 0.1 and 0.2% Sodium Gluconate, solids relative to cement, were selected based on both their retarding and water reducing abilities. The lower 0.1% dosage was selected to provide a moderate level of retardation with a low 2.5% water reduction. The higher 0.2% dosage was selected as the maximum based on a strong retarding effect and a moderate 5% water reduction.

Just like the admixture analyzed above, Sodium Gluconate produced increased compressive strengths at low dosage, for tests conducted at 1 day of age and the higher dosage produced a reduction in compressive strength. As can be seen from the results, the 0.2% dosage had an over powering retarding effect at this curing temperature. However, this dosage was still utilized at higher temperatures due to its high performance recorded in Phase I of the program.

As shown in Figure 4.27, at 28 days of age, this admixture produced the greatest increases in strength of any of the admixtures tested. The 0.1 and 0.2% dosages produced 19.7 and 26.4% increases in strength activity respectively. These increases can only partially be explained by the water reduction incurred by their addition. Since the HRWR produced a much greater reduction in water, but failed to produce as much or more increase in strength, it can be concluded that another mechanism was present. That mechanism is found within the properties of the admixture and goes beyond the scope of this program.

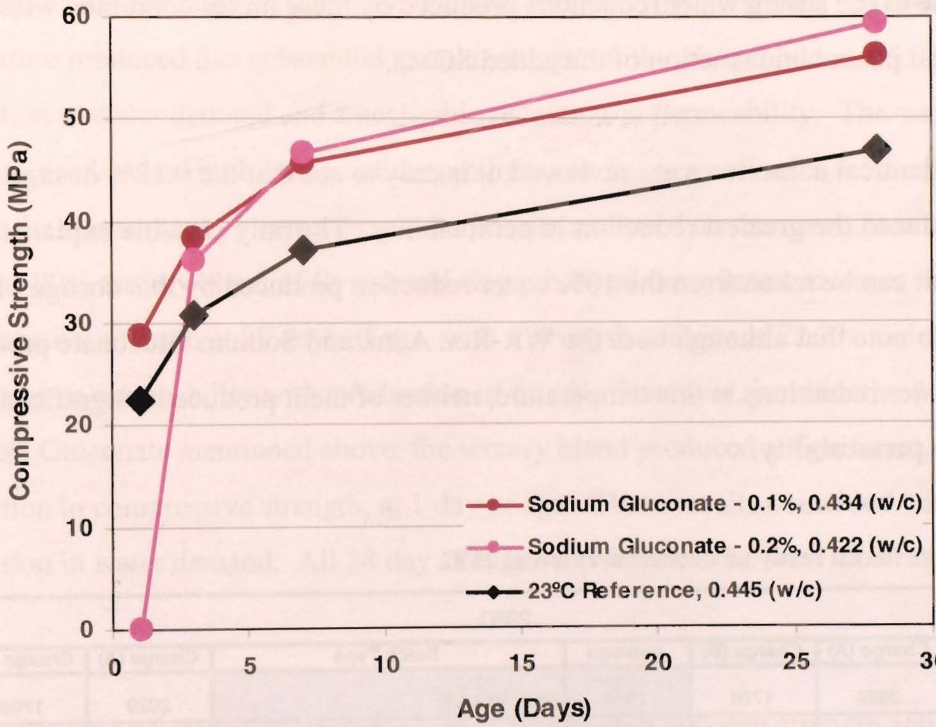


Figure 4.27. Compressive strength of ready mix concrete with Sodium Gluconate cured at 23°C.

4.3.8 – RCPT results for concrete cured at 23°C

For all ready mix concrete batched and cured at 23°C, all SCMs tested had an impact on permeability and by extension, durability. The reference mixes produced an average charge permeability of 1914 coulombs when tested for RCPT. This was the greatest average permeability for all cylinders tested. When the SCMs are analyzed alone, it can be seen illustrated in Table 4.4 that all SCMs produced a reduced permeability with increases in dosages. Out of the individual SCMs tested, the Class F fly ash dosages had the greatest effect on permeability with reductions of 55.0 and 64.0% recorded. It is hypothesized that this occurred due to a refinement of the microstructure, caused by a combination of reduced mix water content and the finer grain structure of the fly ash when compared to Portland cement. Also, the low calcium content of the Class F fly ash combined with the resulting pozzolanic reaction produces a reduction in calcium hydroxide in the paste structure and leads to a more dense, less permeable microstructure. However, when the Ternary blends are analyzed, it can be seen that they in fact produced the greatest reductions in permeability for all SCMs tested. It is hypothesized that this occurred due to the strong water reductions produced by these mixes combined with the hydraulic and pozzolanic reaction of the added SCMs.

When the chemical admixtures are reviewed, it is easy to see that the 0.12% dosage of the HRWR produced the greatest reduction in permeability. The only possible explanation for this result can be taken from the 10% water reduction produced by this dosage. It is interesting to note that although both the WR-Ret. Adm. and Sodium Gluconate produced moderate water reductions at this temperature, neither of them produced a significant reduction in permeability.

Table 4.4. RCPT results for all ready mix concrete cured at 23°C.

23°C							
Batch Type	Charge (A)	Charge (B)	Average	Batch Type	Charge (A)	Charge (B)	Average
REFERENCE	2029	1798	**1914**	REFERENCE	2029	1798	**1914**
25% GGBFS	1320	1300	**1310**	0.05% HRWR	1623	1657	**1640**
40% GGBFS	1058	1030	**1044**	0.12% HRWR	1421	1276	**1349**
20% CLASS C FLY ASH	897	955	**926**	0.08% WR-Ret. Adm.	1888	1854	**1871**
30% CLASS C FLY ASH	824	943	**884**	0.17% WR-Ret. Adm.	2198	1740	**1969**
15% CLASS F FLY ASH	839	884	**862**	0.1% SODIUM GLUCONATE	1766	1578	**1672**
25% CLASS F FLY ASH	750	625	**688**	0.2% SODIUM GLUCONATE	1925	1932	**1929**
15% TERNARY BLEND	692	888	**790**				
20% TERNARY BLEND	655	660	**658**				

4.3.9 – Ready Mix Concrete Cured at 23°C, Results Discussion

For the ready mix concrete batched and cured at 23°C, the best performing mix in terms of increased strength activity relative to the reference mix was the 0.2% Sodium Gluconate batch. The 28 day samples produced a strength activity of 26.1% relative to the reference batch as can be seen in Table 4.5 below. However, it should be noted that the 1 day strengths were completely retarded and a negligible value for compressive strength was recorded. Although this effect occurred at 1 day of age, it was predicted that this dosage would perform well at higher temperatures where the increased rate of hydration could counter act the early retarding effects. Also, it should be noted that this admixture produced this substantial gain in strength with only a moderate, 5.0% reduction in water demand and a negligible reduction in permeability. The water demand of all mixes batched in this stage of the program can be seen in Tables 4.5 and 4.6 below. When the supplementary cementing materials are analyzed on their own, it is plain to see that the 20% ternary blend of fly ash and slag produced the greatest increase in compressive strength at 28 days of age, with a strength activity of 22.7% and the greatest reduction in permeability with a reduction of 65.6%. However, just like the dosage of Sodium Gluconate mentioned above, the ternary blend produced a significant, 32.8% reduction in compressive strength, at 1 day of age. These results coincided with a 7.0% reduction in water demand. All 28 day strength activities can be seen illustrated in Figure 4.28.

It should also be noted that, there is no clear relationship between strength activity and water reduction. In fact, there are batches, such as the 20 and 30% Class C fly ash that produced a moderate water reduction of 6.0% but failed to produce positive strength activities. From these results it is easy to see that there are many other mechanisms involved with producing differences in compressive strength. Also, when the RCPT results are reviewed it is plain to see that only the SCMs had a positive effect in reducing permeability. Although they did not produce the greatest increases in strength activity, all the SCMs cannot be ruled out for use due to their positive effect on durability.

All strength activities are reported as a percentage of the 28 day compressive strength achieved by the reference batch at 23°C.

Table 4.5. 28 day compressive strength activities, water cement ratios and % water reductions of ready mix concrete batched with SCMs and cured at 23°C.

	Reference	GGBFS		Class F Fly Ash		Class C Fly Ash		Ternary Blend	
		25%	40%	15%	25%	20%	30%	15%	20%
28 DayStrength Activity (%)		7.27	-1.77	17.79	9.92	-1.41	-3.39	15.91	22.72
W/C Ratio	0.445	0.445	0.445	0.427	0.427	0.418	0.418	0.418	0.414
% Water Reduction		0.00	0.00	4.04	4.04	6.07	6.07	6.07	6.97

Table 4.6. 28 day compressive strength activities, water cement ratios and % water reductions of ready mix concrete batched with chemical admixtures and cured at 23°C.

	Reference	Commercial Material #1		Commercial Material #2		Sodium Gluconate	
		0.05%	0.12%	0.08%	0.17%	0.1%	0.2%
28 DayStrength Activity (%)		0.32	10.33	8.75	15.43	19.65	26.35
W/C Ratio	0.445	0.423	0.400	0.445	0.423	0.434	0.422
% Water Reduction		4.94	10.11	0.00	4.94	2.47	5.17

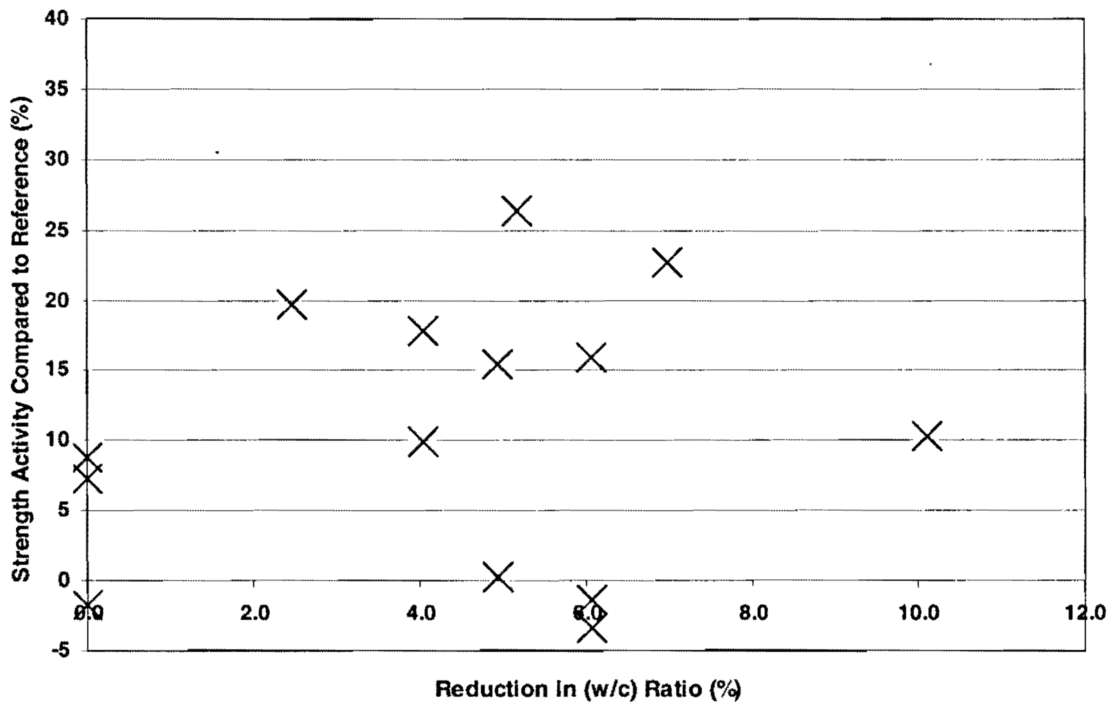


Figure 4.28. 28 day compressive strength activity of ready mix concrete cured at 23°C. vs. reduction in water cement ratio compared to reference.

This graph was included to show that a reduction in w/c ratio does not fully justify or explain the enhancement in strength achieved for some of the samples.

4.4 – Ready Mix Concrete Cured at 35°C, Results and Analysis

4.4.1 – 25 and 40% GGBFS cured at 35°C

At this curing temperature, the GGBFS produced no reduction in water demand and only a moderate increase in 28 day strength. The 28 day strength activities were recorded as 5.8 and 5.4% for the 25 and 40% GGBFS dosages, when compared to the 35°C reference mix. This gain in strength relative to the reference mix is thought to have occurred due to the slower rate of hydration of the slag mixtures resulting in a less permeable more densely hydrated micro structure. However, when the 28 day strength results are compared to the 23°C reference batch, strength reductions of 11.9 and 12.3% are noted.

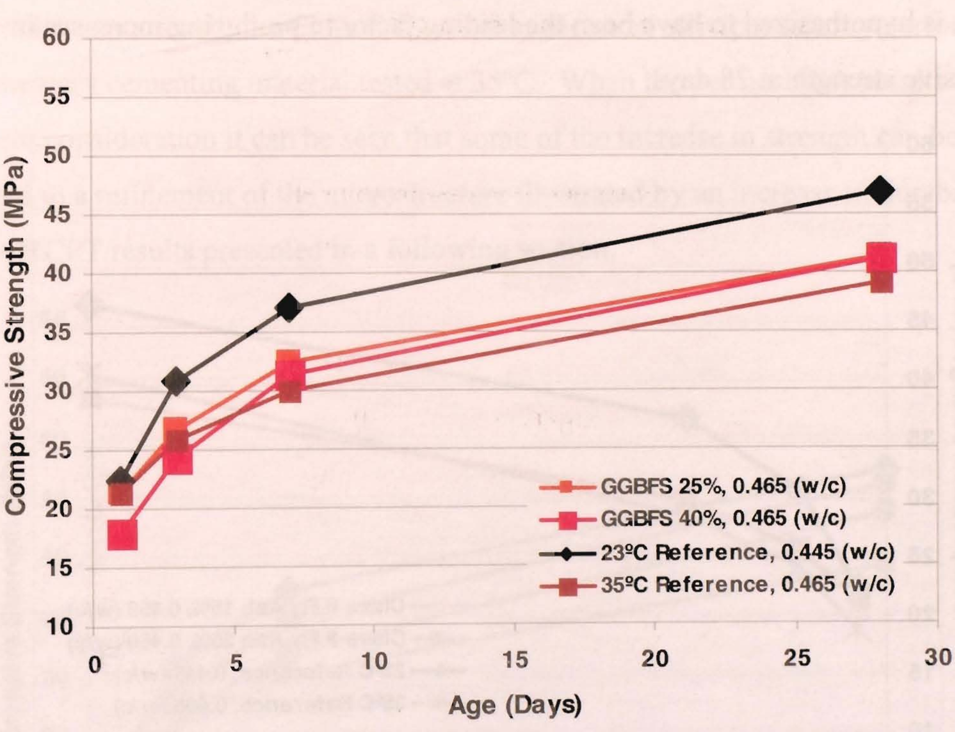


Figure 4.29. Compressive strength of ready mix concrete with GGBFS cured at 35°C.

4.4.2 – 15 and 25% Class F Fly Ash cured at 35°C

Dosages of 15 and 25% Class F fly ash by total cement volume replacement were utilized next. The Class F fly ash mixes produced similar strength activities to that of the GGBFS analyzed above. However, unlike the GGBFS, the Class F fly ash produced a 3.2% reduction in water demand. Also, the Class F fly ash appears to have hydrated at a slower rate then the slag above. This was expected due to the purely pozzolanic nature of this SCM. The 28 day results were very similar to the GGBFS with gains in strength of 6.2 and 5.3% for the 15 and 25% dosages respectively. The gain in strength produced by this material can be partially attributed to the reduction in water demand. Also, refinements in microstructure as made evident by the reduced permeability of these samples, is hypothesized to have been the leading factor in producing increases in compressive strength at 28 days.

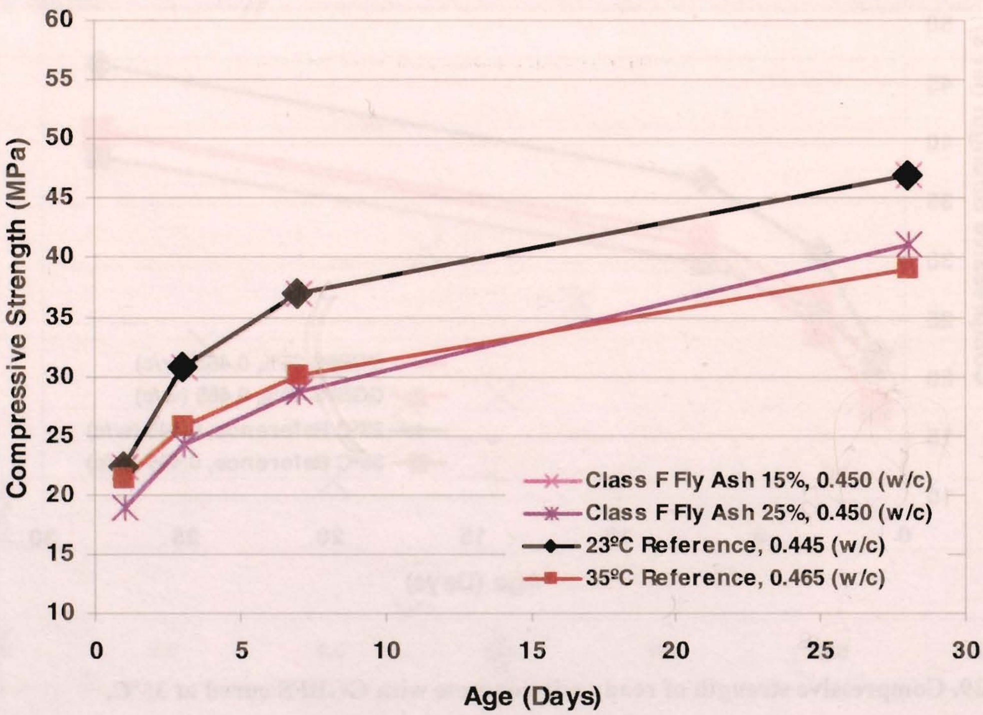


Figure 4.30. Compressive strength of ready mix concrete with Class F fly ash cured at 35°C.

4.4.3 – 20 and 30% Class C Fly Ash cured at 35°C

The next SCM analyzed at 35°C was Class C fly ash. The 20% Class C fly ash mix produced a moderate increase in strength activity at 1 day of age. The gain in strength can be partially attributed to the 5.0% reduction in water demand. However, the slower hydration reaction created by the fly ash addition can also be seen with the reduced 1 day strength of the higher 30% dosage. After the samples were allowed to cure for 28 days, strength activities of 17.5 and 11.6% relative to the 35°C reference were achieved. This is a substantial gain in strength and directly illustrates the ability of Class C fly ash to mitigate reductions in compressive strength caused by curing at high temperature. These gains in strength represent strength reductions of 2.3 and 7.6% when compared to the 23°C results. As a result, the Class C fly ash was the most efficient solitary performing supplementary cementing material tested at 35°C. When the permeability results are taken into consideration it can be seen that some of the increase in strength can be attributed to a refinement of the microstructure illustrated by an increase in durability with the RCPT results presented in a following section.

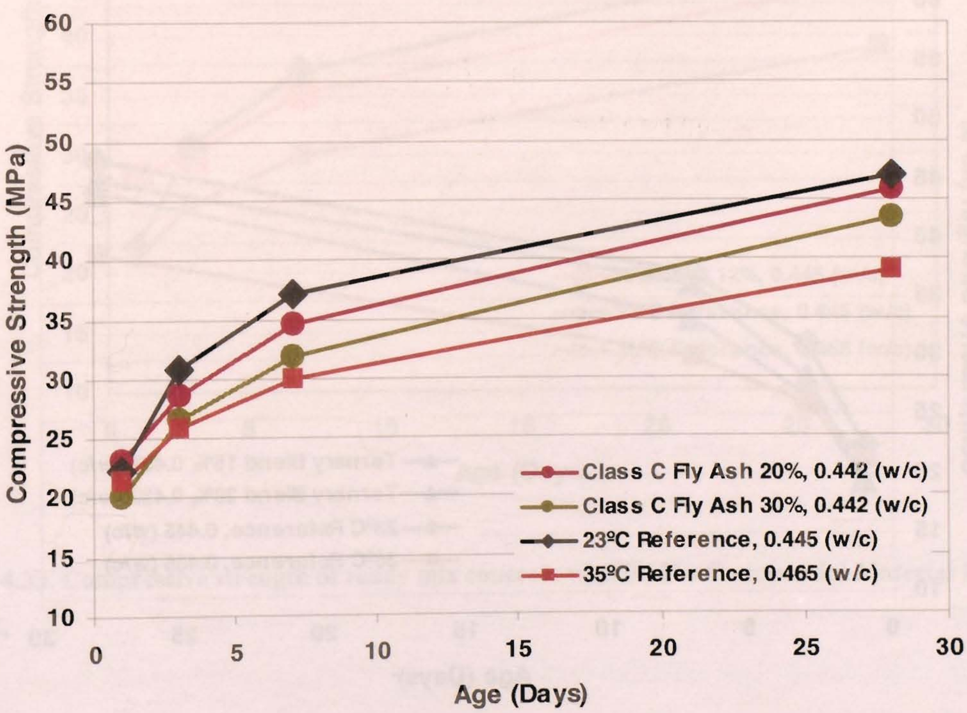


Figure 4.31. Compressive strength of ready mix concrete with Class C fly ash cured at 35°C.

4.4.4 – 15 and 20% Ternary Blends Cured at 35°C

The same Ternary blends of Class C fly ash and GGBFS utilized at 23°C were also used for this stage of the program. These two ternary blends were able to produce the largest reduction in water demand for all SCMs tested at this batching temperature; reductions of 6.0 and 7.1% for the 15 and 20% dosages respectively. However, these water demands were not enough to overcome the slower early rate of hydration incurred when such high dosages of SCMs are utilized. The 28 day results produced strength activities of 13.2 and 15.9% in comparison to the 35°C results. These results represent reduced strength activities 5.8 and 3.6% for the 15 and 20% dosages respectively, when compared to the 23°C reference mix. Although these results were not the highest achieved for the SCM testing, they were both in the top three for strength activity for this stage of the program. Similarly to the slag and fly ash results presented above, when the reduced permeability results of these two mixes are taken into consideration, it is easy to see how a reduction in water demand as well as refinements in microstructure allowed these batches to attain increased 28 day compressive strengths.

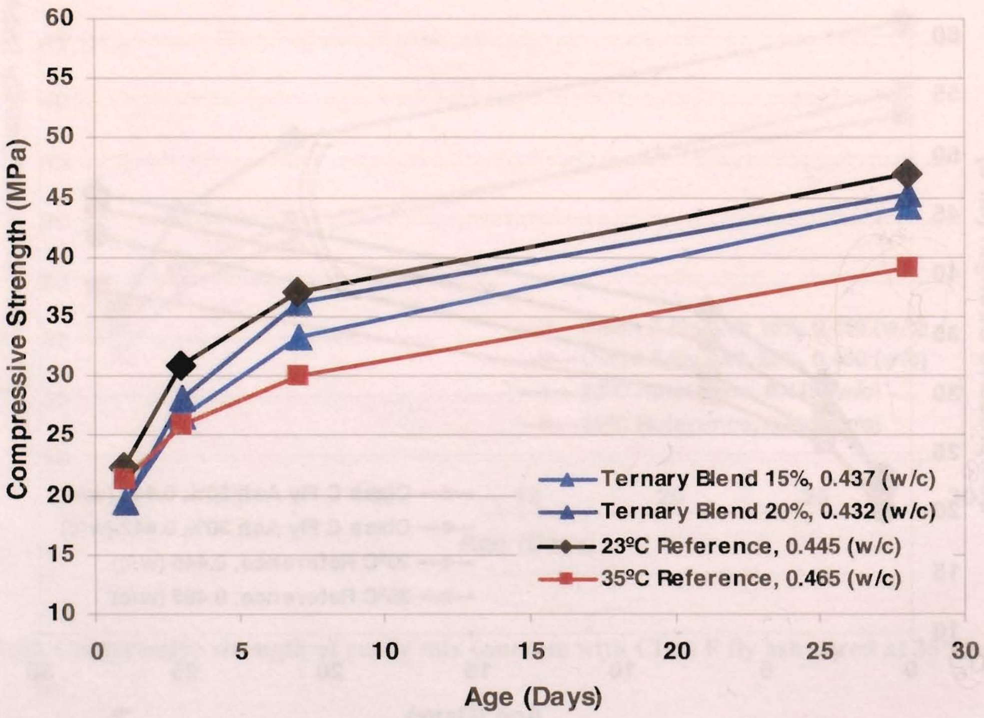


Figure 4.32. Compressive strength of ready mix concrete with Ternary blends of Class C fly ash and GGBFS cured at 35°C.

4.4.5 – 0.12% HRWR Cured at 35°C

At a 35°C batching temperature, it was necessary to increase the dosage of the HRWR to 330mls/100kg cement in order to achieve an approximate 5.0% reduction in water demand. As a result of the high dosage required to achieve only a 5.0% reduction in water demand, a 10.0% water reduction was not tested. However, even at this dosage the HRWR managed to produce very positive increases in strength activity at all ages when compared to the reference mixes. The 28 day strength activity was recorded as 14.4% when compared to the 35°C reference. This was equivalent to a modest 4.8% reduction in strength activity when compared to the 23°C reference. From these results it can seen that a high range water reducer can significantly increase compressive strength results at all test ages when ready mix concrete is cured at 35°C.

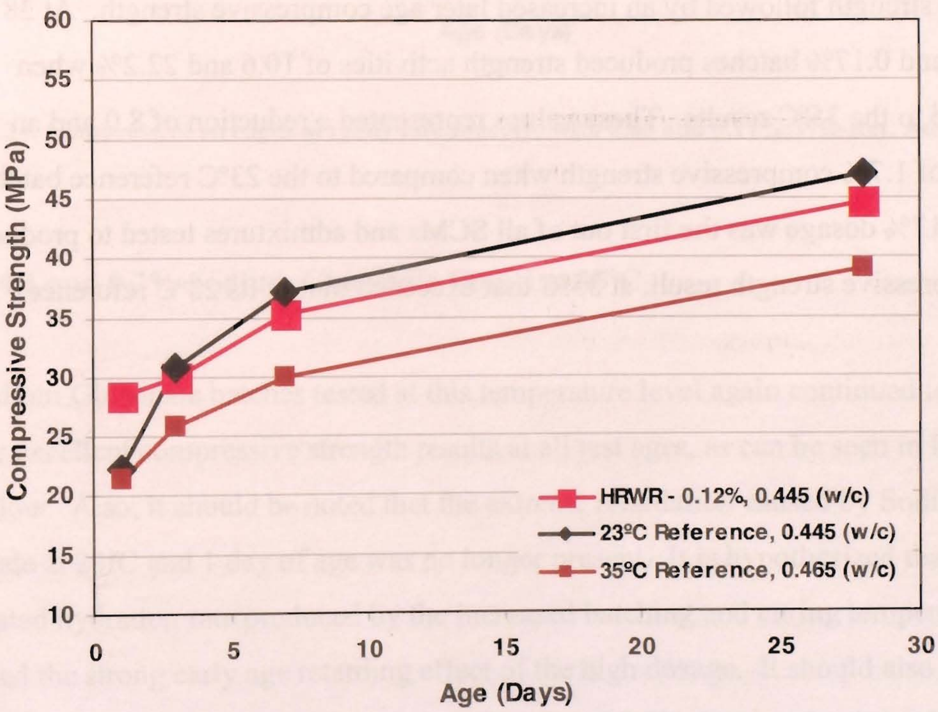


Figure 4.33. Compressive strength of ready mix concrete with 0.12% Commercial Material #1 cured at 35°C.

4.4.6 – 0.08 and 0.17% WR-Ret. Adm. Cured at 35°C

The same dosages of this admixture utilized at 23°C were also tested at this stage of the program. This was done in an effort to make the results comparable. This was also done so that the impact of increased batching and curing temperature could be measured on the ability of a low range water reducer to provide water reduction. At a 35°C batching temperature, this admixture was unable to provide any water reduction. The increased rate of hydration appeared to compromise all facets of water reduction from this product. However, even with no water reduction, the admixture was still able to produce positive compressive strength results at all test ages. The fact that an increased strength activity was observed at early ages again is counter intuitive when using a retarder. Usually the general relationship observed when using retarders, even at higher temperature, is a lower early age strength followed by an increased later age compressive strength. At 28 days, the 0.08 and 0.17% batches produced strength activities of 10.6 and 22.2% when compared to the 35°C results. These values represented a reduction of 8.0 and an increase of 1.7% compressive strength when compared to the 23°C reference batch. The higher 0.17% dosage was the first out of all SCMs and admixtures tested to produce a 28 day compressive strength result, at 35°C that exceeded that of its 23°C reference.

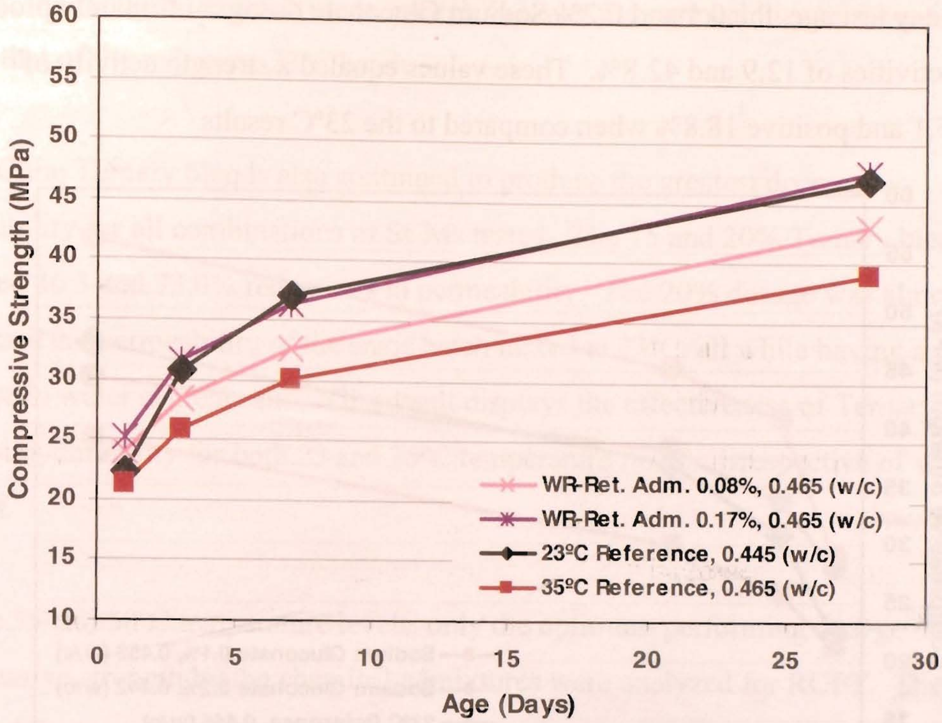


Figure 4.34. Compressive strength of ready mix concrete with 0.08 and 0.17% WR-Ret. Adm. cured at 35°C.

4.4.7 – 0.1 and 0.2% Sodium Gluconate Cured at 35°C

The Sodium Gluconate batches tested at this temperature level again continued to produce excellent compressive strength results at all test ages, as can be seen in Figure 4.35 below. Also, it should be noted that the extreme retardation caused by Sodium Gluconate at 23°C and 1 day of age was no longer present. It is hypothesized that the accelerated hydration rate produced by the increased batching and curing temperature combated the strong early age retarding effect of the high dosage. It should also be noted that Sodium Gluconate was able to maintain its 2.5 and 5.0% water reduction it had exhibited at the 23°C batching level. It is thought that the water reduction partially contributed to the increase in compressive strength at early test ages. However, it should also be noted that this retarder again produced increased early age compressive strengths, similar to the results for the WR-Ret. Adm.

At the 28 day test age, the 0.1 and 0.2% Sodium Gluconate dosages ultimately produced strength activities of 12.9 and 42.8%. These values equaled a strength activity of negative 6.1 and positive 18.8% when compared to the 23°C results.

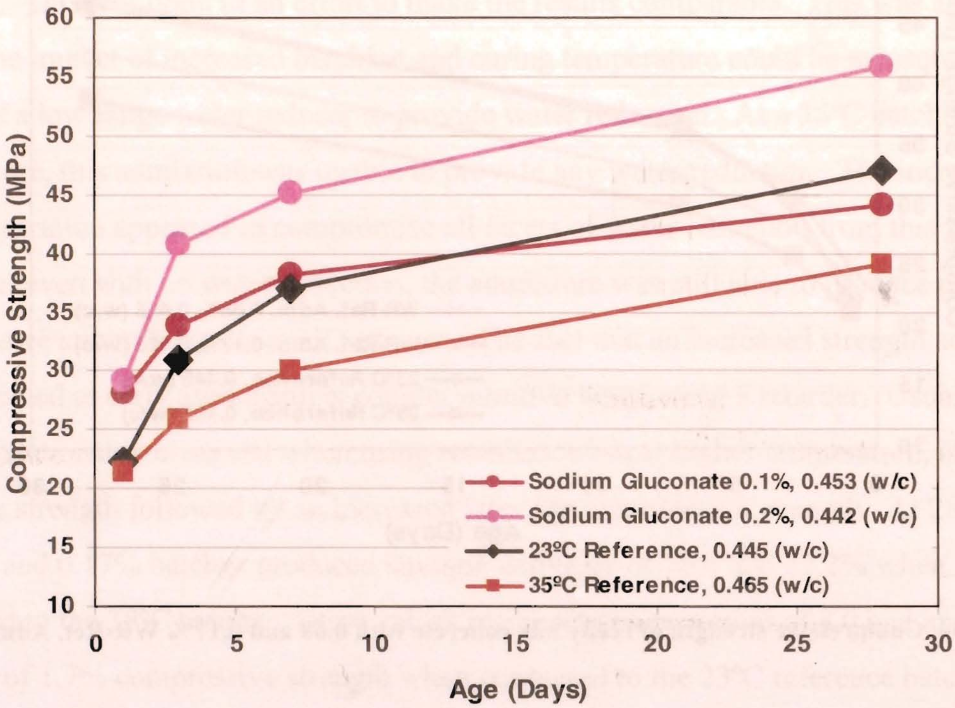


Figure 4.35. Compressive strength of ready mix concrete with 0.1 and 0.2% Sodium Gluconate cured at 35°C.

4.4.8 – RCPT results for concrete cured at 35°C

When reviewing the RCPT results for the ready mix concrete batched at 35°C, it is easy to see that the increased reference mix water content as well as the increased curing temperature had a large impact on permeability. The 35°C reference mix recorded a 33.0% increase in permeability over the 23°C reference batch. From this result, the importance of reducing mix water as well controlling hydration at elevated curing temperatures is very apparent. Just as with the 23°C results, the Class F fly ash produced the greatest improvements in permeability for the individual SCMs analyzed. Improvements of 37.8 and 58.3% were recorded for the 15 and 25% dosages of Class F fly ash respectively. Although these are not as great as was recorded with the 23°C batches, the reduced permeability is enough to lower the permeability of these samples below that of the reference 23°C batch.

At 35°C the Ternary blends also continued to produce the greatest decrease in permeability for all combinations of SCMs tested. The 15 and 20% Ternary blends recorded 46.3 and 73.0% reductions in permeability. The 20% dosage was almost able to reproduce the permeability of the same batch mixed at 23°C, all while having a 5.3% increase in water cement ratio. This result displays the effectiveness of Ternary blends at increasing durability for both 23 and 35°C temperature ranges, irrespective of water content.

For the 35 and 50°C temperature levels, only the optimum performing dosage rates for compressive strength by the chemical admixtures were analyzed for RCPT. The results recorded for samples cured at 35°C can be seen illustrated in Table 4.7. At this curing temperature the HRWR was ineffective at reducing the permeability of the samples. Also, the 0.17% dosage of the WR-Ret. Adm. produced an increase in permeability of 48.3%. The 0.2% dosage of Sodium Gluconate was the most efficient of the chemical admixtures at this batch temperature in reducing permeability. This dosage recorded a decrease in permeability of 14.7%. It is hypothesized that this occurred due to a combined effect of a reduction in water demand and a slower more even hydration of the microstructure.

Table 4.7. RCPT results for all ready mix concrete cured at 35°C.

35ºC							
Batch Type	Charge (A)	Charge (B)	Average	Batch Type	Charge (A)	Charge (B)	Average
REFERENCE	2682	3041	**2862**	REFERENCE	2682	3041	**2862**
25% GGBFS	1917	2215	**2066**	0.05% HRWR	-	-	-
40% GGBFS	1614	1895	**1755**	0.12% HRWR	2750	2711	**2731**
20% CLASS C FLY ASH	2978	2524	**2751**	0.08% WR-Ret. Adm.	-	-	-
30% CLASS C FLY ASH	1868	1805	**1837**	0.17% WR-Ret. Adm.	4596	3892	**4244**
15% CLASS F FLY ASH	1666	1949	**1808**	0.1% SODIUM GLUCONATE	-	-	-
25% CLASS F FLY ASH	1238	1147	**1193**	0.2% SODIUM GLUCONATE	2285	2594	**2440**
15% TERNARY BLEND	1501	1573	**1537**				
20% TERNARY BLEND	779	766	**773**				

4.4.9 – Ready Mix Concrete Cured at 35°C Results Discussion

Just as was the case with the 23°C 28 day results, the 0.2% dosage of Sodium Gluconate produced the greatest increase in compressive strength as can be seen illustrated in Table 4.9. The second highest compressive strength value was produced by the 0.17% dosage of the WR-Ret. Adm. This is a different trend then the 23°C results, where the 20% Ternary blend out performed all admixtures except the 0.2% Sodium Gluconate. However, it should be noted that all SCMs tested produced better results for durability. This further complicates the selection of optimum additives for ameliorating strength and durability loss at high temperatures. Depending on the design specifications of a given project as well as the ambient temperature conditions, a balance of SCMs and chemical admixtures would most likely have to be used to produce optimum results. However, the testing of blends of both additives is outside the scope of this program.

At 35°C and 28 days of age, it would appear that the GGBFS and Class F fly ash produced a very minimal, almost insignificant impact on compressive strength. Whereas Class C fly ash and Ternary blends produced moderate increases in compressive strength.

When the water reductions are analyzed and compared to the 28 day compressive strength activity for each batch no clear relationship is noted. The SCMs had an increasing water reducing effect that generally increased with increasing dosage (with the exception of GGBFS). Also, a higher dosage of the HRWR was necessary to achieve only a 5.0% reduction in water demand. This eludes to the necessity for careful selection of water reducer dosages depending on the batch temperature. This principal will be further presented in the following section.

Another relationship that was recorded was that the low range water reducing qualities of the WR-Ret. Adm. seemed to have a negligible effect at higher temperature. However, even with this retarded effect it was still able to perform quite well in ameliorating compressive strength loss. Also, the high early age compressive strengths indicate that the retarding effect as predicted by the manufacturer must have a much more complicated relationship when utilized at both 23 and 35°C batch temperatures.

All strength activities are reported as a percentage of the 28 day compressive strength achieved by the reference batch at 35°C.

Table 4.8. 28 day compressive strength activities, water cement ratios and % water reductions of ready mix concrete batched with SCMs and cured at 35°C.

	Reference	GGBFS		Class F Fly Ash		Class C Fly Ash		Ternary Blend	
		25%	40%	15%	25%	20%	30%	15%	20%
28 DayStrength Activity (%)		5.75	5.28	6.09	5.16	17.35	10.95	13.03	15.75
W/C Ratio	0.465	0.465	0.465	0.45	0.45	0.442	0.442	0.437	0.432
% Water Reduction		0.00	0.00	3.23	3.23	4.95	4.95	6.02	7.10

Table 4.9. 28 day compressive strength activities, water cement ratios and % water reductions of ready mix concrete batched with chemical admixtures and cured at 35°C.

	Reference	Commercial Material #1		Commercial Material #2		Sodium Gluconate	
		0.05%	0.12%	0.08%	0.17%	0.1%	0.2%
28 DayStrength Activity (%)		-	14.27	10.44	22.11	12.75	42.68
W/C Ratio	0.465	-	0.445	0.465	0.465	0.453	0.442
% Water Reduction		-	4.30	0.00	0.00	2.58	4.95

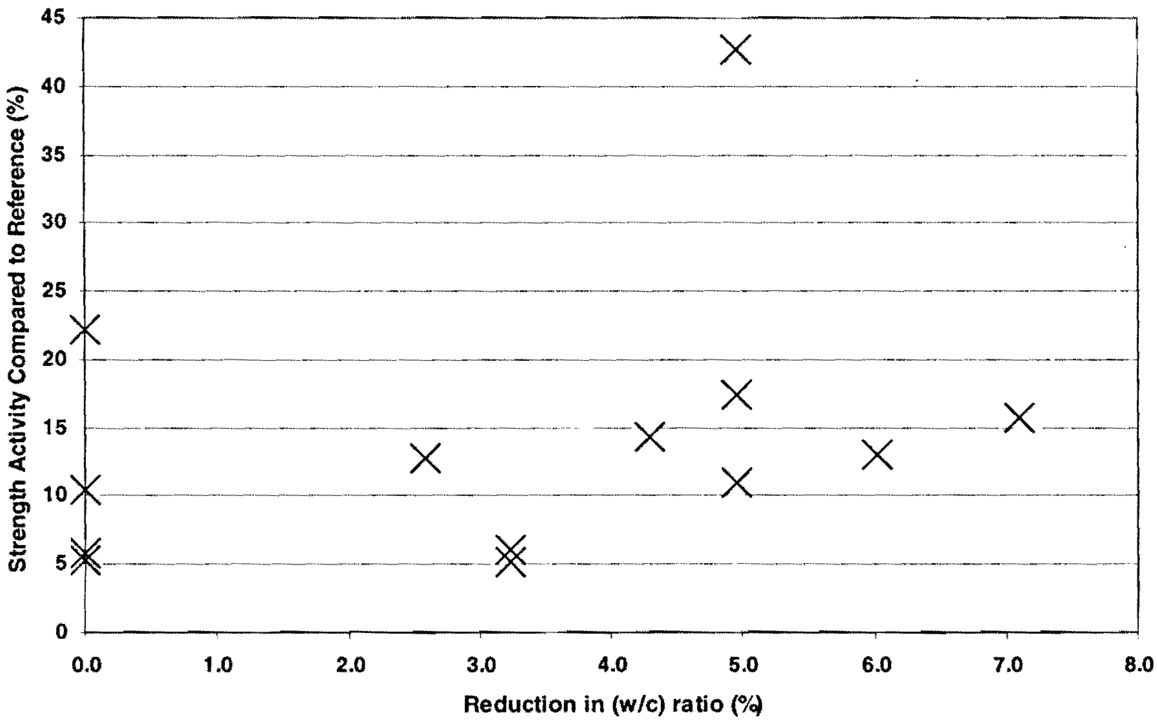


Figure 4.36. Compressive strength activity of ready mix concrete cured at 35°C vs. reduction in water cement ratio compared to reference.

This graph was included to show that a reduction in w/c ratio does not fully justify or explain the enhancement in strength achieved for some of the samples.

4.5 – Ready Mix Concrete Cured at 50°C Results and Analysis

4.5.1 – 25 and 40% GGBFS cured at 50°C

For testing at 50°C, the GGBFS again produced moderate early age gains in strength for the 25% dosage. The increased strength performance of 25% slag over the 40% slag dosage can be explained by the slower hydration of the slag mix at higher dosages compared to Portland cement. At 7 and 28 days of age the strength activities recorded were almost identical for both batches and were relatively insignificant compared to the reference batched.

It should be noted that although no measureable water reduction was recorded for these two slag batches, a qualitative improvement in the workability of the mixture was noted. This was attributed to the slower hydration rate of GGBFS in comparison to the Portland cement.

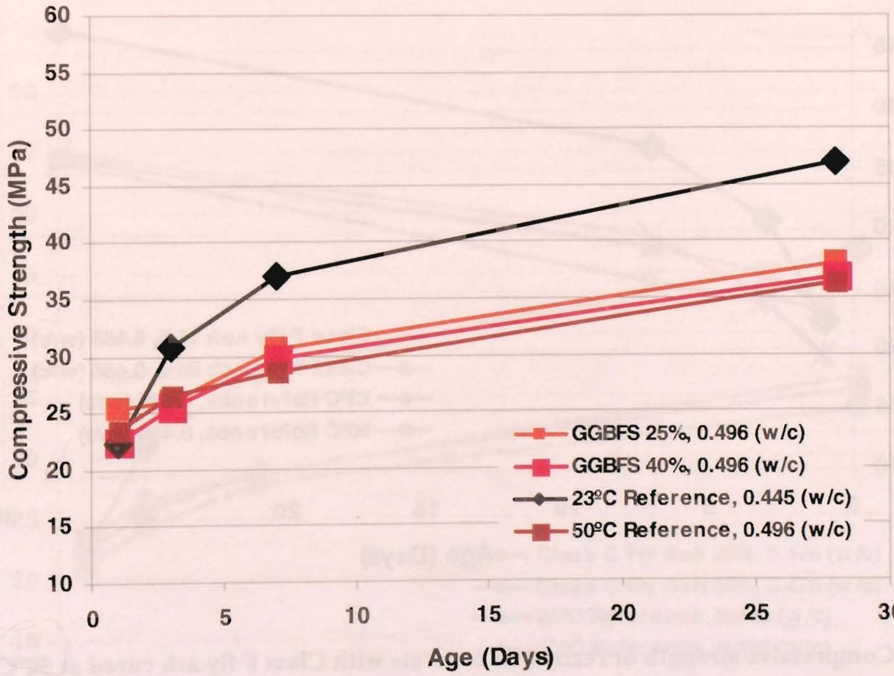


Figure 4.37. Compressive strength of ready mix concrete with GGBFS cured at 50°C.

4.5.2 – 15 and 25% Class F Fly Ash cured at 50°C

The use of Class F fly ash at 50°C produced a 2.0% water reduction for both dosages. This was a decreased water reduction in comparison to the 4.0 and 3.2% achieved at 23 and 35°C respectively. This trend of decreasing water reduction with increasing temperature directly illustrates the effect of increased Portland cement hydration rates at elevated temperature. The Class F fly ash again produced similar 1 day strength activities to the previous curing temperatures illustrated in Figure 4.38 below. The trend of superior strengths for the lower 15% dosage continued throughout all test ages until the 28 day results. When all three temperature levels are considered, the Class F fly ash produced decreasing positive effects on reducing compressive strength loss with increases in batching and curing temperature.

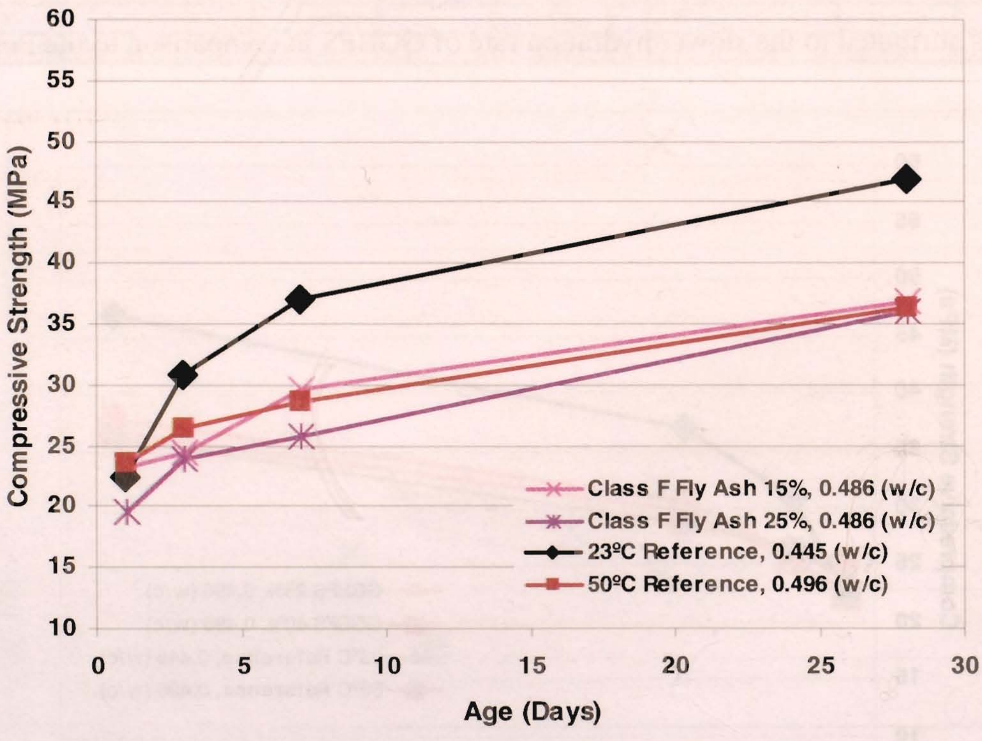


Figure 4.38. Compressive strength of ready mix concrete with Class F fly ash cured at 50°C.

4.5.3 – 20 and 30% Class C Fly Ash cured at 50°C

When the water reducing ability of the Class C fly ash is examined, it can be seen that it also decreased in effectiveness with increasing temperature. The water reducing ability decreased from 6.0 to 5.0% for batches mixed at 23 and 35°C and continued to decrease to only 4.0% for the mix batched at 50°C. The Class C fly ash also had a reduced effect on compressive strength compared to the 35°C results.

It is commonly known that batches of concrete mixed with supplementary cementing materials are more susceptible to strength loss caused by improper curing. However, this explanation cannot be used to explain the reduced strengths achieved with Class C fly ash at 50°C. All specimens were cured in 100% relative humidity with no exceptions. The only differing variable was the curing temperature and water demand to maintain a constant consistency. As a result, it would appear that Class C fly ash is ineffective in producing increases in compressive strength at later ages when batched and cured at 50°C.

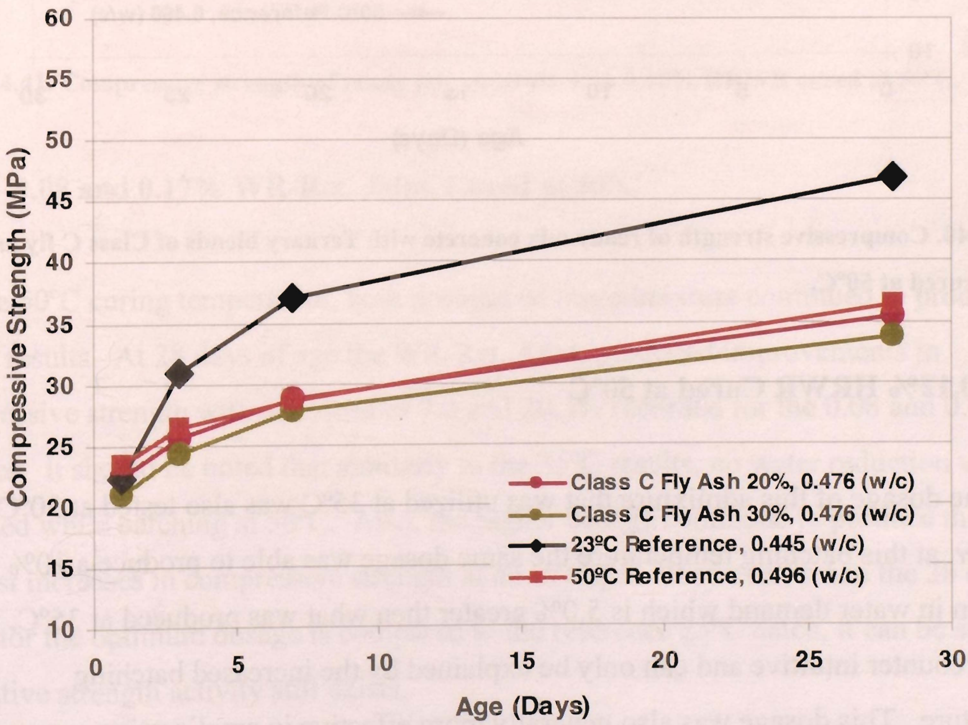


Figure 4.39. Compressive strength of ready mix concrete with Class C fly ash cured at 50°C.

4.5.4 – 15 and 20% Ternary Blends Cured at 50°C

The 15 and 20% ternary blends utilized in this stage of the program were the only SCMs that were able to maintain their water reductions for this batching temperature. However, just like the individual SCMs analyzed previously at 50°C, the ternary blends tested failed to produce a positive effect on ameliorating compressive strength loss.

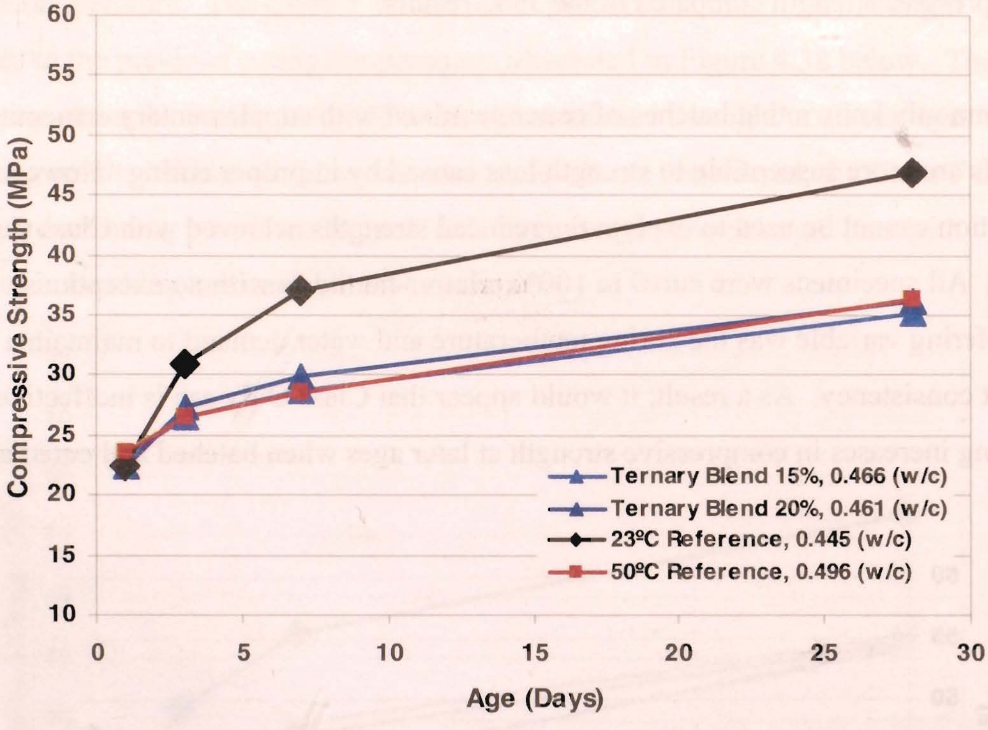


Figure 4.40. Compressive strength of ready mix concrete with Ternary blends of Class C fly ash and GGBFS cured at 50°C.

4.5.5 – 0.12% HRWR Cured at 50°C

The same dosage of this admixture that was utilized at 35°C was also tested at 50°C. However, at this batching temperature the same dosage was able to produce a 10% reduction in water demand which is 5.0% greater then what was produced at 35°C. This result is counter intuitive and can only be explained by the increased batching temperature. This dosage was also generally more effective in ameliorating compressive strength loss when compared to the reference batch at 50°C. Moderate increases in compressive strength were recorded at all early test ages and a 28 day strength activity of

19.3% was recorded. The results recorded outperformed all the supplementary cementing materials results combined at 50°C. However, a negative 9.6% 28 day strength activity was still recorded when compared to the 23°C reference batch.

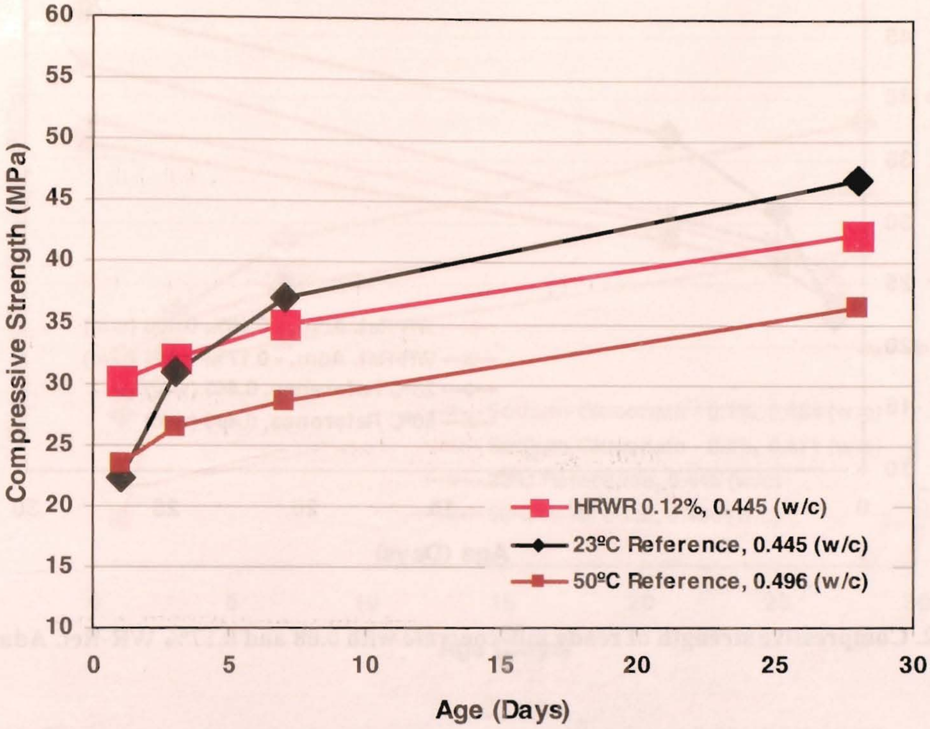


Figure 4.41. Compressive strength of ready mix concrete with 0.12% HRWR cured at 50°C.

4.5.6 – 0.08 and 0.17% WR-Ret. Adm. Cured at 50°C

For the 50°C curing temperature, both dosages of this admixture continued to produce strong results. At 28 days of age the WR-Ret. Adm. produced improvements in compressive strength with activities of 7.0 and 20.3% recorded for the 0.08 and 0.17% dosages. It should be noted that similarly to the 35°C results, no water reduction was recorded while batching at 50°C. Also, the higher dosage continued to produce the greatest increases in compressive strength at all test ages. However, when the 28 day result for the optimum dosage is compared to the reference 23°C batch, it can be seen that a negative strength activity still exists.

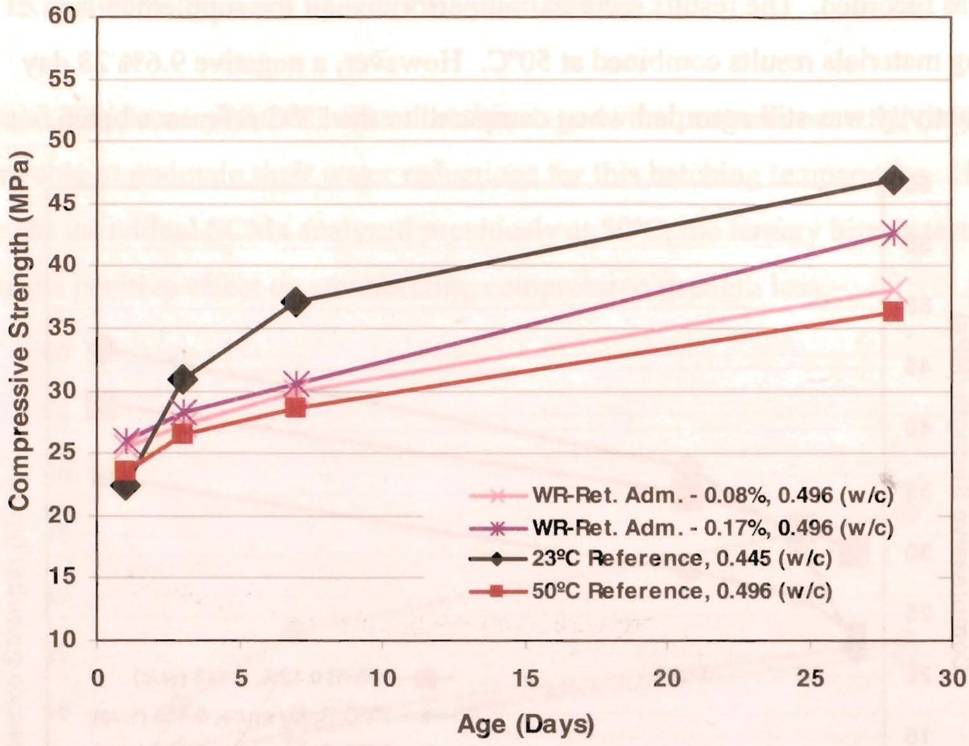


Figure 4.42. Compressive strength of ready mix concrete with 0.08 and 0.17% WR-Ret. Adm. cured at 50°C.

4.5.7 – 0.1 and 0.2% Sodium Gluconate Cured at 50°C

The final mixes cast at 50°C were batches containing 0.1 and 0.2% Sodium Gluconate. The results observed for all test ages were very interesting and presented a trend that more closely echoed the 23°C results rather then the 35°C results. The reduced 1 day strength produced by the higher dosage of Sodium Gluconate was expected at the lower curing temperature, however, having not observed this result with the 35°C results it was unexpected to see a reduced early age strength at 50°C. It should be noted that both dosages of Sodium Gluconate were able to maintain their 2.5 and 5.0% water reduction at this batching temperature as well. From these results it would appear that the increased temperature had a negative effect on the increased dosage of Sodium Gluconate. The only other variable that should be considered is the increased water content of the batch necessary to maintain the consistency of the mix. It is hypothesized that the increased water content as well as the increased temperature of the 50°C batch had an effect on the solubility of the Sodium Gluconate and increased its ability to chelate the free calcium ions and slow down the hydration reaction.

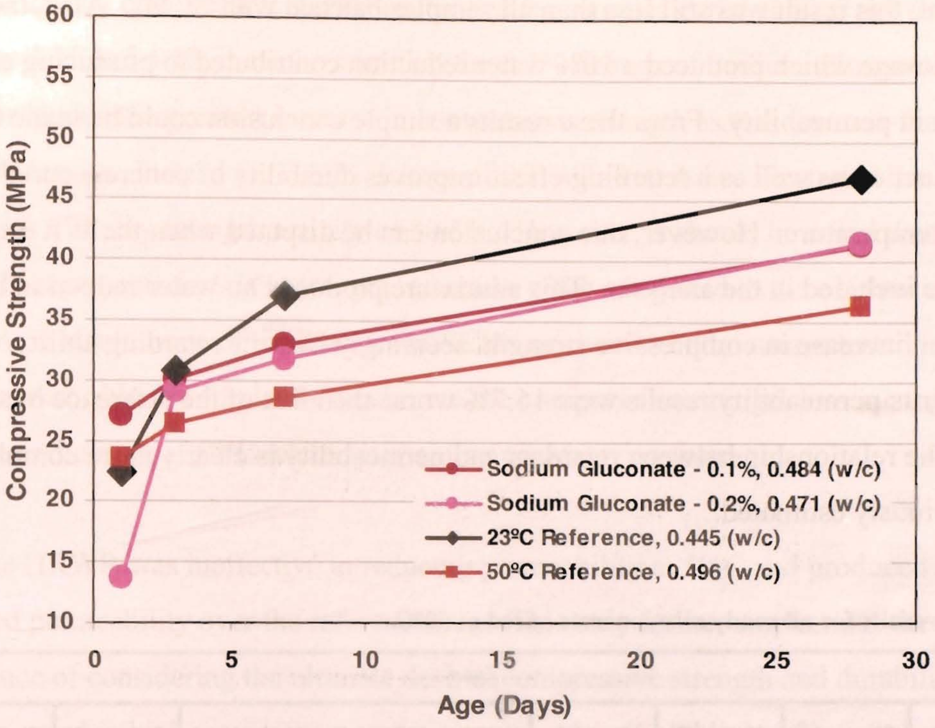


Figure 4.43. Compressive strength of ready mix concrete with 0.1 and 0.2% Sodium Gluconate cured at 50ºC.

4.5.8 – RCPT results for concrete cured at 50ºC

For the 50ºC RCPT results, the average permeability for the reference mix continued to increase with increases in curing temperature. Similarly, the SCM mixes also continued to have the greatest positive influence on permeability, however, at 50ºC a different individual SCM performed the most efficiently. The 25 and 40% dosages of GGBFS slag produced the greatest increase in durability for the individual SCMs analyzed. When all SCMs were considered, the Ternary blends continued to produce the greatest increase in durability for all mixes. Improvements in durability of 73.6 and 80.1% were recorded for the 15 and 20% blends respectively. These results were low enough to produce permeability's less then that of the reference 23ºC mix.

For the chemical admixtures analyzed at 50°C, the 0.2% dosage of Sodium Gluconate was the most efficient in reducing permeability with a reduction of 42.2%. Although significant, this result was still less than all samples batched with SCMs. Also, the HRWR dosage which produced a 10% water reduction contributed to producing a 30.2% reduction in permeability. From these results a simple conclusion could be made that water reduction as well as a retarding effect improves durability of concrete cured at elevated temperature. However, this conclusion can be disputed when the WR-Ret. Adm. results are included in the analysis. This admixture produced no water reduction but did produce an increase in compressive strength, seemingly from its retarding ability. However, its permeability results were 16.7% worse then that of the reference batch. As a result, the relationship between retarders and permeability is clearly more complicated then previously estimated.

Table 4.10. RCPT results for all ready mix concrete cured at 50°C.

50°C							
Batch Type	Charge (A)	Charge (B)	Average	Batch Type	Charge (A)	Charge (B)	Average
REFERENCE	4781	6777	5779	REFERENCE	4781	6777	5779
25% GGBFS	2310	2530	2420	0.05% HRWR	-	-	-
40% GGBFS	1633	1717	1675	0.12% HRWR	4571	3497	4034
20% CLASS C FLY ASH	3478	3349	3414	0.08% WR-Ret. Adm.	-	-	-
30% CLASS C FLY ASH	2530	2557	2544	0.17% WR-Ret. Adm.	6872	6612	6742
15% CLASS F FLY ASH	2586	2760	2673	0.1% SODIUM GLUCONATE	-	-	-
25% CLASS F FLY ASH	1814	2056	1935	0.2% SODIUM GLUCONATE	3279	3393	3336
15% TERNARY BLEND	1557	1500	1529				
20% TERNARY BLEND	1079	1195	1137				

4.5.9 – Ready Mix Concrete Cured at 50°C, Results & Discussion

When all 28 day compressive strength activities for samples cured at 50°C are reviewed in Tables 4.11 and 4.12, it can be seen that the 0.2% dosage of Sodium Gluconate no longer produced the greatest increase in compressive strength as was the case for the 23 and 35°C results. Instead the 0.17% dosage of the WR-Ret. Adm. illustrated the best result with a 28 day strength activity of 20.3%. However, it should be noted that this result still represented a 9.0% strength reduction when compared to the reference 23°C batch. As a result, none of the dosages of SCMs or chemical admixtures tested in this program were able to completely ameliorate the compressive strength loss incurred by batching and curing at 50°C while maintaining constant consistency.

Also, the HRWR was ineffective in reducing permeability at 50°C and produced an increased permeability over the reference mix. This only further emphasizes the importance of considering the ultimate desired compressive strength and durability of concrete cured in high temperature environments. Also, it highlights the fact that chemical admixtures consisting of different general chemical components will have optimum working temperature ranges for strength, durability and water reduction. This was made very apparent with the WR-Ret. Adm. which is claimed to be a low range water reducer but was only able to produce a slight water reduction when batching at 23°C. Another interesting relationship that was recorded was that the same 0.12% dosage of the HRWR produced only a 5% reduction in water demand at 35°C batching temperatures whereas it produced a 10% reduction in water demand at 50°C.

The water reductions produced by the use of individual SCMs at 50°C (presented in Table 4.11) were moderately reduced over that of their 35°C counter parts. The GGBFS continued to produce no measureable reduction in water demand however a qualitative reduction was again observed. It is hypothesized that the water reducing ability was decreased as a result of the increased rate of hydration of the Portland cement. A 15°C increase in batching temperature would have translated into a 150% increase in hydration rate for the Portland cement. This comes as a result of the general axiom of physical chemistry where for every 10°C increase in temperature the reaction rate is doubled.

However, it should be noted that the Ternary blends were able to maintain their 6.0 and 7.0% water reduction. It is hypothesized that this was possible due to their high Portland cement substitution rate.

When the chemical admixtures are examined, the WR-Ret. Adm. again failed to produce a water reduction and the Sodium Gluconate continued to maintain its 2.5 and 5.0% reduction. The only surprise came from the 330mls/100kg dosage of the HRWR. As mentioned in the previous paragraph, the same dosage of this admixture produced only a 5.0% water reduction at 35°C compared to the 10% reduction recorded at 50°C. Originally it was thought that the differing water content could have presented a possible explanation for this phenomenon. However, after a closer investigation it can be seen that due to the differing water reduction levels, the 35°C and the 50°C batches both had the same water content. The only variable present was the difference in temperature. From this information, it is hypothesized that the carboxylated polyether chemical groups that this material consists of have a different level of solubility at differing temperature. It is also possible that a varying degree of alkalinity was present in the paste solution for the two batches due to differences in hydration rate which could have again affected the solubility of the active carboxylated groups.

The differing water reduction results produced by the HRWR as well as the differing strength activities and durability results produced by the retarders highlights the importance of selecting the right chemical admixture for the job depending on the batching and curing temperature and design specifications. Also, as can be seen illustrated in Figure 4.44, the level of water reduction incurred by an additive does not directly correlated to increases in compressive strength activity.

All strength activities are reported as a percentage of the 28 day compressive strength achieved by the reference batch at 50°C.

Table 4.11. 28 day compressive strength activities, water cement ratios and % water reductions of ready mix concrete batched with SCMs and cured at 50°C.

	Reference	GGBFS		Class F Fly Ash		Class C Fly Ash		Ternary Blend	
		25%	40%	15%	25%	20%	30%	15%	20%
28 DayStrength Activity (%)		4.46	1.28	1.23	-1.00	-2.40	-7.06	-3.22	-0.48
W/C Ratio	0.496	0.496	0.496	0.486	0.486	0.476	0.476	0.466	0.461
% Water Reduction		0.00	0.00	-2.02	-2.02	-4.03	-4.03	-6.05	-7.06

Table 4.12. 28 day compressive strength activities, water cement ratios and % water reductions of ready mix concrete batched with chemical admixtures and cured at 50°C.

	Reference	Commercial Material #1		Commercial Material #2		Sodium Gluconate	
		0.05%	0.12%	0.08%	0.17%	0.1%	0.2%
28 DayStrength Activity (%)		-	16.68	4.66	17.63	13.82	14.39
W/C Ratio	0.496	-	0.445	0.496	0.496	0.484	0.471
% Water Reduction		-	-10.28	0.00	0.00	-2.42	-5.04

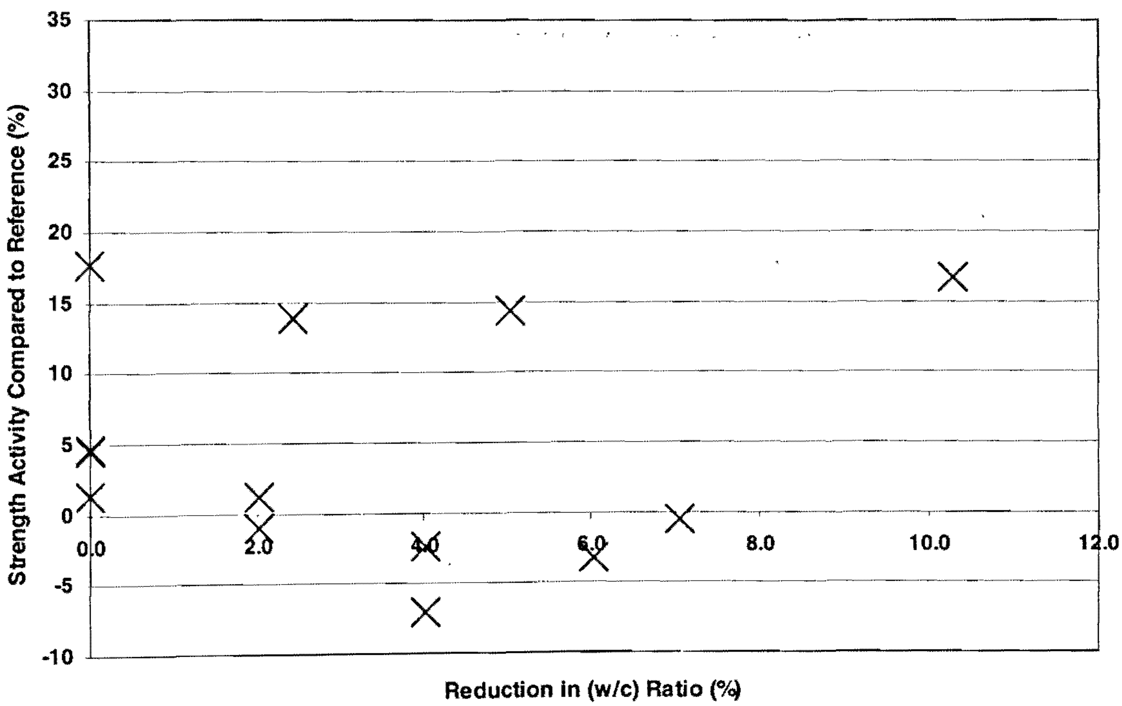


Figure 4.44. Compressive strength activity of ready mix concrete cured at 50°C vs. reduction in water cement ratio compared to reference.

This graph was included to show that a reduction in w/c ratio does not fully justify or explain the enhancement in strength achieved for some of the samples.

4.6 - Phase IIb: Experimental Results and Analysis for Roller Compacted Concrete

4.6.1 – Scope

For this portion of the study, two supplementary cementing materials and two Ternary blends were investigated in a roller compacted concrete program. Also, similar to the ready mix program, as an ancillary benefit it was investigated whether the SCMs tested could reduce the water demand and high cement contents that would otherwise be necessary to achieve high performance, target compressive strengths in hot and humid environments. Once the samples were cured for 56 days, they were also tested for durability.

Class C fly ash and GGBFS were selected for low slump concrete testing based on their proven use in previous projects. They were also selected for their ability to influence the hydration of the Portland cement through a combined hydraulic and pozzolanic reaction. It was hoped that by substituting cement with individual SCMs and Ternary blends of GGBFS and fly ash, that the rate of cement hydration at increased temperature could be decreased resulting in a stronger, less permeability paste structure.

4.6.2 - Establishing the Target Cement Content

As was mentioned in Section 3.4.2, a cement content of 350 kg/m^3 was selected for testing with RCC mixes. This cement content was maintained for all batches cast in Phase IIb of the study.

4.6.3 – The Duration of High Temperature Curing

All samples were cured at high temperature where applicable, for the previously established 24 hour period. After the initial 24 hour cure period the test cylinders were demoulded and transferred to a moisture cure room maintained at 23+/-2°C and 100% relative humidity for the remaining duration of their cure.

4.6.4 – Establishing the Coarse/Fine Aggregate Ratio and Water Content of the Reference Mix

In order to select the optimum RCC mix for testing, it was first necessary to compare different mix designs based on their coarse/fine aggregate volume ratios, water content and consistency. After reviewing the mix design guidelines published in ACI 325, coarse/fine aggregate ratios of 65/35, 60/40 and 55/45 were selected for testing. Also, a wide range of gradually increasing water contents was selected. Samples were cast according to the Soil Compaction Method out lined in Sections 3.4.2 and 3.4.3. Upon demoulding, each sample was weighed and had its density calculated according to the procedure outlined in Section 3.4.5.

The resultant moisture density graphs formed from this data can be seen presented below in Figures 4.45, 4.46 & 4.47. Figure 4.45 compares the average Proctor densities to the water cement ratio of the individual batches. Figure 4.46 compares the average void contents of the same Proctors to the water cement ratio and Figure 4.47 illustrates the average compressive strengths tested at 28 days of age.

4.6.5 - Analyzing the Density of the Proctors

When the three density curves are analyzed in Figure 4.45 it is easy to see that on average the mix containing 55% coarse aggregate by volume ratio produced the highest density results. It was also qualitatively observed to be more cohesive and easily compacted in comparison to the other two coarse aggregate contents tested.

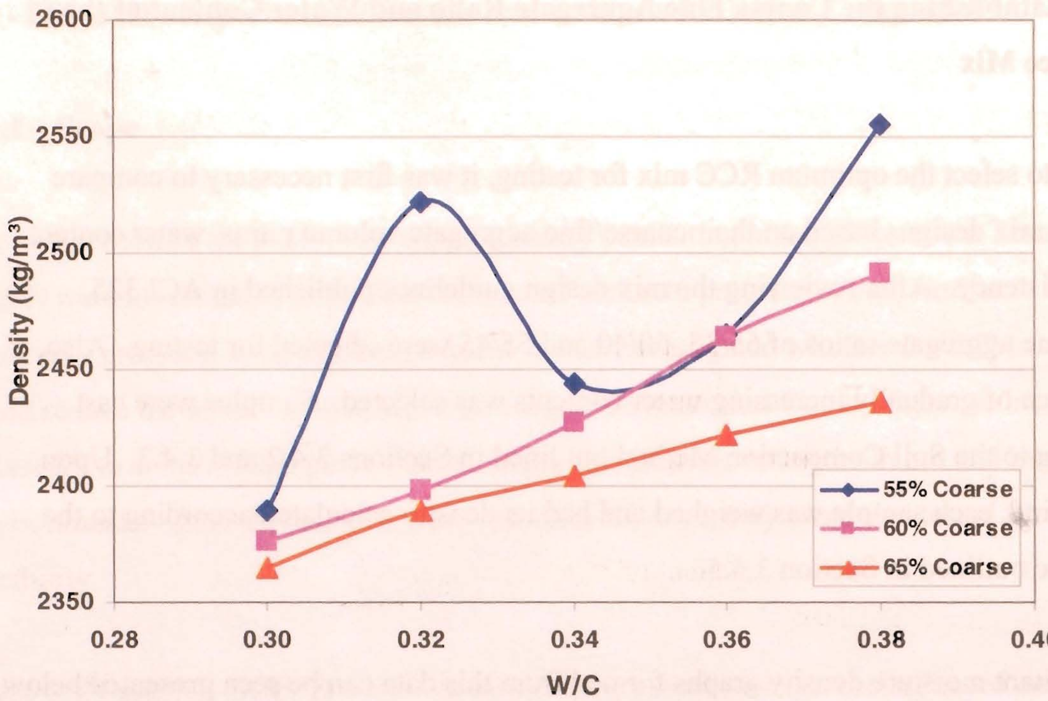


Figure 4.45. Average density results for two Proctors cast at each individual point compared to the water cement ratio of the individual mix. Each line on the graph illustrates a different coarse/fine aggregate volume ratio.

4.6.6 - Analyzing the Void Content of the Proctors

The void content was established theoretically by calculating the density of the fresh specimens and then volumetrically calculating the quantity of air voids necessary to achieve that density. This was done by assuming the initial volume ratio of aggregates, cement and water still applied.

When the void contents of the same specimens are analyzed, the relationship between high density and low void content is illustrated. As was predicted, the higher the density a mix achieves the lower the void content. In practical sense, the density graph is the inverse of the void content graph. From this analysis it was noted that the 55% coarse aggregate mix again performed well producing results with a low void content for all water cement ratios. This translates into a low permeability and thus a higher durability rating for this aggregate ratio.

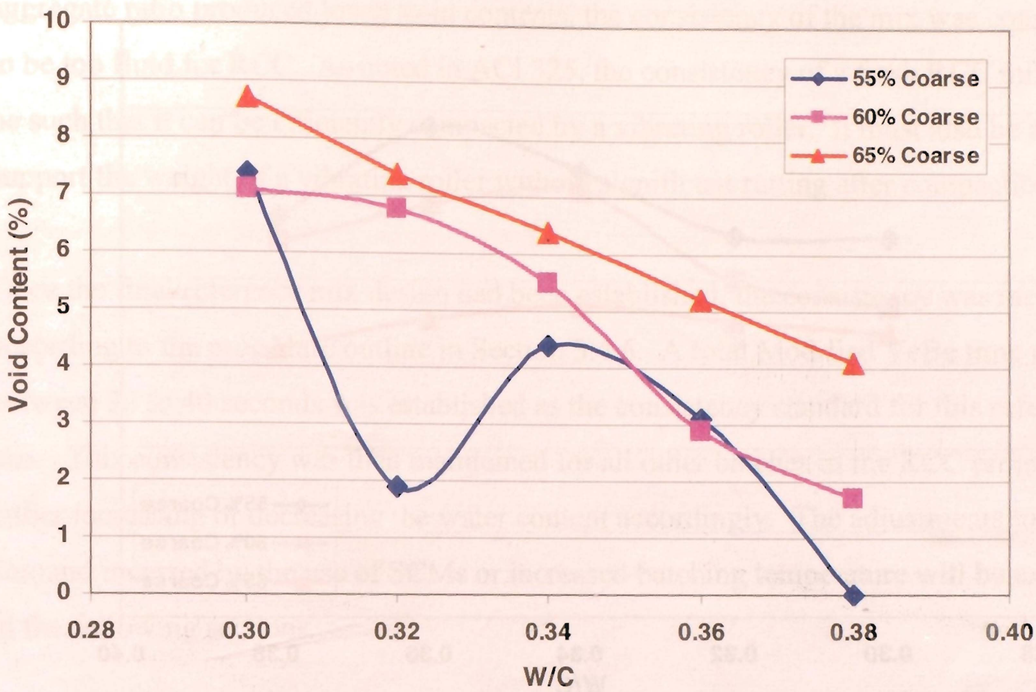


Figure 4.46. Average void content results for two Proctors cast at each individual point compared to the water cement ratio of the individual mix. Each line on the graph illustrates a different coarse/fine aggregate volume ratio.

4.6.7 - Analyzing the Compressive Strength of the Proctors

The specimens cast with 55% coarse aggregate volume continued to perform well when tested for compressive strength. At all water levels tested they produced the highest compressive strengths when compared to the other coarse aggregate volume ratios.

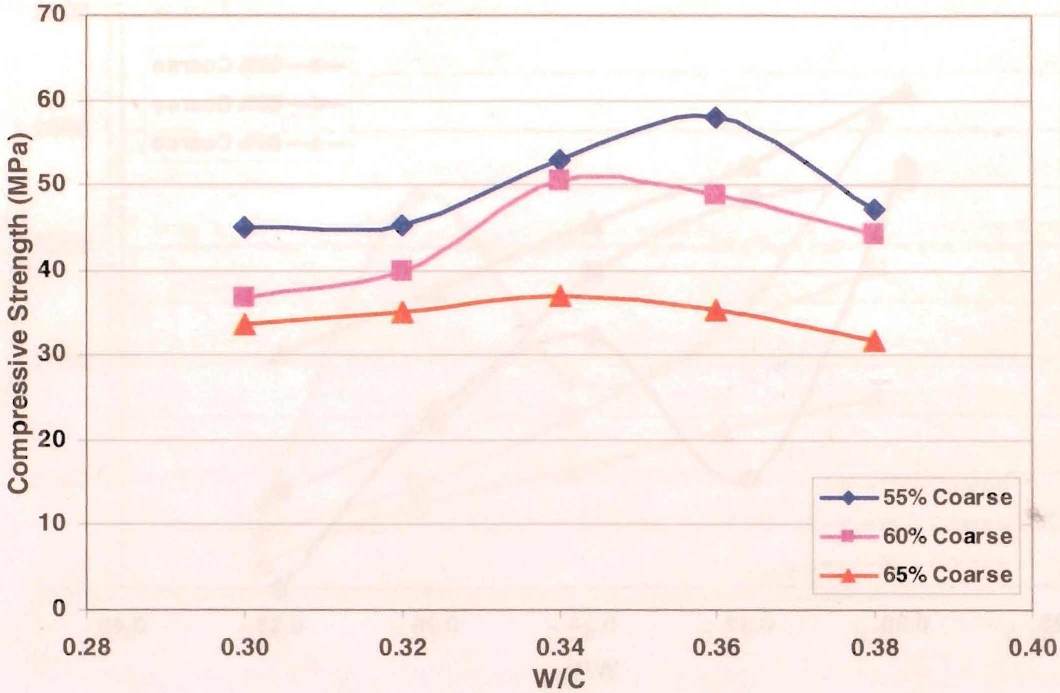


Figure 4.47. Average compressive strength results for two Proctors cast at each individual point compared to the water cement ratio of the individual mix. Each line on the graph illustrates a different coarse/fine aggregate volume ratio.

When all three graphs are taken into consideration it is plain to see that the 55% coarse aggregate volume ratio mixes produced the best results for density, void content and compressive strength. Also, it was qualitatively noted that they were the most cohesive and readily compactable out of all three ratios tested. From this analysis the fine/coarse ratio of 55% limestone to 45% sand that produced a high density and minimum void content (or permeability) while also producing a strong compressive strength was selected as the final fine/coarse ratio for the reference mix design.

4.6.8 – Selecting the Reference Water Content

The last remaining task to establish the reference mix design was selecting the water content. A water cement ratio of 0.36 was selected as the reference water level after all data, both quantitative and qualitative was reviewed. This water level was selected due to its high density, relatively low permeability, high compressive strength and ease of consolidation. It should be noted that although higher water levels at the 55% coarse aggregate ratio produced lower void contents, the consistency of the mix was considered to be too fluid for RCC. As noted in ACI 325, the consistency of a fresh RCC mix must be such that it can be efficiently compacted by a vibrating roller. It must also be able to support the weight of a vibrating roller without significant rutting after compaction.

Once the final reference mix design had been established, the consistency was measured according to the procedure outline in Section 3.4.6. A total Modified VeBe time ranging between 36 to 40 seconds was established as the consistency standard for this reference mix. This consistency was then maintained for all other batches in the RCC program by either increasing or decreasing the water content accordingly. The adjustments to water demand incurred by the use of SCMs or increased batching temperature will be explained in the following sections.

4.7 – Compressive Strength Results for Roller Compacted Concrete

4.7.1 – Compressive Strength Results for RCC Cured at 23°C

For the RCC batched and cured at 23°C with SCMs, all early age strengths were below that of the reference batch. This result was expected due to the slower hydraulic and pozzolanic reactions caused by the addition of large volumes of SCMs.

The final test age analyzed was 28 days of age. As predicted, when the specimens were allowed to cure for an extended period of time they were able to produce increases in compressive strength that exceeded the reference batch containing only Portland cement. It should be noted that part of the positive strength activity achieved by these batches could have occurred from the 2.0% water reduction produced by the fly ash mix, and the 1.4 and 1.1% water reductions achieved for the 15 and 20% Ternary blends.

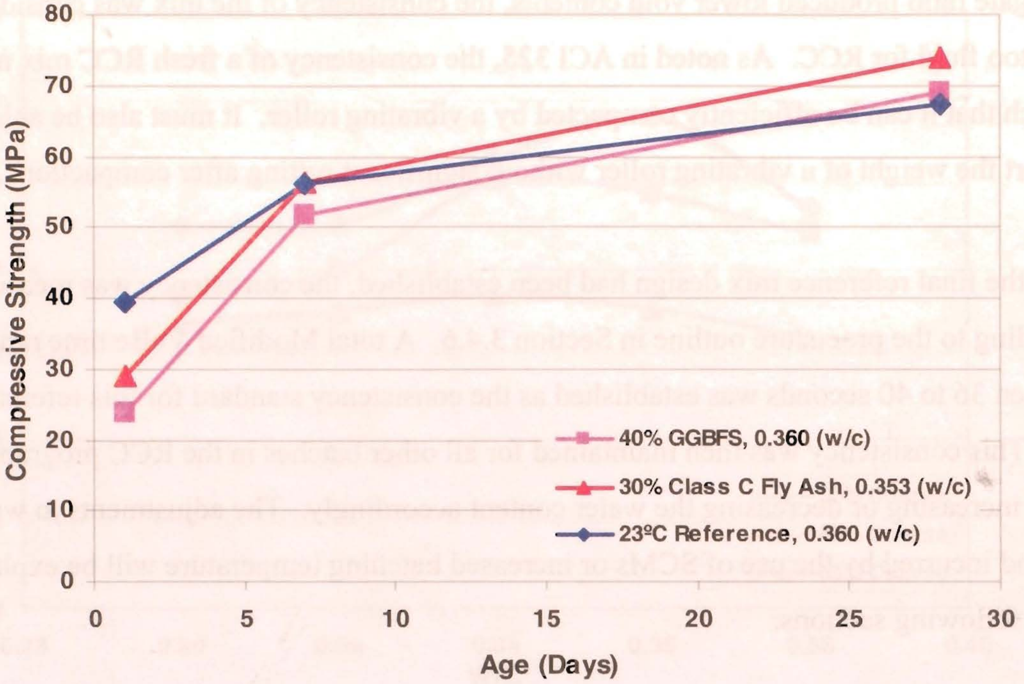


Figure 4.48. Compressive strength results for RCC batched with GGBFS and Class C fly ash, cured at 23ºC.

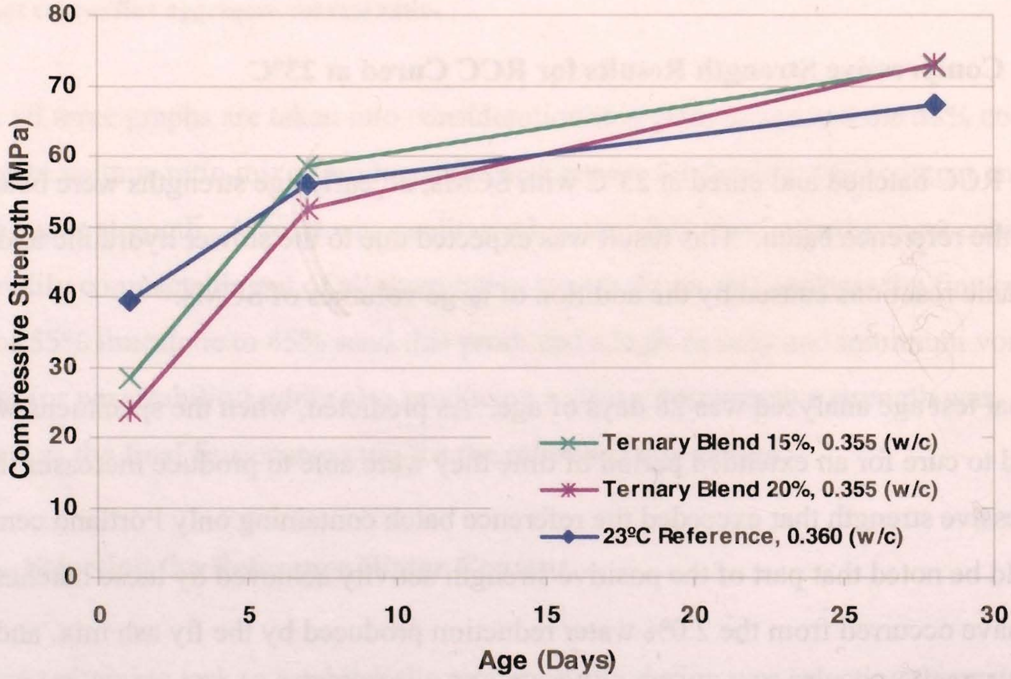


Figure 4.49. Compressive strength results for RCC batched with Ternary blends cured at 23ºC.

4.7.2 – Compressive Strength Results for RCC Cured at 35°C

The next curing temperature for RCC concrete analyzed was 35°C. The same mix designs utilized for casting at 23°C were also mixed with the exception that water contents were increased accordingly in order to maintain the consistency of the concrete. At this temperature, the water cement ratio of the reference mix had to be increased by 4.3% from 0.36 to 0.376 in order to maintain the Modified VeBe time. At this higher water content the SCMs used had a greater effect on water reduction. The 30% Class C fly ash mix was able to achieve a 4.0% w/c ratio reduction followed by a 2.1 and 2.9% reduction for the 15 and 20% Ternary blends. However, the 40% GGBFS mix continued to have no effect on water demand as was expected.

For compressive strength results at 1 day of age, less of a retarding effect was recorded when compared to the 23°C results and the 30% fly ash and 15% Ternary blend continued to have the greatest early age compressive strength results. It is hypothesized that the combined effect of an increased water reduction and the accelerated hydration produced by the 35°C curing temperature resulted in greater early age compressive strengths.

The greatest improvement in compressive strength occurred with the 28 day results. At this test age the batches that contained at least a partial addition of Class C fly ash produced the greatest increases in compressive strength. It should also be noted that all three of these batches produced a 28 day compressive strength result that exceeded the 28 day result for the 23°C reference batch. The greatest increase was recorded by the 30% Class C fly ash batch with a strength activity of 6.2% when compared to the 23°C reference batch. For a curing temperature of 35°C, it can be concluded that Class C fly ash was the most efficient in ameliorating the compressive strength loss of RCC concrete.

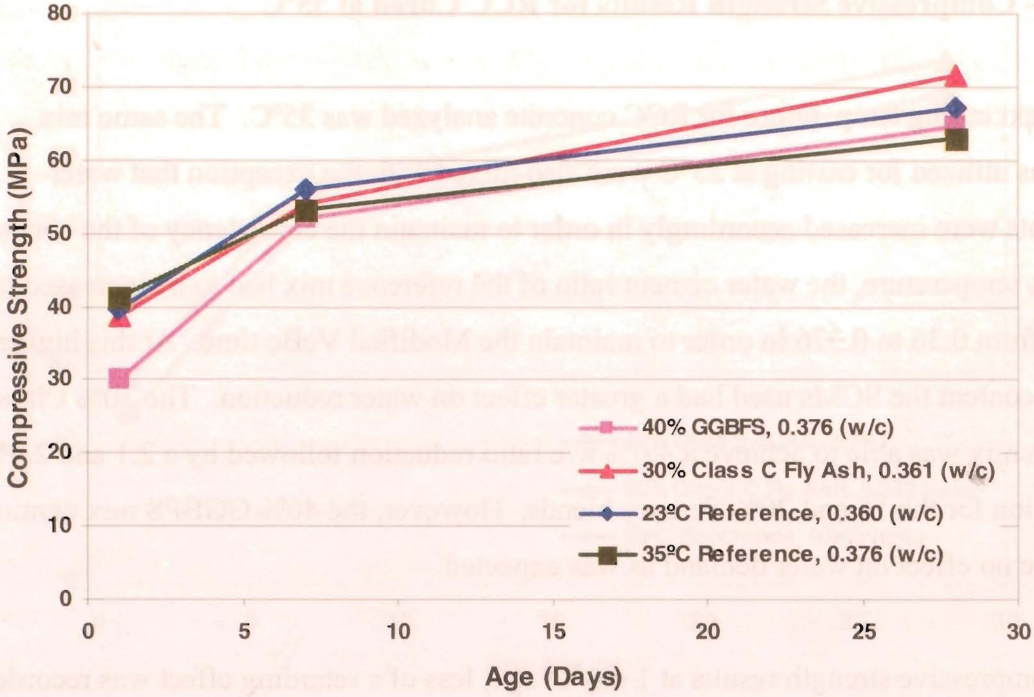


Figure 4.50. Compressive strength results for RCC batched with GGBFS and Class C fly ash, cured at 35ºC.

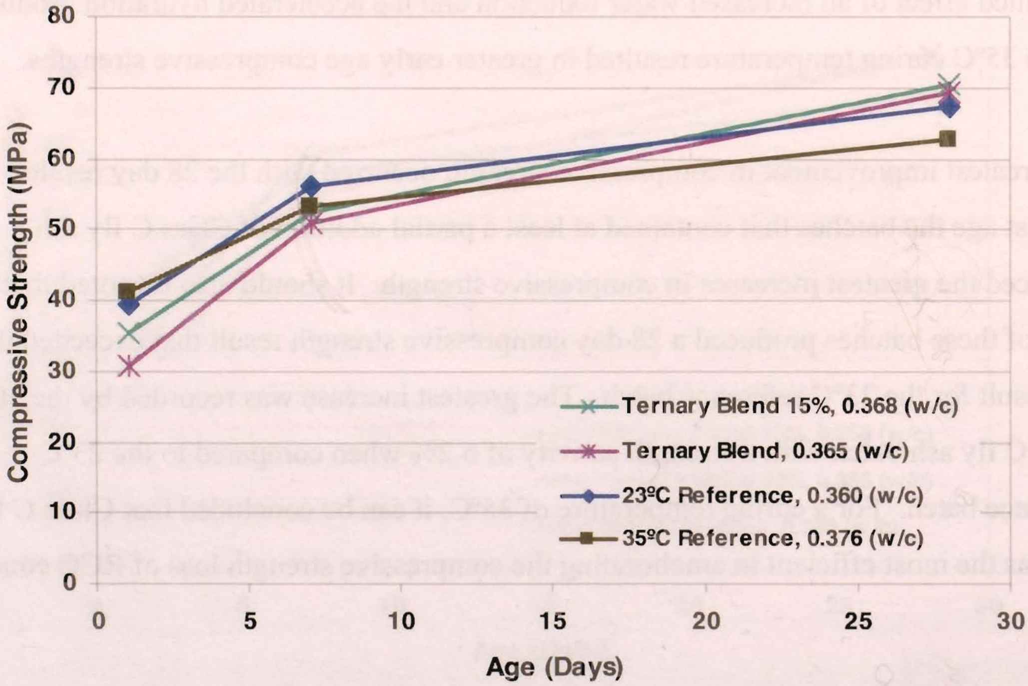


Figure 4.51. Compressive strength results for RCC batched with Ternary blends, cured at 35ºC.

4.7.3 – Compressive Strength Results for RCC Cured at 50°C

The final curing temperature analyzed for this program was 50°C. The reference water cement ratio again had to be increased to correspond with the increased hydration rate. For the 50°C mix, the w/c ratio was increased a further 4.0% over that of the reference 35°C batch, making a total increase in w/c ratio of 9.1%. The trend of increased water reduction produced by the use of SCMs did not continue with the 50°C concrete batches. All 4 mixes batched with SCMs maintained the same percentage of water reduction as those mixed at 35°C. This is thought to have occurred due to the increased rate of hydration produced by the increased curing temperature.

The 1 day compressive strength results continued to show improvement with increases in curing temperature. From the results illustrated in the graphs below it can be observed that the Ternary blends had only a very minimal retarding effect on the RCC mixes cured at 50°C.

The 28 day results recorded at 50°C again recorded the GGBFS mix with the lowest activity. All SCMs produced negligible improvements and in most case caused an increased deleterious effect on compressive strength for RCC cured at 50°C. The optimum performing SCM was 30% Class C fly ash with an activity of 3.9%, however, when this result is compared to the 28 day reference cured at 23°C a reduced activity of 6.4% is recorded. Although this result is not terrible, all SCMs failed to completely mitigate the compressive strength loss incurred from curing at 50°C.

4.7.4 – Rapid Chloride Permeability Results for Roller Compacted Concrete

When the data illustrated in Table 4.13 is compared to the RCPT results presented in Table 4.3.1 the decrease in permeability between ready mix and roller compacted concrete is very evident. The reference mix of RCC cured at 23°C produced a RCPT result that was 63.0% lower then that of its ready mix counterpart. Generally speaking, this relation applied for all levels of SCM addition as well as all curing temperatures.

If the 23°C RCC results are analyzed on their own it is easy to see the positive effect mixes that contained Class C fly ash had on permeability. Reductions in permeability were recorded for all batches containing Class C fly ash. It should be noted that these mixes also produced a reduction in water demand ranging between 1.1 and 1.9%. However, due to the very low level of water reduction it is hypothesized that the majority of permeability reduction was created by refinements in the paste microstructure. The mix containing 40% GGBFS also produced a moderate reduction in permeability. Since GGBFS did not produce a reduced water demand, the reduction in permeability can be directly attributed to refinements in concrete microstructure.

For the reference RCC batch cured at 35°C, an increase in permeability was recorded. This was to be expected as the water cement ratio had to be increased by 4.4% in order to maintain a constant consistency. However, the result that was not expected was the increased effectiveness of the GGBFS over that of 23°C. The GGBFS produced a reduction in permeability of 58.1%, almost as much as the 30% Class C fly ash mix. This result becomes even more prevalent when you consider that the GGBFS provides no water reduction whereas the fly ash produced a 4.0% reduction in the w/c ratio. The two Ternary blends analyzed also performed well at this temperature. The reduction in permeability of 71.1% produced by the 20% Ternary blend was the greatest reduction in permeability recorded for all results. This result is predicted to have occurred as a result of a combined effect of water reduction and paste structure refinement through a more efficiently controlled pozzolanic and hydraulic hydration process.

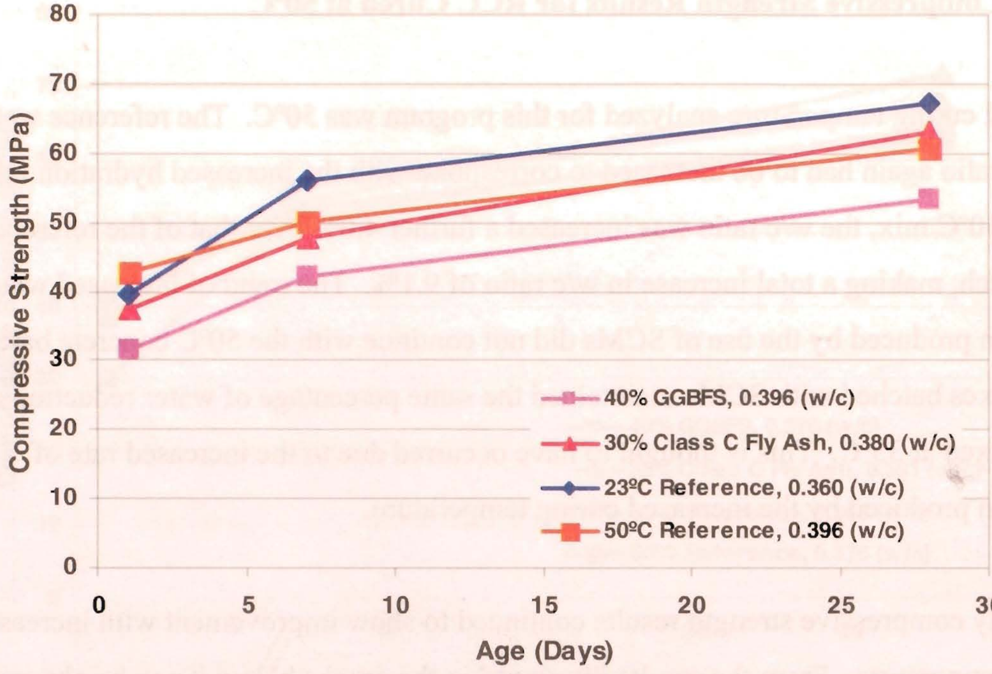


Figure 4.52. Compressive strength results for RCC batched with GGBFS and Class C fly ash, cured at 50ºC.

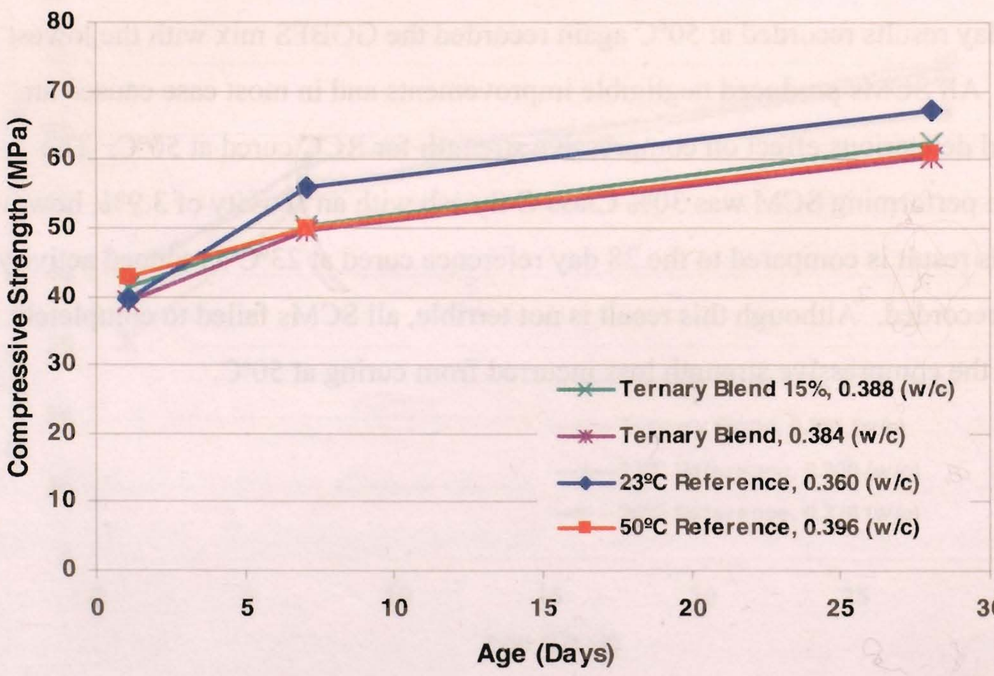


Figure 4.53. Compressive strength results for RCC batched with Ternary blends, cured at 50ºC.

The 50°C results recorded were very similar to those recorded at 35°C. In fact, when the accuracy of the RCPT test is considered there is very little difference observed in the results. From this information it can be conceived that the GGBFS had an increasing effectiveness in reducing permeability when curing temperature and water levels were increased. Also, the 30% Class C fly ash had a slightly reduced effectiveness with increasing temperatures and water contents. When the all the data is taken into account for all temperature levels, it can be seen that the Ternary blends produced not only the most effective results but also the most consistent results over all temperature levels analyzed. From this result it would have to be concluded that the Ternary blends would be the best option for reducing permeability in RCC cured in temperatures ranging from 23-50°C and 100% RH.

Table 4.13. RCPT results for all RCC concrete cured at varying temperature.

RCC	23ºC			35ºC			50ºC		
Batch Type	Charge (A)	Charge (B)	Average	Charge (A)	Charge (B)	Average	Charge (A)	Charge (B)	Average
REFERENCE	730	725	**728**	1039	1039	**1039**	899	1094	**997**
40% GGBFS	647	388	**518**	438	432	**435**	380	379	**380**
30% CLASS C FLY ASH	369	324	**347**	432	404	**418**	513	507	**510**
15% TERNARY BLEND	343	342	**343**	441	393	**417**	340	387	**364**
20% TERNARY BLEND	340	314	**327**	307	293	**300**	271	336	**304**

4.7.5 – Roller Compacted Concrete, Results Discussion

When the 35°C 28 day compressive strength results are analyzed, it can be seen illustrated that all batches tested with SCMs had a positive effect on strength. Although two mixes, the 40% GGBFS and 20% Ternary blend had a substantial retarding effect on 1 day strengths these results are still considered to be an achievement. Even with the retarded 1 day results, the naturally low consistency and high green strength behavior of this material would still allow for on time form removal. When the permeability results are analyzed for the 35°C results it is very apparent that an increase in curing temperature resulted in an increased permeability for the reference concrete batch. However, all SCMs were able to maintain the low permeability levels produced at 23°C. Only negligible increases in permeability were recorded and as a result it can be considered that equal results were obtained. However, it should be noted that the 20% Ternary blend produced the lowest permeability at this curing age.

For the 50°C results, considerably lower levels of compressive strength were generally recorded for all mixes in comparison to the other temperature levels. However, the results at 1 day of age were higher then those containing SCMs cured at 23°C. This increased early age rapid hydration resulted in reduced later age compressive strength activities. The optimum performing fly ash mix did manage to record a strength activity of 3.9% at 28 days of age however, this figure results in a 6.4% strength activity reduction when compared to the 23°C reference mix result. As a result, it is hypothesized that SCMs were unable to combat the effects on strength caused by the increased curing temperature. However, similar permeability results were obtained for all batches at both 35 and 50°C, eluding to the development of a dense microstructure at both elevated curing temperatures. This result was surprising when the increased water content and reduced compressive strengths of the 50°C results were taken into account.

For the 28 day compressive strength results, the optimum performing RCC mix was the mix design that contained 30% Class C fly ash for all temperature levels analyzed. It not only produced superior 28 day strength activities at 23, 35 and 50°C, but it also produced the greatest water reduction at all three curing temperatures. However, even with these increased strength activities, the Class C fly ash was not able to produce concrete at 50°C with equivalent strength to the 23°C reference mix. As a result, it can be concluded that no SCM was able to completely ameliorate the compressive strength loss caused by curing at 50 °C Also the reduction in water content produced by the fly ash did not translate into the lowest permeability mix which was produced by the 20% Ternary blend.

Chapter 5

Summary, Conclusions and Recommendations

5.1 - Phase I: Summary for Mortar

When Sucrose, Glucose and Sodium Gluconate are compared based on their ability to ameliorate the loss of compressive strength on mortar cured at elevated temperature, the optimum performing admixture is Sodium Gluconate. It also managed to produce a similar increase in consistency to the other two retarders analyzed.

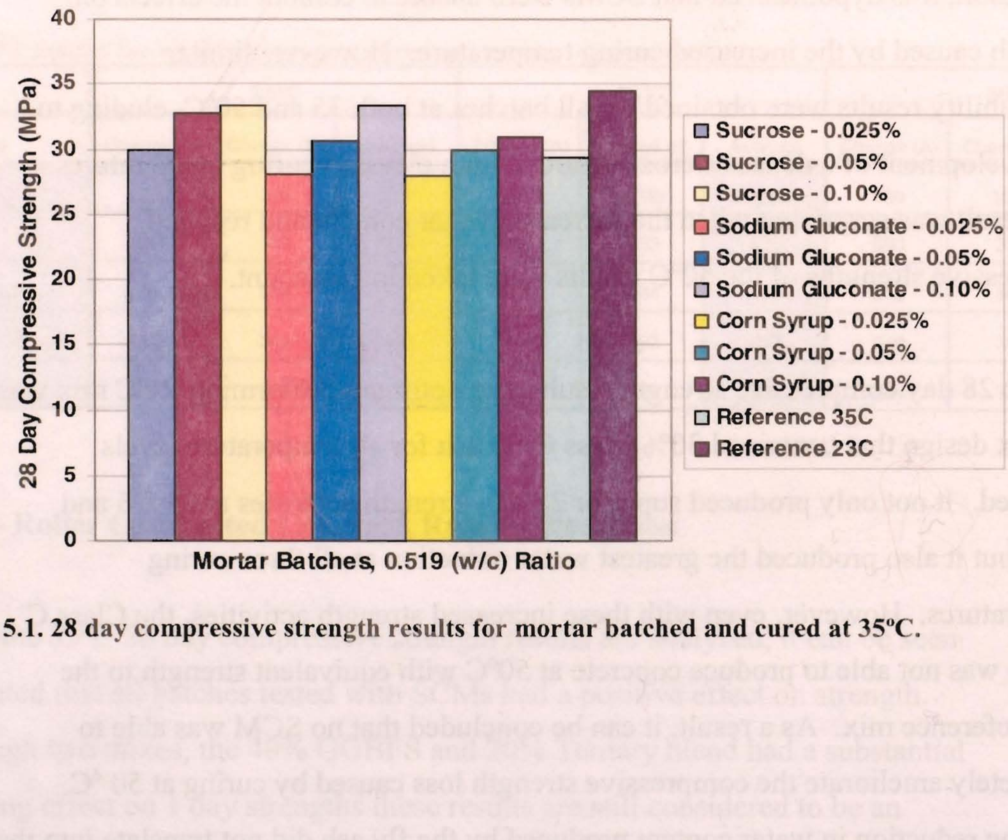
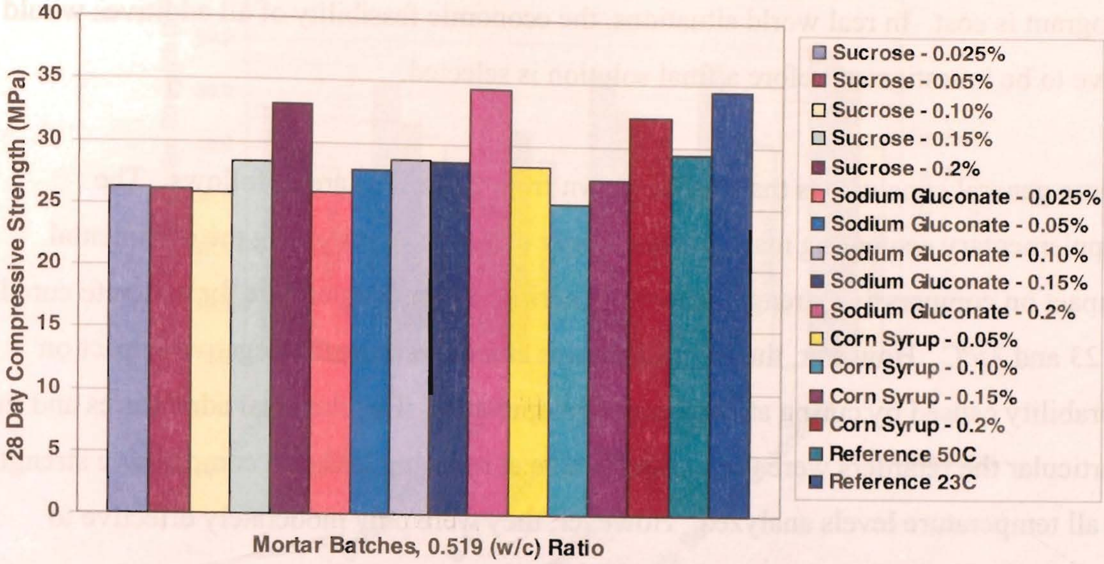


Figure 5.1. 28 day compressive strength results for mortar batched and cured at 35°C.



Note: 0.2% Sucrose and Corn Syrup completely retarded 1 day compressive strengths.

Figure 5.2. 28 day compressive strength results for mortar batched and cured at 50°C.

5.2 - Phase I: Conclusions for Mortar

- Sodium Gluconate provided the greatest increase in 28 day compressive strength for both 35 and 50°C curing temperatures, as seen illustrated in Figures 5.1 and 5.2.
- A dosage of 0.1% Sodium Gluconate, at a curing temperature of 35°C, and 0.2% Sodium Gluconate at a curing temperature of 50°C should be selected for use with mortar.

5.3 - Phase IIa: Summary for Ready Mix Concrete

For this stage of the program it is not possible to select only a single supplementary cementing material or chemical admixture as the optimum performing additive. Instead, a more complicated relationship was discovered. In order to select the best additive for the job, each individual concrete project must be analyzed and a unique mix design composed to suit the needs. Items such as curing temperature, temperature stability, necessary form release deadlines, concrete delivery times and relative humidity must all be considered. One other important factor to consider that is outside the scope of this program is cost. In real world situations, the economic feasibility of all additives would have to be investigated before a final solution is selected.

Some general conclusions that can be drawn from the results are as follows. The supplementary cementing materials were only effective at mitigating the detrimental impact on compressive strength caused by curing at high temperature for concrete cured at 23 and 35°C. However, they were effective at ameliorating the negative impact on durability caused by curing at all elevated temperature. The chemical admixtures and in particular the retarders were the most effective at reducing losses in compressive strength at all temperature levels analyzed. However, they were only moderately effective to completely ineffective at reducing permeability.

Charts of all 28 day compressive strength results and RCPT results are presented in Figures 5.3 to 5.6.

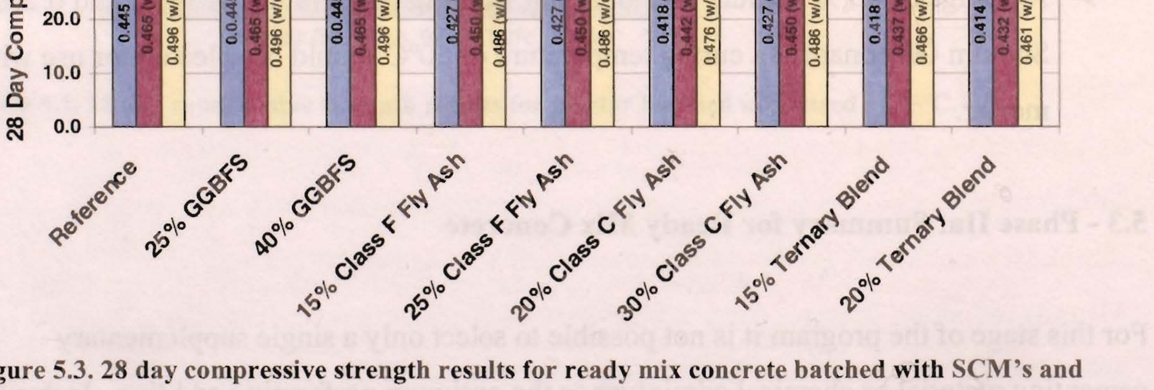


Figure 5.3. 28 day compressive strength results for ready mix concrete batched with SCM's and cured at 23, 35 and 50°C.

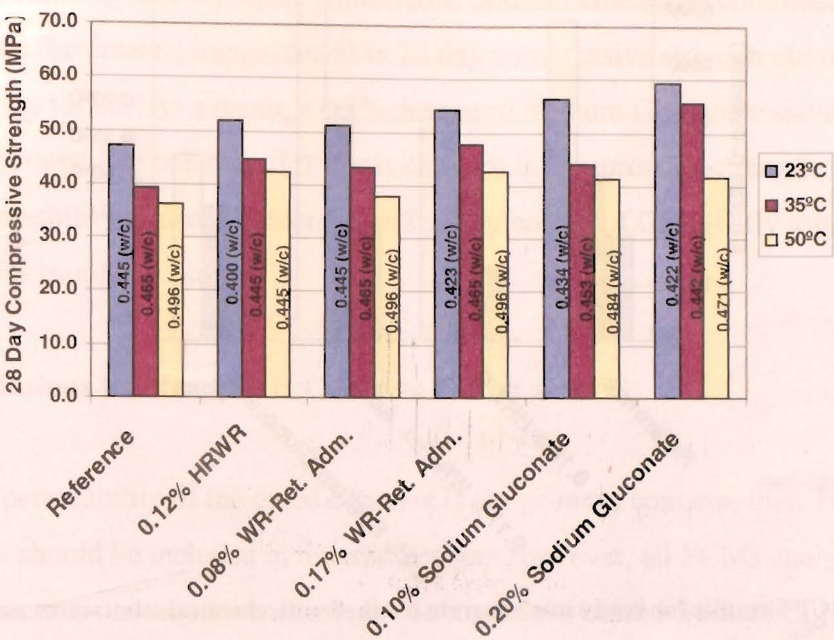


Figure 5.4. 28 day compressive strength results for ready mix concrete batched with chemical admixtures and cured at 23, 35 and 50°C.

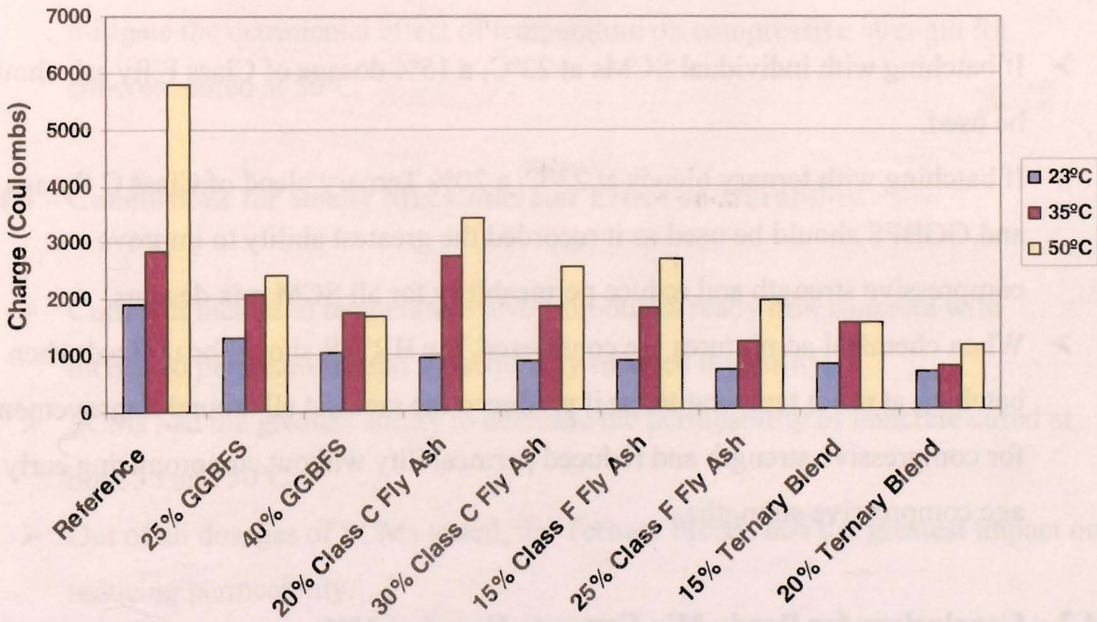


Figure 5.5. RCPT results for ready mix concrete batched with SCM's and cured at 23, 35 and 50°C.

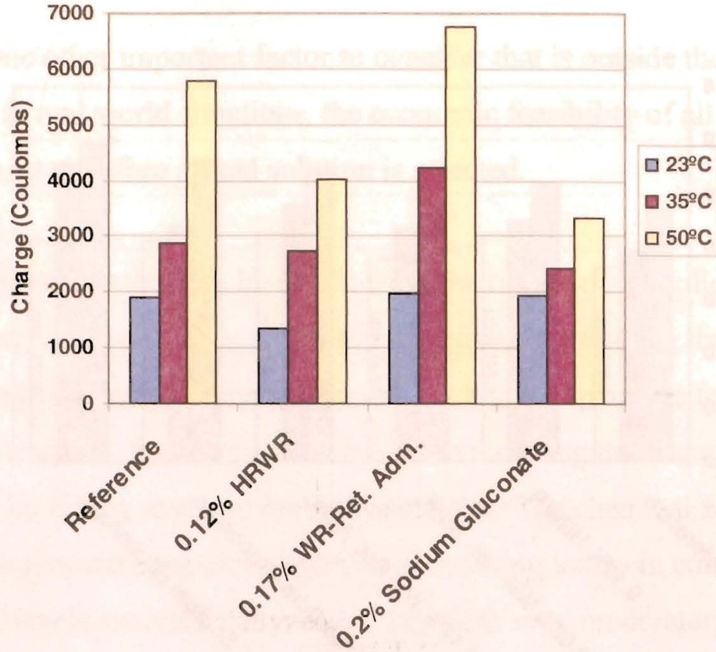


Figure 5.6. RCPT results for ready mix concrete batched with chemical admixtures and cured at 23, 35 and 50°C.

5.4.1 – Conclusions for Ready Mix Concrete Cured at 23°C

- If batching with individual SCMs at 23°C, a 15% dosage of Class F fly ash should be used.
- If batching with ternary blends at 23°C, a 20% Ternary blend of Class C fly ash and GGBFS should be used as it recorded the greatest ability to improve compressive strength and reduce permeability for all SCM mix designs.
- When chemical admixtures are considered, the HRWR should be utilized when batching at room temperature as it produced the greatest all around improvements for compressive strength and reduced permeability without compromising early age compressive strengths.

5.4.2 – Conclusions for Ready Mix Concrete Cured at 35°C

- For batching with individual SCM's, a 20% dosage of Class C fly ash should be utilized.
- However, if available, a 20% Ternary blend should be employed instead of individual SCMs as it provided good strength and permeability results.

- When batching with chemical admixtures, Sodium Gluconate continued to produce the greatest improvement in 28 day compressive strength out of all additives tested. As a result, a 0.2% dosage of Sodium Gluconate should be incorporated into batching if the only concern is compressive strength. However, if permeability is also a concern then Ternary blends of Class C fly ash and GGBFS should be used.

5.4.3 – Conclusions for Ready Mix Concrete Cured at 50°C

- If the permeability of the cured concrete is the primary concern, then Ternary blends should be included in the mix design. However, all SCMs analyzed in this program were not able to mitigate the strength loss caused from curing at 50°C.
- The WR-Ret. Adm. must be utilized at this temperature level to mitigate losses in compressive strength.
- It should be noted that none of the additives tested were able to completely mitigate the detrimental effect of temperature on compressive strength for concrete cured at 50°C.

5.4.4 – Conclusions for Ready Mix Concretes Effect on Durability

- Curing at increased temperature levels produced ready mix concrete with increased permeability and subsequently reduced durability.
- SCMs had the greatest ability to decrease the permeability of concrete cured at both 35 and 50°C.
- Out of all dosages of SCMs tested, the Ternary blends had the greatest impact on reducing permeability.

5.5 – Phase IIb: Summary for Roller Compacted Concrete

Some general conclusions from the roller compacted concrete section are as follows. When all the RCC results are considered together, Class C fly ash performed the best at reducing losses in compressive strength. The Ternary blends had a moderate effect followed by a negligible effect produced by the GGBFS. Also, all SCM batches produced a similar reduction in permeability. As a result, Class C fly ash was selected as the optimum performing additive for roller compacted concrete cured at both elevated temperature levels.

Charts of all 28 day compressive strength results and RCPT results are presented next.

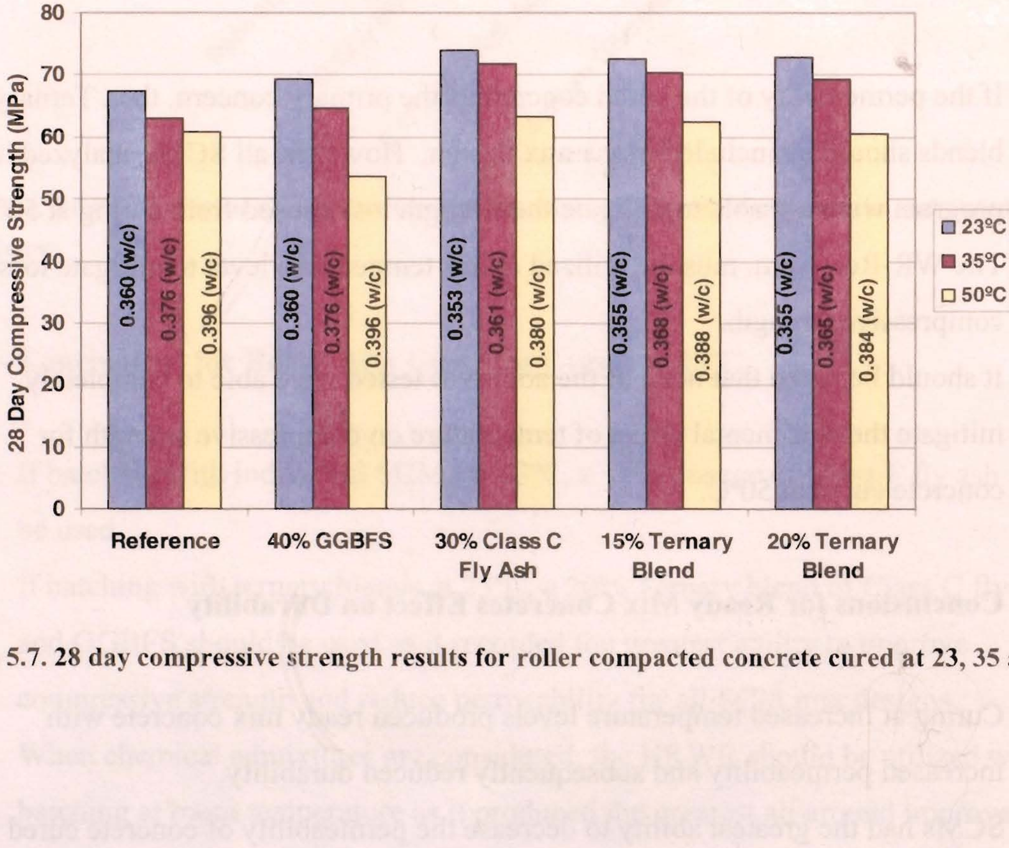


Figure 5.7. 28 day compressive strength results for roller compacted concrete cured at 23, 35 and 50°C.

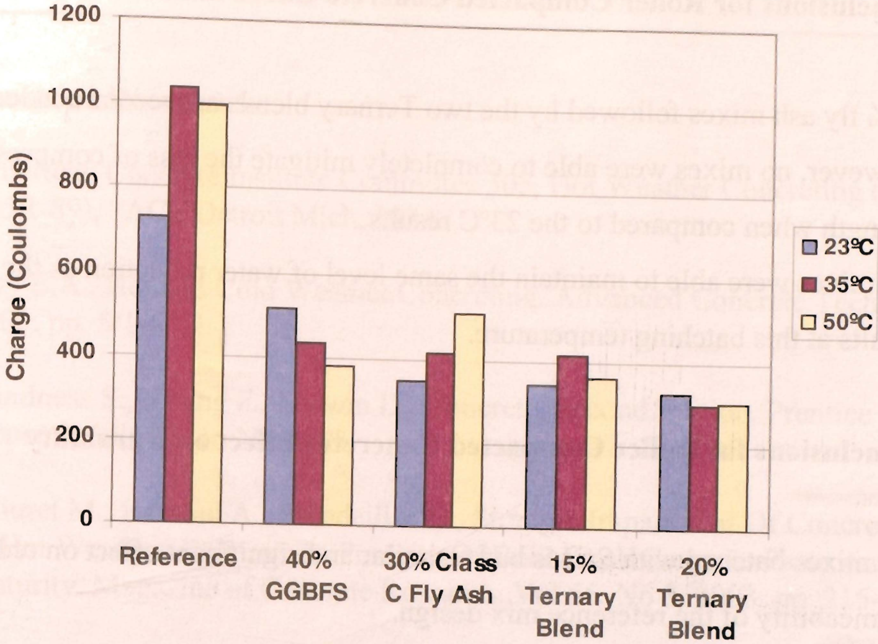


Figure 5.8. RCPT results for roller compacted concrete cured at 23, 35 and 50°C.

5.6.1 – Conclusions for Roller Compacted Concrete Cured at 23°C

- All SCM mix designs tested were able to produce moderate improvements in compressive strength at this curing temperature.
- A dosage of 30% Class C fly ash should be used when batching and casting roller compacted concrete at 23°C.

5.6.2 – Conclusions for Roller Compacted Concrete Cured at 35°C

- At 35°C, only the batches containing Class C fly ash were able to ameliorate the compressive strength losses caused by curing at elevated temperature.
- Due to very similar results for both strength and permeability it is recommended that batches containing either 30% Class C fly ash or 20% Ternary blends should be used at 35°C.
- Mixes batched with fly ash at this temperature had twice the water reducing ability as at 23°C.

5.6.3 – Conclusions for Roller Compacted Concrete Cured at 50°C

- 30% fly ash mixes followed by the two Ternary blends are recommended for use. However, no mixes were able to completely mitigate the loss of compressive strength when compared to the 23°C results.
- All mixes were able to maintain the same level of water reduction as the 35°C results at this batching temperature.

5.6.4 – Conclusions for Roller Compacted Concretes Effect on Durability

- All mixes batched with SCMs had a similar and significant effect on reducing the permeability of the reference mix design.
- Ternary blends should be used if reductions in permeability are a design concern.

5.7 - Recommendations for Further Studies

1. For further research, a program that utilizes both chemical admixtures and SCMs in combination is suggested in an effort to mitigate the detrimental effect of curing RCC at 50°C.
2. Also, more work in terms of studying the effects of dosage of chemical admixture on strength should be conducted. In particular, investigate if low dosages negatively affect compressive strength.
3. The last recommendation is to study the microstructure of samples cured at high temperature to see how chemical and SCM admixtures affect pore size, distribution and hydration products at different ages.

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Appendix A. Phase I Results:

A.1. Results summary for all reference mixes cured at 23, 35 and 50°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		June 10, 2008	June 10, 2008	June 10, 2008	June 10, 2008	June 11, 2008	June 11, 2008	
Code		Control 1-23'C	Control 2-23'C	Control 1- 35'C	Control 2-35'C	Control 1-50'C	Control 2-50'C	
Curing Temperature	**(ºC)**	**23**	**23**	**35**	**35**	**50**	**50**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	**1**	
	Admixture	None	None	None	None	None	None	
	Dosage	N/A	N/A	N/A	N/A	N/A	N/A	
Mix Design	**Notes**							
Cement	740	740.0	740.0	740.0	740.0	740.0	740.0	
Sand	2035	2035.0	2035.0	2035.0	2035.0	2035.0	2035.0	
Water	359	384.0	386.0	359.0	369.0	384.0	384.0	
Ambient Temperature		23.0	23.0	35.0	35.0	55.0	55.0	
Material Temperature	Cement/Sand	23.0	23.0	35.0	35.0	55.0	55.0	
Mortar Temperature		24.0	24.0	34.5	34.5	45.0	45.0	
W/C Ratio	Final	0.519	0.519	0.519	0.519	0.519	0.519	
Flow, %	Initial	99.0	108.0	54.0	62.0	53.0	50.0	
Compressive Strength, Mpa, 2" x 2" cubes								
Age	MPa	16.8	17.6	18.8	20.4	19.4	18.0	
	g	272.3	272.0	275.5	274.5	275.1	276.4	
	MPa	17.8	16.5	17.5	20.8	19.5	19.1	
	g	271.8	272.7	276.4	274.2	275.5	275.9	
	MPa	17.9	16.4	18.6	20.4	20.0	19.5	
Date	g	272.6	271.5	276.0	273.6	275.5	276.3	
1 day	**Average MPa**	**17.5**	**16.8**	**18.3**	**20.5**	**19.6**	**18.9**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.8**	**3.8**	**3.8**	**1.1**	**1.5**	**4.1**	**3.0**
	Average g/cc	0.1	0.2	0.2	0.2	0.1	0.1	0.1
Age	MPa	28.4	29.6	25.9	25.2	23.3	23.5	
	g	275.1	272.7	275.4	274.6	277.9	276.1	
	MPa	30.0	31.2	27.0	24.1	21.7	23.8	
	g	275.2	273.3	273.4	275.4	277.3	275.0	
	MPa	30.4	28.9	22.4	26.3	21.7	23.0	
Date	g	273.9	273.4	275.9	273.5	276.5	275.3	
7 day	**Average MPa**	**29.6**	**29.9**	**25.1**	**25.2**	**22.3**	**23.4**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.6**	**4.0**	**9.5**	**4.3**	**4.1**	**1.6**	**4.5**
	Average g/cc	0.3	0.1	0.5	0.3	0.3	0.2	0.3
	MPa	36.8	33.9	30.6	31.8	26.1	28.0	
	g	276.6	274.2	275.3	275.9	277.9	277.9	
	MPa	37.9	34.4	30.0	30.9	28.2	27.3	
	g	275.5	274.4	275.2	274.8	278.4	275.5	
	MPa	38.7	32.9	30.2	30.7	27.2	27.9	
Date	g	276.8	274.4	276.0	275.5	278.7	276.9	
28 day	**Average MPa**	**35.7**	**33.0**	**28.8**	**29.8**	**28.8**	**29.8**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.7**	**2.4**	**1.0**	**2.0**	**3.6**	**1.2**	**2.1**
	Average g/cc	0.3	0.0	0.2	0.2	0.1	0.4	0.2

A.2. Results summary for all mortar mixes cured at 35°C with the addition of retarders

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		June 26, 2008	June 12, 2008	June 12, 2008	June 26, 2008	June 12, 2008	June 12, 2008	
Code		Sucrose-35'C	Sucrose-35'C	Sucrose-35'C	SG-35'C	SG-35'C	SG-35'C	
Curing Temperature	**(ºC)**	**35**	**35**	**35**	**35**	**35**	**35**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	**1**	
	Admixture	Sucrose	Sucrose	Sucrose	Sodium Gluconate	Sodium Gluconate	Sodium Gluconate	
	Dosage	0.025%	0.050%	0.100%	0.025%	0.050%	0.100%	
Mix Design	**Notes**							
Cement	740	740.0	740.0	740.0	740.0	740.0	740.0	
Sand	2035	2035.0	2035.0	2035.0	2035.0	2035.0	2035.0	
Water	384	384.0	384.0	384.0	384.0	384.0	384.0	
Ambient Temperature		35.0	35.0	35.0	35.0	35.0	35.0	
Material Temperature	Cement/Sand	35.0	35.0	35.0	35.0	35.0	35.0	
Mortar Temperature		26.0	33.0	34.0	27.0	33.5	33.5	
W/C Ratio	Final	0.519	0.519	0.519	0.519	0.519	0.519	
Flow, %	Initial	90.0	101.0	86.0	83.0	93.0	90.0	
Compressive Strength, Mpa, 2" x 2" cubes								
Age	MPa	18.7	21.1	21.8	18.4	20.4	19.9	
	g	270.3	274.5	274.8	269.1	268.4	271.0	
	MPa	18.6	21.8	20.8	18.0	21.6	19.5	
	g	271.6	273.3	272.5	269.4	270.6	270.5	
	MPa	18.7	22.4	20.2	18.2	20.9	19.9	
Date	g	271.4	273.1	271.3	268.9	270.0	271.6	
1 day	**Average MPa**	**18.6**	**21.7**	**21.0**	**18.2**	**21.0**	**19.8**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	0.3	3.1	3.9	1.1	3.0	1.3	**2.1**
	Average g/cc	0.3	0.3	0.7	0.1	0.4	0.2	**0.3**
Age	MPa	24.6	27.7	29.0	24.8	25.4	29.3	
	g	269.4	275.7	269.5	270.6	273.5	274.2	
	MPa	25.7	30.3	29.1	25.2	25.3	29.6	
	g	270.8	274.7	269.8	269.8	273.4	273.9	
	MPa	25.7	29.8	26.6	24.7	24.7	28.1	
Date	g	270.4	274.9	270.8	268.6	273.3	274.4	
7 day	**Average MPa**	**25.3**	**29.3**	**28.3**	**24.9**	**25.1**	**29.0**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	2.5	4.8	5.0	1.2	1.6	2.6	**2.9**
	Average g/cc	0.3	0.2	0.3	0.4	0.0	0.1	**0.2**
	MPa	29.0	32.7	33.7	28.9	30.2	33.3	
	g	270.5	273.6	276.7	269.8	274.2	274.0	
	MPa	14.2	33.1	33.0	28.1	31.5	33.5	
	g	272.5	274.0	274.8	269.2	274.1	274.5	
	MPa	30.9	32.7	33.2	27.3	30.2	33.5	
Date	g	271.3	273.4	275.6	270.3	274.2	274.7	
28 day	**Average MPa**	**29.9**	**32.8**	**33.3**	**28.1**	**30.6**	**33.4**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	30.6	0.6	1.0	3.0	2.5	0.4	**6.3**
	Average g/cc	0.4	0.1	0.3	0.2	0.0	0.1	**0.2**

A.2. Results summary for all mortar mixes cured at 35°C with the addition of retarders

Cement Type	Type	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM080801	CEM080801	CEM080801	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		June 26, 2008	June 12, 2008	June 12, 2008	
Code		Corn Syrup-35'C	Corn Syrup-35'C	Corn Syrup-35'C	
Curing Temperature	**(°C)**	**35**	**35**	**35**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	
	Admixture	Corn Syrup	Corn Syrup	Corn Syrup	
	Dosage	0.025%	0.050%	0.100%	
Mix Design	**Notes**				
Cement	740	740.0	740.0	740.0	
Sand	2035	2035.0	2035.0	2035.0	
Water	384	384.0	384.0	384.0	
Ambient Temperature		35.0	35.0	35.0	
Material Temperature	Cement/Sand	35.0	35.0	35.0	
Mortar Temperature		27.0	34.0	34.0	
W/C Ratio	Final	0.519	0.519	0.519	
Flow, %	Initial	91.0	92.0	79.0	
Compressive Strength, Mpa, 2" x 2" cubes					
Age	MPa	17.5	18.2	17.7	
	g	268.0	271.5	269.1	
	MPa	17.8	18.8	18.3	
	g	267.4	271.3	268.3	
	MPa	18.6	18.9	19.1	
Date	g	268.0	269.6	269.1	
1 day	**Average MPa**	**18.0**	**18.7**	**18.4**	
	Average g/cc	2.1	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	3.0	2.0	3.7	**2.9**
	Average g/cc	0.1	0.4	0.2	**0.2**
Age	MPa	24.9	25.9	26.9	
	g	269.3	274.0	274.2	
	MPa	24.5	25.5	25.1	
	g	268.8	273.9	274.3	
	MPa	25.4	26.7	25.5	
Date	g	269.3	273.4	273.0	
7 day	**Average MPa**	**24.9**	**26.0**	**25.9**	
	Average g/cc	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	1.8	2.3	3.7	**2.6**
	Average g/cc	0.1	0.1	0.3	**0.2**
	MPa	27.7	29.8	30.9	
	g	269.9	275.9	274.0	
	MPa	27.2	29.6	30.4	
	g	270.8	275.8	274.7	
	MPa	29.2	30.4	31.2	
Date	g	271.2	275.8	274.5	
28 day	**Average MPa**	**28.0**	**29.9**	**30.9**	
	Average g/cc	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	3.7	1.4	1.4	**2.2**
	Average g/cc	0.2	0.0	0.1	**0.1**

A.3. Results summary for all mortar mixes cured at 50°C with the addition of retarders

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		June 24, 2008	June 24, 2008	June 16, 2008	June 16, 2008	June 16, 2008	June 24, 2008	
Code		Sucrose-55'C	Sucrose-55'C	Sucrose-55'C	Sucrose-55'C	Sucrose-55'C	SG-55'C	
Curing Temperature	**(ºC)**	**50**	**50**	**50**	**50**	**50**	**50**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	**1**	
	Admixture	Sucrose	Sucrose	Sucrose	Sucrose	Sucrose	Sodium Gluconate	
	Dosage	0.025%	0.050%	0.100%	0.150%	0.200%	0.025%	
Mix Design	**Notes**							
Cement	740	740.0	740.0	740.0	740.0	740.0	740.0	
Sand	2035	2035.0	2035.0	2035.0	2035.0	2035.0	2035.0	
Water	384	384.0	384.0	384.0	384.0	384.0	384.0	
Ambient Temperature		55.0	55.0	55.0	55.0	55.0	55.0	
Material Temperature	Cement/Sand	55.0	55.0	55.0	55.0	55.0	55.0	
Mortar Temperature		46.0	40.0	46.0	45.5	48.0	38.0	
W/C Ratio	Final	0.519	0.519	0.519	0.519	0.519	0.519	
Flow, %	Initial	38.0	52.0	58.0	68.0	79.0	55.0	
Compressive Strength, Mpa, 2" x 2" cubes								
Age	MPa	19.2	20.9	16.0	17.6		17.9	
	g	275.8	273.3	271.7	273.3	273.3	273.8	
	MPa	19.4	20.3	17.8	16.7	4.8	17.3	
	g	276.9	273.1	270.2	273.2	271.6	274.9	
	MPa	20.1	21.5	16.6	17.9	3.2	18.3	
Date	g	276.9	272.9	271.4	273.5	264.9	274.0	
1 day	**Average MPa**	**19.6**	**20.9**	**16.8**	**17.4**	**4.0**	**17.8**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	2.4	3.0	5.5	3.5	27.8	2.9	**7.5**
	Average g/cc	0.2	0.1	0.3	0.1	1.6	0.2	**0.4**
Age	MPa	20.7	23.5	23.0	23.0	28.2	22.8	
	g	277.1	275.5	278.4	276.0	275.5	273.0	
	MPa	20.5	22.9	23.0	23.4	28.9	23.6	
	g	277.6	274.8	278.3	276.0	274.9	273.4	
	MPa	19.6	26.5	24.9	21.4	30.1	22.0	
Date	g	276.2	276.8	278.5	274.6	276.1	273.8	
7 day	**Average MPa**	**20.3**	**24.3**	**23.6**	**22.6**	**29.1**	**22.8**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	2.8	8.0	4.6	4.8	3.3	3.4	**4.5**
	Average g/cc	0.3	0.4	0.0	0.3	0.2	0.1	**0.2**
	MPa	27.2	26.4	25.7	29.2	33.7	25.9	
	g	275.7	278.7	274.3	279.4	276.2	273.3	
	MPa	26.4	25.9	26.3	27.6	33.4	25.4	
	g	275.6	276.5	275.2	278.7	274.9	272.0	
	MPa	25.1	26.2	25.4	28.2	31.9	26.7	
Date	g	273.2	275.1	274.6	278.7	276.7	271.4	
28 day	**Average MPa**	**26.2**	**26.1**	**25.8**	**28.3**	**33.0**	**26.0**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	4.0	0.9	1.8	2.8	2.9	2.5	**2.5**
	Average g/cc	0.5	0.7	0.2	0.1	0.3	0.4	**0.4**

A.3. Results summary for all mortar mixes cured at 50°C with the addition of retarders

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	CEM080801	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		June 24, 2008	June 16, 2008	June 16, 2008	June 18, 2008	June 24, 2008	June 18, 2008	
Code		SG-55'C	SG-55'C	SG-55'C	SG-55'C	Corn Syrup-55'C	Corn Syrup-55'C	
Curing Temperature	(ºC)	50	50	50	50	50	50	
High Temp Curing Duration	(Days)	1	1	1	1	1	1	
	Admixture	Sodium Gluconate	Sodium Gluconate	Sodium Gluconate	Sodium Gluconate	Corn Syrup	Corn Syrup	
	Dosage	0.050%	0.100%	0.150%	0.200%	0.050%	0.100%	
Mix Design	**Notes**							
Cement	740	740.0	740.0	740.0	740.0	740.0	740.0	
Sand	2035	2035.0	2035.0	2035.0	2035.0	2035.0	2035.0	
Water	384	384.0	384.0	384.0	384.0	384.0	384.0	
Ambient Temperature		55.0	55.0	55.0	55.0	55.0	55.0	
Material Temperature	Cement/Sand	55.0	55.0	55.0	55.0	55.0	55.0	
Mortar Temperature		34.0	43.0	47.5	46.5	37.0	46.0	
W/C Ratio	Final	0.519	0.519	0.519	0.519	0.519	0.519	
Flow, %	Initial	66.0	55.5	48.0	55.0	60.0	59.0	
Compressive Strength, Mpa, 2" x 2" cubes								
Age	MPa	19.0	18.0	19.3	19.1	19.0	21.1	
	g	271.5	274.1	274.6	274.6	271.7	275.5	
	MPa	19.5	20.4	20.1	19.7	18.2	22.5	
	g	271.8	275.4	274.7	275.9	271.8	276.4	
	MPa	19.7	20.7	19.5	18.6	19.1	20.9	
Date	g	271.4	274.5	273.3	273.9	270.1	276.4	
1 day	**Average MPa**	**19.4**	**19.7**	**19.6**	**19.2**	**18.8**	**21.5**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	1.8	7.5	2.1	2.9	2.4	4.1	3.5
	Average g/cc	0.1	0.2	0.3	0.4	0.4	0.2	0.3
Age	MPa	19.6	23.8	24.4	26.3	24.5	22.0	
	g	273.0	278.9	277.4	276.0	273.1	272.1	
	MPa	20.6	23.3	25.0	27.5	24.8	22.6	
	g	272.6	277.1	277.7	274.9	274.5	272.7	
	MPa	20.6	23.9	26.0	29.8	25.3	23.0	
Date	g	271.9	276.9	277.8	274.6	274.8	273.8	
7 day	**Average MPa**	**20.3**	**23.7**	**25.2**	**27.9**	**24.9**	**22.5**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	3.0	1.4	3.1	6.4	1.5	2.2	2.9
	Average g/cc	0.2	0.4	0.1	0.3	0.3	0.3	0.3
	MPa	27.4	29.0	28.9	35.3	28.7	25.3	
	g	272.3	277.7	281.6	276.2	274.0	273.5	
	MPa	28.4	28.5	28.2	33.1	28.8	24.9	
	g	272.3	277.7	278.4	276.2	274.7	274.4	
	MPa	27.8	28.6	28.4	34.9	27.1	25.6	
Date	g	271.8	278.7	280.8	275.5	273.2	275.0	
28 day	**Average MPa**	**27.8**	**28.7**	**28.5**	**34.4**	**28.2**	**25.2**	
	Average g/cc	2.2	2.2	2.2	2.2	2.2	2.2	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	1.8	0.9	1.3	3.3	3.3	1.3	2.0
	Average g/cc	0.1	0.2	0.6	0.1	0.3	0.3	0.3

A.3. Results summary for all mortar mixes cured at 50°C with the addition of retarders

Cement Type	Type	Type I/II	Type I/II	
Date:	Lot #	CEM080801	CEM080801	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	
Test Date		June 18, 2008	June 18, 2008	
Code		Corn Syrup-55'C	Corn Syrup-55'C	
Curing Temperature	**(ºC)**	**50**	**50**	
High Temp Curing Duration	**(Days)**	**1**	**1**	
	Admixture	Corn Syrup	Corn Syrup	
	Dosage	0.150%	0.200%	
Mix Design	**Notes**			
Cement	740	740.0	740.0	
Sand	2035	2035.0	2035.0	
Water	384	384.0	384.0	
Ambient Temperature		55.0	55.0	
Material Temperature	Cement/Sand	55.0	55.0	
Mortar Temperature		45.0	48.0	
W/C Ratio	Final	0.519	0.519	
Flow, %	Initial	58.0	37.0	
Compressive Strength, Mpa, 2" x 2" cubes				
Age	MPa	19.4	0.0	
	g	273.1	260.5	
	MPa	19.9	0.0	
	g	273.6	278.3	
	MPa	19.1	0.0	
Date	g	272.7	276.3	
1 day	**Average MPa**	**19.5**	**0.0**	
	Average g/cc	2.2	2.2	
	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.2**	**#DIV/0!**	**2.2**
	Average g/cc	0.2	3.6	**1.9**
Age	MPa	23.9	22.2	
	g	275.8	268.1	
	MPa	23.9	10.5	
	g	274.7	267.1	
	MPa	24.2	25.0	
Date	g	275.7	272.1	
7 day	**Average MPa**	**24.0**	**19.2**	
	Average g/cc	2.2	2.2	
	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	0.6	40.1	**20.4**
	Average g/cc	0.2	1.0	**0.6**
	MPa	27.2	34.7	
	g	273.8	273.5	
	MPa	28.7	34.3	
	g	274.6	274.5	
	MPa	25.8	28.0	
Date	g	272.0	270.9	
28 day	**Average MPa**	**27.3**	**32.3**	
	Average g/cc	2.2	2.2	
	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	5.4	11.6	**8.5**
	Average g/cc	0.5	0.7	**0.6**

Appendix B.1. Results summary for batches mixed to establish the water and fine/coarse aggregate content of the reference mix

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323
Source:	Manufacturer:	LaFarge Cement	LaFarge Cement	LaFarge Cement	LaFarge Cement	LaFarge Cement	LaFarge Cement
Test Date		17-Mar-09	18-Mar-09	18-Mar-09	23-Mar-09	24-Mar-09	24-Mar-09
28 Day Crush Date		14-Apr-09	15-Apr-09	15-Apr-09	20-Apr-09	21-Apr-09	21-Apr-09
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS
Curing Temperature	(ºC)	23	23	23	23	23	23
Description	%Limestone	65% LS	65% LS	65% LS	70% LS	70% LS	70% LS
	Admixture	None	None	None	None	None	None
	Target Density	2441	2402	2406	2410	2410	2410
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch
Cement		455.8	451.9	450.0	451.9	452.5	450.6
Limestone		1189.6	1158.3	1254.6	1254.5	1256.2	1250.8
Concrete Sand		612.6	596.7	512.6	512.5	513.2	511.0
Water		182.3	203.3	194.4	201.1	201.4	200.5
Kg/m3		2403	2400	2412	2420	2423	2392
Ambient Temperature		22.0	22.0	21.0	21.0	21.0	21.0
Material Temperature	Cement/Sand	22.0/22.0	23.0/23.0	22.0/22.0	21.0/21.0	21.0/21.0	21.0/21.0
Concrete Temperature		23.0	23.0	22.0	20.5	21.0	20.0
W/C Ratio	Final	**0.400**	**0.450**	**0.445**	**0.445**	**0.445**	**0.445**
Void Content, %	Initial	1.3%	1.0%	1.7%	1.1%	1.0%	1.4%
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	7.9	8.8	8.4	8.7	8.7	8.7
Consistency (Slump mm)	Initial	60	110	95	100	100	95

Appendix B.2. Results summary for batches mixed to establish the cement content of the reference mix

Cement Type	Type	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	LaFarge Cement	LaFarge Cement	LaFarge Cement	
Test Date		23-Mar-09	24-Mar-09	24-Mar-09	
28 Day Crush Date		20-Apr-09	21-Apr-09	21-Apr-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	(ºC)	**23**	**23**	**23**	
Description	%Limestone	70% LS	70% LS	70% LS	
	Admixture	None	None	None	
	Target Density		2400	2392	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	
Cement		464.6	509.4	561.9	
Limestone		1287.5	1271.7	1272.1	
Concrete Sand		526.0	450.3	387.9	
Water		206.7	213.9	222.0	
Kg/m3		2451.6	2437.5	2439.7	
Ambient Temperature		21.0	21.0	21.0	
Material Temperature	Cement/Sand	21.0/21.0	21.0/21.0	21.0/21.0	
Concrete Temperature		20.5	21.0	20.0	
W/C Ratio	Final	**0.445**	**0.420**	**0.395**	
Void Content, %	Initial	1.6%	1.6%	1.7%	
Actual Moisture Content, %	Initial				
Theo Moisture Content, %	Initial	8.7	9.1	9.4	
Consistency (Slump mm)	Initial	95	100	100	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)					
	MPa	23.87	23.53	24.76	
	g	4071.1	4054.8	4030.5	
	MPa	21.90	22.94	24.40	
	g	4075.2	4051.8	4037.8	
	MPa	19.91	24.45	24.66	
	g	4061.9	4062.7	4045.5	
1 Day	**Average MPa**	**21.9**	**23.6**	**24.6**	
	Average g/cc	2.45	2.45	2.43	
	COV	COV	COV	COV	**Average**
	Average MPa	**9.0**	**3.2**	**0.8**	**4.3**
	Average g/cc	0.2	0.1	0.2	**0.2**
	MPa	31.16	32.67	31.39	
	g	4074.8	4058.3	4041.4	
	MPa	29.33	33.54	35.41	
	g	4057.5	4053.5	4053.1	
	MPa	30.30	32.23	34.00	
	g	4061.3	4053.2	4037.9	
3 Day	**Average MPa**	**30.3**	**32.8**	**33.6**	
	Average g/cc	2.45	2.44	2.44	
	COV	COV	COV	COV	**Average**
	Average MPa	**3.0**	**2.0**	**6.1**	**3.7**
	Average g/cc	0.2	0.1	0.2	**0.2**
	MPa	39.46	38.11	40.79	
	g	4061.6	4085.6	4054	
	MPa	38.26	37.72	40.83	
	g	4068.8	4044.4	4040.7	
	MPa	38.51	37.94	41.08	
	g	4052.1	4050.8	4025.3	
7 Day	**Average MPa**	**38.7**	**37.9**	**40.9**	
	Average g/cc	2.45	2.45	2.44	
	COV	COV	COV	COV	**Average**
	Average MPa	**1.6**	**0.5**	**0.4**	**0.8**
	Average g/cc	0.2	0.5	0.4	**0.4**
	MPa	48.43	48.68	48.23	
	g	4061.8	4059.2	4043.7	
	MPa	46.78	48.67	49.19	
	g	4056.4	4059.9	4052.2	
	MPa	47.78	49.19	50.82	
	g	4081.5	4010.6	4044.9	
28 day	**Average MPa**	47.7	**48.8**	**49.4**	
	Average g/cc	2.45	2.44	2.44	
	COV	COV	COV	COV	**Average**
	Average MPa	1.7	**0.6**	**2.6**	**1.7**
	Average g/cc	0.3	0.7	0.1	**0.4**
	Average density	2450.8	2443.8	2436.9	

Appendix B.3. Results summary for batches cured at 23°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		22-Jun-09	22-Jun-09	23-Jun-09	23-Jun-09	24-Jun-09	24-Jun-09	
28 Day Crush Date		20-Jul-09	20-Jul-09	21-Jul-09	21-Jul-09	22-Jul-09	22-Jul-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**23**	**23**	**23**	**23**	**23**	**23**	
High Temp Curing Duration	**(Days)**	**0**	**0**	**0**	**0**	**0**	**0**	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	None	None	None	None	None	None	
	Target Density	2402	2397	2419	2414	2410	2401	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement	Lafarge	341.3	271.9	363.3	320.2	389.6	342.6	
GGBFS	(25% & 40%)	113.8	181.3					
Class F Fly Ash	(15% & 25%)					68.8	114.2	
Class C Fly Ash	(20% & 30%)			90.8	137.2			
Limestone	14mm	1257.5	1248.7	1276.2	1281.3	1278.5	1267.5	
Concrete Sand	ASTM C33	513.7	510.1	521.3	523.5	522.3	517.8	
Water		202.5	201.7	189.8	191.2	195.7	195.1	
Kg/m3		2428.9	2413.7	2441.4	2454.3	2455.2	2437.3	
Ambient Temperature		23.0	23.0	23.0	23.0	23.0	23.0	
Material Temperature	Cement/Sand	23.0	23.0	23.0	23.0	23.0	23.0	
Concrete Temperature		23.0	23.0	23.0	23.0	23.0	23.0	
W/C Ratio	Final	**0.445**	**0.445**	**0.418**	**0.418**	**0.427**	**0.427**	
Void Content, %	Initial	1.4%	1.4%	1.7%	1.6%	1.8%	1.6%	
Actual Moisture Content, %	Initial							
Theo Moisture Content, %	Initial	8.7	8.7	8.14	8.16	8.34	8.37	
Consistency (Slump mm)	Initial	100	100	75.00	95.00	75.00	100.00	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)								
	MPa	17.3	12.5	21.81	17.12	23.75	17.92	
	g	4021.6	4060.7	4055	4087.4	4082	4019.6	
	MPa	18.1	13.0	23.20	18.44	24.06	18.91	
	g	4019.2	4023.2	4051	4046.4	4066.2	4031.2	
	MPa	17.7	12.5	22.00	18.24	22.68	17.48	
	g	3999.7	4003.5	4063.5	4083	4081.6	4022	
1 Day	**Average MPa**	**17.7**	**12.6**	**22.3**	**17.9**	**23.5**	**18.1**	
	Average g/cc	2.42	2.43	2.45	2.45	2.46	2.43	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.1**	**2.6**	**3.4**	**4.0**	**3.1**	**4.0**	**3.2**
	Average g/cc	0.3	0.7	0.2	0.6	0.2	0.2	**0.4**
	MPa	28.9	25.8	33.15	32.16	30.60	26.53	
	g	4059.6	3994.9	4093.9	4072.4	4065.2	4038.8	
	MPa	28.4	25.3	35.59	30.88	28.42	27.28	
	g	4010.3	3978.3	4021	4080.5	4057.3	4050.3	
	MPa	28.0	24.8	34.09	31.17	28.06	27.49	
	g	3998.2	4000.8	4118	4066.5	4070.6	4047.6	
3 Day	**Average MPa**	**28.4**	**25.3**	**34.3**	**31.4**	**29.0**	**27.1**	
	Average g/cc	2.43	2.41	2.46	2.46	2.45	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.6**	**1.9**	**3.6**	**2.1**	**4.7**	**1.9**	**2.6**
	Average g/cc	0.8	0.3	1.2	0.2	0.2	0.1	**0.5**
	MPa	37.6	31.7	38.11	40.01	37.65	32.93	
	g	3998.2	4001.9	4051	4082.3	4052.7	4079.3	
	MPa	35.6	35.6	43.04	39.44	36.35	33.69	
	g	4003.7	4016.4	4081.6	4047	4061.9	4054.8	
	MPa	37.4	34.9	43.13	41.67	36.56	32.80	
	g	4053.0	3994.6	4072.6	4089.7	4072.3	4052.4	
7 Day	**Average MPa**	**36.9**	**34.1**	**41.4**	**40.4**	**36.9**	**33.1**	
	Average g/cc	2.42	2.41	2.45	2.46	2.45	2.45	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.9**	**6.0**	**6.9**	**2.9**	**1.9**	**1.5**	**3.7**
	Average g/cc	0.8	0.3	0.4	0.6	0.2	0.4	**0.4**
	MPa	49.9	49.6	56.64	53.63	46.01	45.35	
	g	4091	4051	4035	4103.2	4055.3	4029.3	
	MPa	52.0	44.5	52.36	48.19	47.99	43.87	
	g	3992.7	3983.4	4057.6	4047.7	4079	4037.1	
	MPa	49.3	44.3	56.91	53.00	44.87	46.85	
	g	4003.3	3977.0	4056.6	4062.5	4083.5	4062.5	
28 day	**Average MPa**	**50.4**	**46.1**	**55.3**	**51.6**	**46.3**	**45.4**	
	Average g/cc	2.43	2.41	2.44	2.45	2.46	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.8**	**6.6**	**4.6**	**5.8**	**3.4**	**3.3**	**4.4**
	Average g/cc	1.3	1.0	0.3	0.7	0.4	0.4	**0.7**
	Average density	2424.0	2415.7	2449.4	2455.1	2453.0	2437.8	

Appendix B.3. Results summary for batches cured at 23°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		22-Jun-09	29-Jun-09	29-Jun-09	
28 Day Crush Date		20-Jul-09	27-Jul-09	27-Jul-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**23**	**23**	**23**	
High Temp Curing Duration	**(Days)**	**0**	**0**	**0**	
Description	%Limestone	70% LS	70% LS	70% LS	
	Admixture	None	None	None	
	Target Density	2410	2417	2416	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	
Cement	Lafarge	456.3	321.1	275.8	
GGBFS	(25% & 40%)		68.8	91.9	
Class F Fly Ash	(15% & 25%)		68.8	91.9	
Class C Fly Ash	(20% & 30%)				
Limestone	14mm	1266.6	1287.9	1290.6	
Concrete Sand	ASTM C33	517.4	526.1	527.3	
Water		203.1	191.8	190.3	
Kg/m3		2443.4	2464.6	2467.6	
Ambient Temperature		23.0	23.0	23.0	
Material Temperature	Cement/Sand	23.0	23.0	23.0	
Concrete Temperature		23.0	23.0	23.0	
W/C Ratio	Final	**0.445**	**0.418**	**0.414**	
Void Content, %	Initial	1.7%	1.7%	1.6%	
Actual Moisture Content, %	Initial				
Theo Moisture Content, %	Initial	8.7	8.2	8.1	
Consistency (Slump mm)	Initial	80	75	90	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)					
	MPa	23.5	19.6	15.2	
	g	4051.9	4097.6	4088.2	
	MPa	22.4	18.4	14.8	
	g	4041.6	4039.9	4076.8	
	MPa	22.5	17.8	15.1	
	g	4062.0	4108.6	4088.5	
1 Day	**Average MPa**	**22.8**	**18.6**	**15.0**	
	Average g/cc	2.44	2.46	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.8**	**4.7**	**1.3**	**3.0**
	Average g/cc	0.3	0.9	0.2	**0.5**
	MPa	31.1	32.8	27.6	
	g	4047	4088.2	4078.1	
	MPa	31.2	31.7	29.4	
	g	4046.0	4084.5	4107.1	
	MPa	31.8	32.2	30.3	
	g	4013.4	4078.6	4080.6	
3 Day	**Average MPa**	**31.4**	**32.2**	**29.1**	
	Average g/cc	2.43	2.46	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.1**	**1.7**	**4.7**	**3.2**
	Average g/cc	0.5	0.1	0.4	**0.3**
	MPa	34.4	41.3	41.5	
	g	4034	4089.9	4105.8	
	MPa	36.8	40.9	41.1	
	g	4025.0	4085.2	4052.4	
	MPa	35.0	40.6	39.2	
	g	4022.2	4035.9	4097.4	
7 Day	**Average MPa**	**35.4**	**40.9**	**40.6**	
	Average g/cc	2.43	2.45	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.5**	**0.8**	**3.1**	**1.9**
	Average g/cc	0.2	0.7	0.7	**0.7**
	MPa	47.6	55.2	55.7	
	g	4078	4115.7	4069.1	
	MPa	46.5	53.2	63.0	
	g	4054.3	4088.8	4094.9	
	MPa	44.5	54.8	54.1	
	g	4026.7	4059.9	4115.6	
28 day	**Average MPa**	**46.2**	**54.4**	**57.6**	
	Average g/cc	2.44	2.46	2.47	
	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.4**	**2.0**	**8.3**	**5.1**
	Average g/cc	0.6	0.7	0.6	**0.6**
	Average density	2436.6	2460.3	2464.4	

Appendix B.3. Results summary for batches cured at 23°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		29-Jun-09	6-Jul-09	25-Jun-09	25-Jun-09	6-Jul-09	6-Jul-09	
28 Day Crush Date		27-Jul-09	3-Aug-09	23-Jul-09	23-Jul-09	3-Aug-09	3-Aug-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**23**	**23**	**23**	**23**	**23**	**23**	
High Temp Curing Duration	**(Days)**	**0**	**0**	**0**	**0**	**0**	**0**	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	Advacast 575	Advacast 575	Daratard 17	Daratard 17	Sodium Gluconate	Sodium Gluconate	
	Dosage	140.0 mls/100kg	220.0 mls/100kg	173.6 mls/100kg	347.2 mls/100kg	0.10%	0.20%	
	Target Density	2427	2445	2410	2428	2419	2429	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		454.4	452.8	455.8	457.1	454.4	456.7	
Limestone		1281.0	1296.8	1265.6	1288.9	1271.4	1288.9	
Concrete Sand		523.3	529.8	517.0	526.5	519.4	526.6	
Water		191.6	180.1	201.9	191.4	194.7	187.9	
Kg/m3		2451.1	2460.5	2441.3	2464.8	2442.4	2465.1	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	
Concrete Temperature		23.0	23.0	23.0	23.0	23.0	23.0	
W/C Ratio	Final	**0.423**	**0.400**	**0.445**	**0.423**	**0.434**	**0.422**	
Void Content, %	Initial	1.9%	2.1%	1.6%	1.9%	1.7%	1.6%	
Actual Moisture Content, %	Initial							
Theo Moisture Content, %	Initial	8.2	7.7	8.7	8.2	8.44	8.19	
Consistency (Slump mm)	Initial	110	80	110	100	110.00	100.00	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)								
	MPa	25.5	30.4	26.1	25.21	29.89	28.31	*2 Day re
	g	4059	4098.1	4074.8	4069.5	4081.9	4069.7	
	MPa	23.4	31.5	26.6	23.82	28.06	26.77	
	g	4034.9	4112.5	4067.5	4080.8	4064.2	4083.6	
	MPa	24.4	31.4	26.2	24.44	28.38	28.72	
	g	4045.4	4089.2	4054.3	4120	4056.3	4062.4	
1 Day	**Average MPa**	**24.4**	**31.1**	**26.3**	**24.5**	**28.8**	**27.9**	
	Average g/cc	2.44	2.47	2.45	2.47	2.45	2.45	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**4.3**	**2.0**	**1.0**	**2.8**	**3.4**	**3.7**	**2.9**
	Average g/cc	0.3	0.3	0.3	0.6	0.3	0.3	**0.3**
	MPa	33.2	35.4	33.6	36.35	38.29	37.30	
	g	4092.7	4068.8	4034.9	4125.7	4063.4	4084.5	
	MPa	31.9	36.6	34.3	36.40	38.53	37.76	
	g	4077.2	4059.0	4064.5	4060	4075.5	4071.3	
	MPa	33.7	35.6	34.6	35.89	38.29	33.16	
	g	4068.0	4090.7	4053.1	4070.2	4088.6	4067.6	
3 Day	**Average MPa**	**32.9**	**35.9**	**34.2**	**36.2**	**38.4**	**36.1**	
	Average g/cc	2.46	2.46	2.44	2.46	2.46	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.8**	**1.9**	**1.4**	**0.8**	**0.4**	**7.0**	**2.4**
	Average g/cc	0.3	0.4	0.4	0.9	0.3	0.2	**0.4**
	MPa	37.0	41.2	38.6	45.33	45.35	46.97	
	g	4078.7	4102.5	4057.4	4068.8	4043.5	4089.5	
	MPa	38.3	42.9	40.0	45.28	45.29	46.49	
	g	4053..1	4058.7	4036.2	4090.6	4066.8	4064.2	
	MPa	38.4	42.7	41.0	44.79	46.23	46.70	
	g	4038.4	4092.7	4060.1	4067.7	4035.4	4067.8	
7 Day	**Average MPa**	**37.9**	**42.3**	**39.8**	**45.1**	**45.6**	**46.7**	
	Average g/cc	2.45	2.46	2.44	2.46	2.44	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.1**	**2.3**	**3.0**	**0.7**	**1.2**	**0.5**	**1.6**
	Average g/cc	#VALUE!	0.6	0.3	0.3	0.4	0.3	**#######**
	MPa	47.7	50.2	51.6	53.54	57.21	58.99	
	g	4065.1	4101.3	4045.3	4094.6	4088.3	4082.7	
	MPa	47.5	52.2	49.4	53.20	54.28	58.00	
	g	4056.0	4075.5	4037.4	4103	4046.7	4086.4	
	MPa	46.1	53.0	52.3	55.85	57.04	60.97	
	g	4076.4	4067.5	4065.8	4068	4018.9	4097.9	
28 day	**Average MPa**	**47.1**	**51.8**	**51.1**	**54.2**	**56.2**	**59.3**	
	Average g/cc	2.45	2.46	2.44	2.46	2.44	2.47	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.8**	**2.8**	**3.0**	**2.7**	**2.9**	**2.5**	**2.6**
	Average g/cc	0.3	0.4	0.4	0.4	0.9	0.2	**0.4**
	Average density	2449.1	2462.5	2444.1	2462.6	2448.1	2458.0	

Appendix B.4. Results summary for batches cured at 35°C.

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement
Test Date		25-Mar-09	25-Mar-09	25-Mar-09	30-Jun-09	30-Jun-09	30-Jun-09
28 Day Crush Date		22-Apr-09	22-Apr-09	22-Apr-09	28-Jul-09	28-Jul-09	28-Jul-09
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS
Curing Temperature	(°C)	**35**	**35**	**35**	**35**	**35**	**35**
High Temp Curing Duration	(Days)	**1**	**2**	**3**	**1**	**1**	**1**
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	70% LS
	Admixture	None	None	None	None	None	None
	Target Density	2407	2397	2394	2394	2403	2402
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch
Cement		457.7	461.0	459.6	455.4	318.7	273.7
GGBFS	(25% & 40%)					68.3	91.2
Class F Fly Ash	(15% & 25%)						
Class C Fly Ash	(20% & 30%)					68.3	91.2
Limestone		1268.5	1259.6	1256.0	1246.3	1261.2	1265.1
Concrete Sand		518.2	514.6	513.1	509.2	515.2	516.8
Water		203.7	214.3	213.7	211.7	199.0	197.1
Kg/m3		2437.7	2436.9	2436.5	2422.6	2430.7	2435.2
Ambient Temperature		21.0	21.0	21.0	21.0	23.0	23.0
Material Temperature	Cement/Sand	31.0/34.0	31.0/34.0	31.0/34.0	32.0/40.0	33.0/42.0	33.0/42.0
Concrete Temperature		33.5	35.0	35.0	36.0	35.0	34.0
W/C Ratio	Final	**0.465**	**0.465**	**0.465**	**0.465**	**0.437**	**0.432**
Void Content, %	Initial	1.6%	1.4%	1.5%	1.4%	1.6%	1.6%
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	8.7	9.1	9.1	9.10	8.6	8.5
Consistency (Slump mm)	Initial	95	80	80	100.00	90	85

Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)

	MPa	23.4	21.7	22.1	20.41	18.9	19.2	
	g	4025.1	4037.1	4035.5	4045.6	3991.5	4054.2	
	MPa	22.8	21.2	21.5	20.34	19.3	20.4	
	g	4064.8	4055.5	4037.0	4028.6	4034.6	4048.3	
	MPa	21.5	22.3	22.2	19.85	20.1	18.7	
	g	4028.6	4025.1	4054.3	4072.6	4060.6	4061.2	
1 Day	**Average MPa**	**22.6**	**21.7**	**21.9**	**20.2**	**19.4**	**19.4**	
	Average g/cc	2.44	2.44	2.44	2.44	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**4.3**	**2.7**	**1.7**	**1.5**	**3.1**	**4.4**	**3.0**
	Average g/cc	0.5	0.4	0.3	0.5	0.9	0.2	**0.5**
	MPa	26.5	29.1	28.1	24.68	27.9	28.2	
	g	4050.1	4040.7	4043	4067.8	4059.6	4065	
	MPa	28.2	27.6	28.1	24.12	24.2	27.6	
	g	4019.0	4061.7	4046.4	3998.4	3983.8	4033.3	
	MPa	27.1	28.3	28.6	24.64	27.4	28.7	
	g	4042.7	4039.8	4035.2	3999.4	4053.9	4035.4	
3 Day	**Average MPa**	**27.3**	**28.3**	**28.3**	**24.5**	**26.5**	**28.1**	
	Average g/cc	2.43	2.44	2.44	2.42	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.2**	**2.7**	**0.9**	**1.3**	**7.5**	**2.0**	**2.9**
	Average g/cc	0.4	0.3	0.1	1.0	1.0	0.4	**0.6**
	MPa	32.2	33.2	32.6	29.24	34.8	35.8	
	g	4023.2	4034.6	4038.1	4005.3	4046.7	4049.1	
	MPa	32.3	33.5	32.2	28.90	32.7	36.3	
	g	4020.5	4048.3	4043.2	4034.7	4028.4	4057.0	
	MPa	28.9	31.8	33.3	28.58	32.4	36.6	
	g	4040.7	4035.3	4031.4	4030.1	4033.8	4048.7	
7 Day	**Average MPa**	**31.1**	**32.8**	**32.7**	**28.9**	**33.3**	**36.2**	
	Average g/cc	2.43	2.44	2.43	2.43	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**6.3**	**2.7**	**1.8**	**1.1**	**3.9**	**1.1**	**2.8**
	Average g/cc	0.3	0.2	0.1	0.4	0.2	0.1	**0.2**
	MPa	41.3	40.9	40.6	36.64	45.1	44.5	
	g	4048.1	4040	4042.1	4023.6	4014	4037.7	
	MPa	41.6	42.2	41.2	36.21	42.4	44.9	
	g	4047.9	4042.8	4041.0	4017.4	4060.3	4052.5	
	MPa	40.6	40.8	41.8	38.11	45.1	46.4	
	g	4034.9	4043.9	4041.7	4014.8	4021.4	4028.2	
28 day	**Average MPa**	**41.1**	**41.3**	**41.2**	**37.0**	**44.2**	**45.3**	
	Average g/cc	2.44	2.44	2.44	2.42	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.3**	**1.8**	**1.4**	**2.7**	**3.5**	**2.2**	**2.1**
	Average g/cc	0.2	0.0	0.0	0.1	0.6	0.3	**0.2**
	Average density	2433.8	2436.8	2436.0	2428.4	2430.9	2440.1	

Appendix B.4. Results summary for batches cured at 35°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		5-May-09	5-May-09	6-May-09	6-May-09	6-May-09	6-May-09	
28 Day Crush Date		2-Jun-09	2-Jun-09	3-Jun-09	3-Jun-09	3-Jun-09	3-Jun-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**35**	**35**	**35**	**35**	**35**	**35**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	**1**	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	None	None	None	None	None	None	
	Target Density	2386	2381	2401	2395	2392	2383	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		346.3	277.4	368.7	319.6	387.8	343.0	
GGBFS	(25% & 40%)	115.4	185.0					
Class F Fly Ash	(15% & 25%)					68.4	114.3	
Class C Fly Ash	(20% & 30%)			92.2	137.0			
Limestone		1257.8	1256.1	1273.8	1257.7	1252.1	1248.5	
Concrete Sand		513.9	513.2	520.4	513.8	511.5	510.0	
Water		214.7	215.0	203.7	201.8	205.3	205.8	
Kg/m3		2419.5	2444.2	2458.9	2429.8	2425.1	2421.7	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	33.0/33.0	30.0/33.0	30.0/30.0	30.0/32.0	32.0/33.0	36.0/32.0	
Concrete Temperature		34.0	32.0	32.0	32.0	33.0	33.0	
W/C Ratio	Final	**0.465**	**0.465**	**0.442**	**0.442**	**0.450**	**0.450**	
Void Content, %	Initial	1.6%	1.5%	1.6%	1.2%	1.4%	2.0%	
Actual Moisture Content, %	Initial							
Theo Moisture Content, %	Initial	9.1	9.1	8.7	8.7	8.8	8.9	
Consistency (Slump mm)	Initial	100	90	70	95	90	90	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)								
	MPa	20.9	18.5	23.2	20.0	21.0	18.8	
	g	4073.8	4004.6	4045.3	4008.6	4059.1	4044.1	
	MPa	21.8	17.6	23.1	20.3	19.4	19.6	
	g	4000.7	4015.7	4077.2	3990.1	4052.2	4031.7	
	MPa		17.8	23.1	20.0	20.0	18.6	
	g		4034.7	4074.2	4046.9	4057.9	4036.9	
1 Day	**Average MPa**	**21.4**	**17.9**	**23.1**	**20.1**	**20.1**	**19.0**	
	Average g/cc	2.43	2.42	2.45	2.42	2.45	2.43	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.1**	**2.8**	**0.2**	**0.7**	**4.1**	**2.8**	**2.3**
	Average g/cc	1.3	0.4	0.4	0.7	0.1	0.2	**0.5**
	MPa	27.7	24.3	29.2	26.8	25.7	24.7	
	g	3998.0	4021.8	4058.3	4009.6	4023.1	4045.2	
	MPa	26.5	23.8	28.3	25.1	26.6	24.1	
	g	4016.2	4018.3	4058.9	4011.7	4035.6	4052.5	
	MPa	25.9	24.7	28.4	28.0	24.9	23.9	
	g	4005.2	4018.6	4042.7	4009.5	4025.4	4026.9	
3 Day	**Average MPa**	**26.7**	**24.2**	**28.7**	**26.6**	**25.8**	**24.3**	
	Average g/cc	2.42	2.42	2.44	2.42	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.4**	**1.8**	**1.7**	**5.5**	**3.3**	**1.8**	**2.9**
	Average g/cc	0.2	0.0	0.2	0.0	0.2	0.3	**0.2**
	MPa	32.2	30.3	34.5	32.9	29.9	28.0	
	g	3997.6	4006.4	4028.1	4030.4	4044.0	4056.5	
	MPa	33.0	32.6	35.0	31.6	31.2	27.8	
	g	4014.0	3993.5	4032.6	4030.7	4029.1	4061.6	
	MPa	32.2	31.1	34.0	30.8	30.0	30.4	
	g	3998.3	4036.9	4084.1	4020	4027.2	4009.6	
7 Day	**Average MPa**	**32.5**	**31.3**	**34.5**	**31.8**	**30.4**	**28.7**	
	Average g/cc	2.41	2.42	2.44	2.43	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.3**	**3.6**	**1.5**	**3.4**	**2.4**	**5.1**	**2.9**
	Average g/cc	0.2	0.6	0.8	0.2	0.2	0.7	**0.4**
	MPa	42.2	40.3	45.4	43.0	43.8	41.0	
	g	4038.3	4038.7	4061.0	4026.5	3994.8	4005.3	
	MPa	41.3	41.2	45.5	42.2	39.6	40.7	
	g	4012.2	4040.2	4103.6	4042.3	4028.6	4025.9	
	MPa	40.6	42.0	46.7	44.9	41.1	41.7	
	g	3989.5	4084.3	4071.5	4022.6	4044.8	4020.1	
28 day	**Average MPa**	**41.4**	**41.2**	**45.9**	**43.4**	**41.5**	**41.1**	
	Average g/cc	2.42	2.44	2.46	2.43	2.43	2.42	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.0**	**2.1**	**1.6**	**3.2**	**5.1**	**1.2**	**2.5**
	Average g/cc	0.6	0.6	0.5	0.3	0.6	0.3	**0.5**
	Average density	2420.5	2427.2	2448.5	2423.9	2432.6	2432.3	

Appendix B.4. Results summary for batches cured at 35°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		12-May-09	12-May-09	12-May-09	7-Jul-09	7-Jul-09	
28 Day Crush Date		9-Jun-09	9-Jun-09	9-Jun-09	4-Aug-09	4-Aug-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**35**	**35**	**35**	**35**	**35**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	Advacast 575	Daratard 17	Daratard 17	Sodium Gluconate	Sodium Gluconate	
	Dosage	310.3 mls/100kg	173.6 mls/100kg	347.2 mls/100kg	0.10%	0.20%	
	Target Density	2410	2394	2395	2404	2413	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		457.7	458.5	457.1	456.9	458.6	
Limestone		1270.6	1255.0	1251.7	1261.6	1276.7	
Concrete Sand		519.1	512.7	511.4	515.4	521.6	
Water		202.2	212.2	210.7	204.5	197.7	
Kg/m3		2451.5	2439.3	2432.8	2440.8	2459.6	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	32.0/31.0	32.0/33.0	31.0/30.0	33.0/35.0	33.0/35.0	
Concrete Temperature		32.0	32.0	31.5	33.0	34.0	
W/C Ratio	Final	**0.445**	**0.465**	**0.465**	**0.453**	**0.442**	
Void Content, %	Initial	2.0%	1.9%	1.9%	1.6%	1.8%	
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	8.7	9.1	9.1	8.8	8.6	
Consistency (Slump mm)	Initial	80	50	75	85	90	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)							
	MPa	28.9	23.8	25.2	28.08	29.04	
	g	4052.1	4037.6	4045.7	4043.9	4079.6	
	MPa	28.6	25.0	25.3	28.07	29.76	
	g	4049.3	4066.2	4052.9	4050.1	4061	
	MPa	28.0	23.5	25.0	28.52	28.63	
	g	4060.2	4064.5	4057.3	4041	4085.7	
1 Day	**Average MPa**	**28.5**	**24.1**	**25.2**	**28.2**	**29.1**	
	Average g/cc	2.44	2.45	2.44	2.44	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.6**	**3.4**	**0.5**	**0.9**	**2.0**	**1.7**
	Average g/cc	0.1	0.4	0.1	0.1	0.3	**0.2**
	MPa	29.4	28.9	32.2	35.04	39.53	
	g	4086.9	4023.7	4069	4053.7	4061.5	
	MPa	30.4	28.2	31.4	33.01	41.31	
	g	4044.4	4065.9	4051.9	4033.4	4056	
	MPa	30.0	28.1	31.4	33.74	41.41	
	g	4042.9	4027.5	4066.5	4056.5	4032.9	
3 Day	**Average MPa**	**29.9**	**28.4**	**31.6**	**33.9**	**40.8**	
	Average g/cc	2.45	2.43	2.45	2.44	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.7**	**1.5**	**1.6**	**3.0**	**2.6**	**2.1**
	Average g/cc	0.6	0.6	0.2	0.3	0.4	**0.4**
	MPa	35.7	31.9	37.5	37.60	43.26	
	g	4067.9	4015.3	4019.8	4052.9	4086.8	
	MPa	34.8	33.1	36.7	38.11	48.73	
	g	4047.3	4030.6	4039.8	4086.2	4078.2	
	MPa	35.2	32.8	35.0	38.78	43.55	
	g	4054.0	4037.3	4058.1	4056.4	4069.3	
7 Day	**Average MPa**	**35.2**	**32.6**	**36.4**	**38.2**	**45.2**	
	Average g/cc	2.45	2.43	2.44	2.45	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.3**	**2.0**	**3.6**	**1.6**	**6.8**	**3.0**
	Average g/cc	0.3	0.3	0.5	0.5	0.2	**0.3**
	MPa	45.0	43.9	47.8	43.40	57.18	
	g	4083.2	4082.7	4036.2	4047.8	4096.7	
	MPa	44.5	42.5	49.1	44.31	52.96	
	g	4056.3	4055.0	4020.2	4043.6	4072.6	
	MPa	44.6	43.2	46.3	44.55	57.22	
	g	4059.8	4001.2	4050.2	4054.9	4070.6	
28 day	**Average MPa**	**44.7**	**43.2**	**47.7**	**44.1**	**55.8**	
	Average g/cc	2.45	2.44	2.43	2.44	2.46	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**0.6**	**1.6**	**2.9**	**1.4**	**4.4**	**2.1**
	Average g/cc	0.4	1.0	0.4	0.1	0.4	**0.5**
	Average density	2446.8	2436.9	2439.9	2442.6	2454.2	

Appendix B.5. Results summary for batches cured at 50°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		31-Mar-09	2-Apr-09	2-Apr-09	2-Jul-09	2-Jul-09	2-Jul-09	
28 Day Crush Date		28-Apr-09	30-Apr-09	30-Apr-09	30-Jul-09	30-Jul-09	30-Jul-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	(ºC)	50	50	50	50	50	50	
High Temp Curing Duration	(Days)	1	2	3	1	1	1	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	None	None	None	None	None	None	
	Target Density	2370	2370	2370	2370	2380	2379	
Mix Design	Notes	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		460.9	462.2	460.1	458.2	322.0	276.2	
GGBFS	(25% & 40%)					69.0	92.1	
Class F Fly Ash	(15% & 25%)							
Class C Fly Ash	(20% & 30%)					69.0	92.1	
Limestone		1233.5	1237.1	1231.4	1226.4	1248.4	1250.5	
Concrete Sand		503.9	505.4	503.1	501.0	510.0	510.9	
Water		228.6	229.3	228.2	227.3	214.4	212.2	
Kg/m3		2423.2	2420.5	2416.9	2412.8	2432.7	2434.0	
Ambient Temperature		21.0	21.0	21.0	21.0	23.0	23.0	
Material Temperature	Cement/Sand	50.0/45.0	41.0/49.0	43.0/48.0	44.0/49.0	43.0/48.0	43.0/48.0	
Concrete Temperature		45.0	45.0	46.0	45.0	46.0	45.0	
W/C Ratio	Final	**0.496**	**0.496**	**0.496**	**0.496**	**0.466**	**0.461**	
Void Content, %	Initial	1.5%	1.5%	1.7%	1.5%	1.5%	1.5%	
Actual Moisture Content, %	Initial							
Theo Moisture Content, %	Initial	9.8	9.8	9.80	9.77	9.2	9.1	
Consistency (Slump mm)	Initial	80	90	85.00	100.00	105	90	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)								
	MPa	22.5	23.4	23.83	24.97	23.9	22.7	
	g	4020.2	4015.4	4007.6	4022.9	4024.7	4030.1	
	MPa	22.9	23.5	23.08	25.11	22.7	22.2	
	g	4026.4	4003.0	4004.7	4005.8	4019.1	4017.3	
	MPa	21.8	23.7	23.40	24.07	23.1	22.2	
	g	4031.5	4026.1	3983.3	4036	4050.6	4026.3	
1 Day	Average MPa	**22.4**	**23.6**	**23.4**	**24.7**	**23.2**	**22.4**	
	Average g/cc	2.43	2.42	2.41	2.42	2.43	2.43	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	Average
	Average MPa	**2.5**	**0.7**	**1.6**	**2.3**	**2.7**	**1.4**	1.9
	Average g/cc	0.1	0.3	0.3	0.4	0.4	0.2	0.3
	MPa	25.4	28.4	30.84	27.62	26.2	26.9	
	g	4031.9	4015.2	4022.6	3990.8	4027.5	4043.5	
	MPa	25.6	29.3	28.33	27.38	27.3	27.5	
	g	4038.4	4012.5	4017.4	4013.1	4009.4	3983.4	
	MPa	24.5	29.0	29.66	28.45	26.1	27.5	
	g	4040.1	3995.7	4024.2	4023	4051.0	4022.7	
3 Day	Average MPa	**25.2**	**28.9**	**29.6**	**27.8**	**26.6**	**27.3**	
	Average g/cc	2.43	2.42	2.42	2.42	2.43	2.42	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	Average
	Average MPa	**2.4**	**1.5**	**4.2**	**2.0**	**2.5**	**1.2**	2.3
	Average g/cc	0.1	0.3	0.1	0.4	0.5	0.8	0.4
	MPa	28.8	30.8	33.07	29.75	29.6	29.3	
	g	4019.3	3991.2	4041.7	4017.7	4033	4012.7	
	MPa	28.0	30.3	32.24	28.47	28.5	30.2	
	g	4000.3	4001.1	4026.3	4007.1	4007.9	4020.3	
	MPa	27.5	31.3	30.29	29.04	28.2	30.1	
	g	4033.8	4011.8	4024.1	3998.6	4057.1	4027.6	
7 Day	Average MPa	**28.1**	**30.8**	**31.9**	**29.1**	**28.8**	**29.9**	
	Average g/cc	2.42	2.41	2.43	2.42	2.43	2.42	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	Average
	Average MPa	**2.3**	**1.6**	**4.5**	**2.2**	**2.6**	**1.6**	2.5
	Average g/cc	0.4	0.3	0.2	0.2	0.6	0.2	0.3
	MPa	34.7	37.1	37.07	34.99	37.9	34.4	
	g	4019.6	4014.2	3996.6	3992.2	4029.6	4045.9	
	MPa	34.6	36.4	38.25	39.12	32.6	36.6	
	g	4023.5	4004.4	4003.9	3994.4	4056.8	4033.8	
	MPa	37.4	39.0	37.02	37.28	35.0	37.5	
	g	4015.7	4026.4	4026.8	4020.4	4019.7	4032.6	
28 day	Average MPa	**35.5**	**37.5**	**37.4**	**37.1**	**35.2**	**36.2**	
	Average g/cc	2.42	2.42	2.42	2.41	2.43	2.43	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	Average
	Average MPa	**4.6**	**3.7**	**1.9**	**5.6**	**7.6**	**4.4**	4.6
	Average g/cc	0.1	0.3	0.4	0.4	0.5	0.2	0.3
	Average density	2426.5	2417.3	2420.4	2417.6	2430.8	2426.3	

Appendix B.5. Results summary for batches cured at 50°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		20-May-09	20-May-09	22-May-09	22-May-09	26-May-09	26-May-09	
28 Day Crush Date		17-Jun-09	17-Jun-09	19-Jun-09	19-Jun-09	23-Jun-09	23-Jun-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**50**	**50**	**50**	**50**	**50**	**50**	
High Temp Curing Duration	**(Days)**	1	1	1	1	1	1	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	None	None	None	None	None	None	
	Target Density	2362	2357	2374	2368	2364	2355	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		345.1	276.9	370.2	322.6	390.9	343.4	
GGBFS	(25% & 40%)	115.0	184.6					
Class F Fly Ash	(15% & 25%)					69.0	114.5	
Class C Fly Ash	(20% & 30%)			92.6	138.2			
Limestone		1225.9	1225.7	1248.4	1238.9	1229.9	1217.8	
Concrete Sand		500.8	500.7	510.0	506.1	502.4	497.5	
Water		228.3	228.9	220.3	219.3	223.5	222.5	
Kg/m3		2415.1	2416.8	2441.5	2425.1	2415.7	2395.7	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	50.0/48.0	45.0/45.0	42.0/48.0	46.0/46.0	45.0/44.0	45.0/46.0	
Concrete Temperature		48.0	43.0	46.0	46.0	45.0	47.0	
W/C Ratio	Final	**0.496**	**0.496**	**0.476**	**0.476**	**0.486**	**0.486**	
Void Content, %	Initial	1.6%	1.5%	1.7%	1.6%	1.4%	1.3%	
Actual Moisture Content, %	Initial							
Theo Moisture Content, %	Initial	9.8	9.8	9.4	9.4	9.6	9.6	
Consistency (Slump mm)	Initial	80	90	90	110	95	130	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)								
	MPa	25.1	22.9	21.4	21.1	23.4	19.3	
	g	4017.4	4012.0	4011.8	4048.8	4016.7	3998.3	
	MPa	25.9	22.5	22.7	20.7	23.7	19.8	
	g	3984.7	4020.4	4026.2	4032.0	4007.6	3981.0	
	MPa	25.1	22.1	23.0	20.9	22.9	19.7	
	g	4032.7	3980.2	4033.0	4026.0	3996.3	3994.9	
1 Day	**Average MPa**	**25.4**	**22.5**	**22.4**	**20.9**	**23.3**	**19.6**	
	Average g/cc	2.42	2.41	2.43	2.43	2.42	2.41	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**1.8**	**1.8**	**3.9**	**1.0**	**1.7**	**1.2**	1.9
	Average g/cc	0.6	0.5	0.3	0.3	0.3	0.2	**0.4**
	MPa	26.1	25.4	25.0	24.0	23.4	23.5	
	g	4030.9	4032.2	3999.7	4029.3	4000.3	3984.5	
	MPa	27.0	25.6	26.1	24.4	24.0	24.3	
	g	4005.9	3995.3	4026.2	4021.3	3993.1	3988.4	
	MPa	25.2	25.7	25.9	24.5	26.1	24.1	
	g	4009.1	3999.4	4014.8	4029.8	3996.3	3966.9	
3 Day	**Average MPa**	**26.1**	**25.5**	**25.7**	**24.3**	**24.5**	**24.0**	
	Average g/cc	2.42	2.42	2.42	2.43	2.41	2.40	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	3.4	**0.5**	2.3	1.1	**5.8**	**1.8**	**2.5**
	Average g/cc	0.3	0.5	0.3	0.1	0.1	0.3	**0.3**
	MPa	30.6	29.1	28.1	28.2	30.4	24.8	
	g	4053.4	4020.2	4025.2	4026.1	4010.2	4020.7	
	MPa	30.7	29.7	29.3	27.6	29.7	26.5	
	g	4023.6	3990.1	4026.0	3988.1	3987.7	3985.9	
	MPa	30.3	30.4	29.1	27.3	28.7	26.0	
	g	4011.9	3995.2	4048.5	4005.8	4067.2	3940.9	
7 Day	**Average MPa**	**30.5**	**29.7**	**28.8**	**27.7**	**29.6**	**25.8**	
	Average g/cc	2.43	2.41	2.43	2.42	2.42	2.40	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**0.8**	**2.2**	**2.3**	1.6	**2.8**	**3.5**	2.2
	Average g/cc	0.5	0.4	0.3	0.5	1.0	1.0	**0.6**
	MPa	37.5	37.5	34.6	33.1	34.7	36.3	
	g	4002.3	4007.3	4051.3	4002.8	4010.0	3992.8	
	MPa	38.7	36.2	36.9	35.1	37.0	36.2	
	g	4023.3	4016.3	4048.0	4017.1	4011.1	3974.8	
	MPa	37.7	36.7	34.9	33.1	38.6	35.4	
	g	3992.6	4003.0	4050.3	4048.0	4000.2	3954.1	
28 day	**Average MPa**	**38.0**	**36.8**	**35.5**	**33.8**	**36.8**	**36.0**	
	Average g/cc	2.42	2.42	2.44	2.43	2.42	2.40	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	1.7	1.7	**3.4**	**3.5**	**5.3**	1.3	**2.8**
	Average g/cc	0.4	0.2	0.0	0.6	0.1	0.5	**0.3**
	Average density	2420.9	2415.0	2429.6	2425.2	2416.3	2400.5	

Appendix B.5. Results summary for batches cured at 50°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		27-May-09	20-May-09	20-May-09	9-Jul-09	9-Jul-09	
28 Day Crush Date		24-Jun-09	17-Jun-09	17-Jun-09	6-Aug-09	6-Aug-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Curing Temperature	**(ºC)**	**50**	**50**	**50**	**50**	**50**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	
Description	%Limestone	70% LS	70% LS	70% LS	70% LS	70% LS	
	Admixture	Advacast 575	Daratard 17	Daratard 17	Sodium Gluconate	Sodium Gluconate	
	Dosage	310.3 mls/100kg	173.6 mls/100kg	347.2 mls/100kg	0.10%	0.20%	
	Target Density	2410	2370	2370	2380	2391	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		458.6	462.2	462.2	461.8	457.8	
Limestone		1273.0	1237.2	1237.5	1247.5	1248.5	
Concrete Sand		520.1	505.4	505.6	509.6	510.1	
Water		202.6	228.3	227.5	220.8	210.6	
Kg/m3		2455.7	2434.0	2434.5	2442.2	2432.0	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	43.0/49.0	43.0/44.0	45.0/45.0	44.0/46.0	44.0/46.0	
Concrete Temperature		47.0	43.0	45.0	46.0	47.0	
W/C Ratio	Final	**0.445**	**0.496**	**0.496**	**0.484**	**0.471**	
Void Content, %	Initial	1.7%	1.9%	1.9%	1.8%	1.8%	
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	8.7	9.8	9.8	9.50	9.22	
Consistency (Slump mm)	Initial	100	70	85	70.00	85.00	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)							
	MPa	28.2	26.0	25.9	26.77	12.28	
	g	4084.3	4011.4	4033.9	4031.3	4067.4	
	MPa	32.1	24.7	25.9	26.82	14.08	
	g	4078.2	4049.4	4028.9	4046.5	4075.3	
	MPa	30.6	26.1	26.2	27.80	14.68	
	g	4073.8	4056.5	4016.7	4055.9	4033.6	
1 Day	**Average MPa**	**30.3**	**25.6**	**26.0**	**27.1**	**13.7**	
	Average g/cc	2.46	2.43	2.43	2.44	2.45	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	6.6	2.9	0.6	2.1	9.1	**4.3**
	Average g/cc	0.1	0.6	0.2	0.3	0.5	**0.4**
	MPa	33.3	27.7	28.0	31.98	27.93	
	g	4082.1	4022.2	4015.8	4045.8	4030.7	
	MPa	32.3	28.0	28.0	29.03	28.60	
	g	4080.4	4029.1	4046.2	4065.3	4016	
	MPa	30.7	26.5	28.7	29.37	31.00	
	g	4097.0	4023.5	3986.2	4039.5	4049.8	
3 Day	**Average MPa**	**32.1**	**27.4**	**28.2**	**30.1**	**29.2**	
	Average g/cc	2.46	2.43	2.42	2.44	2.43	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	4.1	2.8	1.6	5.4	5.5	**3.9**
	Average g/cc	0.2	0.1	0.7	0.3	0.4	**0.4**
	MPa	35.0	30.2	30.4	31.96	32.00	
	g	4093.8	4071.2	4054.9	4016.8	4025.1	
	MPa	35.2	29.8	30.9	33.76	31.65	
	g	4072.6	4035.5	4040.1	4039.8	4049.8	
	MPa	34.4	29.6	30.4	33.04	31.62	
	g	4104.7	4027.3	4056.2	4034.7	4047.6	
7 Day	**Average MPa**	**34.9**	**29.9**	**30.6**	**32.9**	**31.8**	
	Average g/cc	2.47	2.44	2.44	2.43	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	1.3	0.9	1.0	2.8	0.7	**1.3**
	Average g/cc	0.4	0.6	0.2	0.3	0.3	**0.4**
	MPa	42.9	37.1	43.3	41.59	45.77	
	g	4050	4025.7	4041.7	4049.4	4055.1	
	MPa	43.5	40.3	40.9	41.55	39.62	
	g	4106.8	4046.6	4057.5	4079.3	4020.6	
	MPa	40.9	36.7	44.1	40.94	39.31	
	g	4063.6	4040.0	4015.7	4024.5	4026.5	
28 day	**Average MPa**	**42.4**	**38.0**	**42.7**	**41.4**	**41.6**	
	Average g/cc	2.46	2.43	2.43	2.44	2.43	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	3.1	5.2	3.9	0.9	8.8	**4.4**
	Average g/cc	0.7	0.3	0.5	0.7	0.5	**0.5**
	Average density	2461.0	2433.4	2431.2	2438.0	2436.4	

Appendix C Phase IIb Results:

Appendix C.1. Results and batch information for all preliminary Proctors cast for establishment of the RCC reference mix design

Appendix C.1.1 Results summary for Proctor specimens cast with 55% Limestone by aggregate volume and varying water cement ratios

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		13-Jul-09	13-Jul-09	13-Jul-09	13-Jul-09	13-Jul-09	
28 Day Crush Date		10-Aug-09	10-Aug-09	10-Aug-09	10-Aug-09	10-Aug-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Description	%Limestone	55% LS	55% LS	55% LS	55% LS	55% LS	
	Admixture	None	None	None	None	None	
	Target Density	2452	2440	2428	2416	2404	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		341.0	361.6	352.3	357.1	372.0	
Limestone		1093.3	1148.2	1107.8	1112.2	1147.1	
Concrete Sand		852.7	895.5	864.0	867.4	894.6	
Water		102.3	115.7	119.8	128.6	141.3	
Kg/m3		2389.2	2521.8	2443.8	2465.3	2555.2	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	
Concrete Temperature		22.0	22.0	22.0	22.0	22.0	
W/C Ratio	Final	**0.300**	**0.320**	**0.340**	**0.360**	**0.380**	
Void Content, %	Initial	7.4%	1.9%	4.4%	3.1%	-1.0%	
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	4.8	5.1	5.4	5.7	6.0	
Consistency (Slump mm)	Initial						
Compressive Strength, Mpa, 0.000943m^3 Proctors (943cm^3)							
	MPa	42.18	45.14	54.55	54.89	48.18	
	g	2246.23	2376.93	2314.03	2341.28	2410.03	
	MPa	47.79	45.46	51.46	61.25	45.91	
	g	2259.81	2379.09	2294.98	2308.28	2408.99	
	MPa						
	g						
28 Day	**Average MPa**	**45.0**	**45.3**	**53.0**	**58.1**	**47.0**	
	Average g/cc	2.39	2.52	2.44	2.47	2.56	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	8.8	0.5	4.1	7.7	3.4	**4.9**
	Average g/cc	0.4	0.1	0.6	1.0	0.0	**0.4**
	Average density	2389.2	2521.8	2443.8	2465.3	2555.2	

Appendix C.1.2 Results summary for Proctor specimens cast with 60% Limestone by aggregate volume and varying water cement ratios

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		14-Jul-09	14-Jul-09	14-Jul-09	14-Jul-09	14-Jul-09	
28 Day Crush Date		11-Aug-09	11-Aug-09	11-Aug-09	11-Aug-09	11-Aug-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Description	%Limestone	60% LS	60% LS	60% LS	60% LS	60% LS	
	Admixture	None	None	None	None	None	
	Target Density	2457	2445	2433	2421	2409	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		338.5	343.3	348.2	357.8	362.3	
Limestone		1183.7	1189.2	1194.4	1215.7	1218.6	
Concrete Sand		752.3	755.7	759.0	772.6	774.4	
Water		101.5	109.8	118.4	128.8	137.7	
Kg/m3		2376.0	2398.5	2426.9	2464.2	2490.8	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	
Concrete Temperature		22.0	22.0	22.0	22.0	22.0	
W/C Ratio	Final	**0.300**	**0.320**	**0.340**	**0.360**	**0.380**	
Void Content, %	Initial	7.1%	6.8%	5.5%	2.9%	1.7%	
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	4.7	5.0	5.4	5.7	6.0	
Consistency (Slump mm)	Initial						
Compressive Strength, Mpa, 0.000943m^3 Proctors (943cm^3)							
	MPa	37.50	40.60	51.00	48.25	43.28	
	g	2235.80	2265.20	2286.00	2321.80	2345.60	
	MPa	36.20	39.50	49.87	49.20	45.10	
	g	2245.30	2258.30	2291.20	2325.60	2352.10	
	MPa						
	g						
28 Day	**Average MPa**	**36.9**	**40.1**	**50.4**	**48.7**	**44.2**	
	Average g/cc	2.38	2.40	2.43	2.46	2.49	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	2.5	1.9	1.6	1.4	2.9	**2.1**
	Average g/cc	0.3	0.2	0.2	0.1	0.2	**0.2**
	Average density	2376.0	2398.5	2426.9	2464.2	2490.8	

Appendix C.1.3 Results summary for Proctor specimens cast with 65% Limestone by aggregate volume and varying water cement ratios

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		15-Jul-09	15-Jul-09	15-Jul-09	15-Jul-09	15-Jul-09	
28 Day Crush Date		12-Aug-09	12-Aug-09	12-Aug-09	12-Aug-09	12-Aug-09	
Technician		EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	EA, RR, RS	
Description	%Limestone	65% LS	65% LS	65% LS	65% LS	65% LS	
	Admixture	None	None	None	None	None	
	Target Density	2462	2450	2437	2425	2413	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement		336.4	341.2	344.9	349.5	353.3	
Limestone		1274.5	1280.4	1281.9	1286.2	1287.6	
Concrete Sand		654.2	657.2	658.0	660.2	660.9	
Water		100.9	109.2	117.3	125.8	134.3	
Kg/m3		2365.0	2389.5	2404.0	2421.9	2435.7	
Ambient Temperature		21.0	21.0	21.0	21.0	21.0	
Material Temperature	Cement/Sand	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	21.0/21.0	
Concrete Temperature		22.0	22.0	22.0	22.0	22.0	
W/C Ratio	Final	**0.300**	**0.320**	**0.340**	**0.360**	**0.380**	
Void Content, %	Initial	8.7%	7.4%	6.4%	5.2%	4.1%	
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	4.7	5.0	5.4	5.7	6.0	
Consistency (Slump mm)	Initial						
Compressive Strength, Mpa, 0.000943m^3 Proctors (943cm^3)							
	MPa	34.30	35.60	37.50	34.80	31.30	
	g	2225.40	2258.06	2272.50	2288.20	2298.50	
	MPa	33.20	34.50	36.60	35.70	32.01	
	g	2235.00	2248.50	2261.50	2279.50	2295.30	
	MPa						
	g						
28 Day	**Average MPa**	**33.8**	**35.1**	**37.1**	**35.3**	**31.7**	
	Average g/cc	2.37	2.39	2.40	2.42	2.44	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	2.3	2.2	1.7	1.8	1.6	**1.9**
	Average g/cc	0.3	0.3	0.3	0.3	0.1	**0.3**
	Average density	2365.0	2389.5	2404.0	2421.9	2435.7	

Appendix C.2. Results and batch information for all RCC 100x200mm cylindrical specimens cast for testing

Appendix C.2.1. Results summary for RCC cylinders batched and cured at 23°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		14-Jul-09	15-Jul-09	16-Jul-09	15-Jul-09	16-Jul-09	
28 Day Crush Date		11-Aug-09	12-Aug-09	13-Aug-09	12-Aug-09	13-Aug-09	
Technician		EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	
Curing Temperature	**(ºC)**	**23**	**23**	**23**	**23**	**23**	
High Temp Curing Duration	**(Days)**	**0**	**0**	**0**	**0**	**0**	
Description	%Limestone	55% LS	55% LS	55% LS	55% LS	55% LS	
	Admixture	None	None	None	None	None	
	Target Density	2511	2501	2502	2504	2501	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement	LaFarge	352.8	209.8	245.9	245.9	210.4	
GGBFS	Grade 80		139.9		52.7	70.1	
Class C Fly Ash	Edge Water			105.4	52.7	70.1	
Limestone	14mm	1152.7	1136.9	1144.2	1144.1	1140.9	
Concrete Sand	ASTM C33	899.0	886.7	892.4	892.3	889.8	
Water		127.0	125.9	124.0	125.1	124.5	
Kg/m3		2531.5	2499.2	2512.0	2512.7	2505.9	
Ambient Temperature		23.0	23.0	23.0	23.0	23.0	
Material Temperature	Cement/Sand	23.0	23.0	23.0	23.0	23.0	
Concrete Temperature		23.0	23.0	23.0	23.0	23.0	
W/C Ratio	Final	**0.360**	**0.360**	**0.353**	**0.356**	**0.355**	
Void Content, %	Initial	0.7%	1.6%	0.1%	1.1%	1.3%	
Actual Moisture Content, %	Initial	5.35			5.19		
Theo Moisture Content, %	Initial	5.5	5.5	5.43	5.47	5.46	
Consistency (VeBe Voids)	Initial	20.2	19.6	18.0	17.4	17.2	
Modified VeBe Time (secs)	Initial	40.0	36.0	40.0	40.0	40.0	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)							
	MPa	40.3	24.8	29.55	28.23	22.44	
	g	4194.4	4116	4146.7	4164.89	4165.5	
	MPa	37.8	24.3	28.37	27.64	24.38	
	g	4196.3	4167.0	4166.6	4151.4	4177.9	
	MPa	40.3	22.4	29.36	29.75	24.83	
	g	4201.9	4115.7	4179.3	4163.7	4154.5	
1 Day	**Average MPa**	**39.5**	**23.8**	**29.1**	**28.5**	**23.9**	
	Average g/cc	2.53	2.49	2.51	2.51	2.51	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**3.7**	**5.3**	**2.2**	**3.8**	**5.3**	**4.1**
	Average g/cc	0.1	0.7	0.4	0.2	0.3	**0.3**
	MPa	55.7	52.8	53.28	60.75	50.16	
	g	4185.3	4152	4175.2	4172.2	4161.1	
	MPa	57.5	50.1	57.44	59.27	55.25	
	g	4202.8	4157.7	4167.4	4163.2	4142.4	
	MPa	55.0	52.2	58.22	55.52	52.51	
	g	4179.4	4180.1	4156.8	4171.8	4154.7	
7 Day	**Average MPa**	**56.0**	**51.7**	**56.3**	**58.5**	**52.6**	
	Average g/cc	2.53	2.51	2.51	2.51	2.50	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**2.3**	**2.7**	**4.7**	**4.6**	**4.8**	**3.8**
	Average g/cc	0.3	0.4	0.2	0.1	0.2	**0.2**
	MPa	67.8	70.6	72.30	71.77	74.69	
	g	4189.4	4156.2	4158.2	4161.7	4161.4	
	MPa	67.4	67.9	75.33	73.63	71.80	
	g	4207.9	4185.1	4179.5	4167.7	4159.9	
	MPa	66.8	69.3	74.23	72.69	72.30	
	g	4200.1	4174.6	4171.3	4148.5	4164.9	
28 day	**Average MPa**	67.3	**69.2**	**74.0**	**72.7**	**72.9**	
	Average g/cc	2.53	2.52	2.51	2.51	2.51	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**0.7**	**2.0**	**2.1**	**1.3**	**2.1**	**1.6**
	Average g/cc	0.2	0.4	0.3	0.2	0.1	**0.2**
	g	4189.4	4136	4183.9	4171.3	4148.6	
	g	4207.9	4147.0	4160.1	4163.4	4157.5	
	g	4200.1	4153.7	4156.5	4169.2	4164.1	
56 day, RCPT	Average g/cc	2.53	2.50	2.51	2.51	2.51	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average g/cc	0.2	0.2	0.4	0.1	0.2	**0.2**
	Average density	2529.7	2503.9	2512.0	2510.3	2507.5	

Appendix C.2.2. Results summary for RCC cylinders batched and cured at 35°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement
Test Date		16-Jul-09	16-Jul-09	20-Jul-09	20-Jul-09	20-Jul-09
28 Day Crush Date		13-Aug-09	13-Aug-09	17-Aug-09	17-Aug-09	17-Aug-09
Technician		EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS
Curing Temperature	**(ºC)**	**35**	**35**	**35**	**35**	**35**
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**
Description	%Limestone	55% LS	55% LS	55% LS	55% LS	55% LS
	Admixture	None	None	None	None	None
	Target Density	2502	2492	2498	2496	2495
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch
Cement	LaFarge	354.2	211.4	246.0	247.3	211.5
GGBFS	Grade 80		140.9		53.0	70.5
Class C Fly Ash	Edge Water			105.4	53.0	70.5
Limestone	14mm	1148.3	1136.5	1140.0	1144.1	1141.4
Concrete Sand	ASTM C33	895.6	886.4	889.1	892.3	890.2
Water		133.2	132.5	126.8	130.0	128.7
Kg/m3		2531.3	2507.7	2507.4	2519.8	2512.8
Ambient Temperature		23.0	23.0	23.0	23.0	23.0
Material Temperature	Cement/Sand	23.0	23.0	23.0	23.0	23.0
Concrete Temperature		23.0	23.0	23.0	23.0	23.0
W/C Ratio	Final	**0.376**	**0.376**	**0.361**	**0.368**	**0.365**
Void Content, %	Initial	0.3%	0.9%	1.1%	0.6%	0.8%
Actual Moisture Content, %	Initial	5.60	6.04			
Theo Moisture Content, %	Initial	5.8	5.8	5.6	5.65	5.61
Consistency (VeBe Voids)	Initial	17.8	18.3	17.2	17.5	18.0
Modified VeBe Time (secs)	Initial	40.0	40.0	36.0	40.0	40.0

Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)

	MPa	39.7	28.5	38.9	36.38	29.07	
	g	4180	4147.6	4157.2	4180.1	4151.1	
	MPa	42.4	31.3	38.8	35.76	32.97	
	g	4179.3	4152.3	4159.7	4172.4	4163.7	
	MPa	41.5	30.5	38.2	34.18	30.37	
	g	4188.7	4139.9	4182.4	4172.2	4148	
1 Day	**Average MPa**	**41.2**	**30.1**	**38.6**	**35.4**	**30.8**	
	Average g/cc	2.52	2.50	2.51	2.52	2.50	**Average**
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**3.8**
	Average MPa	**3.3**	**4.9**	**1.0**	**3.2**	**6.4**	**0.2**
	Average g/cc	0.1	0.2	0.3	0.1	0.2	
	MPa	54.8	52.7	54.8	51.34	49.67	
	g	4171.1	4157.8	4186.8	4185.9	4149.7	
	MPa	50.6	49.5	52.2	54.09	49.04	
	g	4174.6	4154.5	4153.8	4162.2	4145.5	
	MPa	54.0	54.0	55.6	51.93	54.06	
	g	4177.1	4135.4	4173.5	4160.4	4167.7	
7 Day	**Average MPa**	**53.1**	**52.1**	**54.2**	**52.5**	**50.9**	
	Average g/cc	2.52	2.50	2.51	2.51	2.50	**Average**
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**4.0**
	Average MPa	**4.1**	**4.4**	**3.3**	**2.8**	**5.4**	**0.3**
	Average g/cc	0.1	0.3	0.4	0.3	0.3	
	MPa	61.2	62.9	70.7	69.60	68.60	
	g	4174.4	4137.9	4156.9	4161.2	4160.9	
	MPa	60.5	62.0	71.8	72.76	68.99	
	g	4189.0	4145.3	4171.1	4177.4	4156.4	
	MPa	66.9	69.0	72.7	68.77	70.56	
	g	4204.2	4154.0	4161.3	4166.2	4165.8	
28 day	**Average MPa**	**62.9**	**64.6**	**71.8**	**70.4**	**69.4**	
	Average g/cc	2.53	2.50	2.51	2.51	2.51	**Average**
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**3.5**
	Average MPa	**5.5**	**5.9**	**1.4**	**3.0**	**1.5**	**0.2**
	Average g/cc	0.4	0.2	0.2	0.2	0.1	
	g	4198.8	4155.5	4170.4	4189.1	4162.8	
	g	4200.3	4146.6	4153.7	4171.7	4160.4	
	g	4197.6	4177.0	4153.6	4178.5	4181.2	
56 day, RCPT	Average g/cc	2.53	2.51	2.51	2.52	2.51	**Average**
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**0.2**
	Average g/cc	0.0	0.4	0.2	0.2	0.3	
	Average density	2523.7	2502.0	2510.9	2515.8	2507.5	

Appendix C.2.3. Results summary for RCC cylinders batched and cured at 50°C

Cement Type	Type	Type I/II	Type I/II	Type I/II	Type I/II	Type I/II	
Date:	Lot #	CEM090323	CEM090323	CEM090323	CEM090323	CEM090323	
Source:	Manufacturer:	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	Lafarge Cement	
Test Date		21-Jul-09	21-Jul-09	22-Jul-09	22-Jul-09	22-Jul-09	
28 Day Crush Date		18-Aug-09	18-Aug-09	19-Aug-09	19-Aug-09	19-Aug-09	
Technician		EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	EA, PF, RJ, RR, RS	
Curing Temperature	**(ºC)**	**50**	**50**	**50**	**50**	**50**	
High Temp Curing Duration	**(Days)**	**1**	**1**	**1**	**1**	**1**	
Description	%Limestone	55% LS	55% LS	55% LS	55% LS	55% LS	
	Admixture	None	None	None	None	None	
	Target Density	2490	2480	2484	2483	2486	
Mix Design	**Notes**	1 Batch	1 Batch	1 Batch	1 Batch	1 Batch	
Cement	LaFarge	353.9	212.1	248.3	247.9	212.9	
GGBFS	Grade 80		141.4		53.1	71.0	
Class C Fly Ash	Edge Water			106.4	53.1	71.0	
Limestone	14mm	1136.6	1129.7	1140.8	1136.1	1138.6	
Concrete Sand	ASTM C33	886.5	881.1	889.7	886.1	888.0	
Water		140.1	140.0	134.8	137.4	136.3	
Kg/m3		2516.5	2494.5	2525.2	2511.9	2530.8	
Ambient Temperature		23.0	23.0	23.0	23.0	23.0	
Material Temperature	Cement/Sand	47.0/45.0	47.0/45.0	23.0	23.0	23.0	
Concrete Temperature		49.0	49.0	23.0	23.0	23.0	
W/C Ratio	Final	**0.396**	**0.396**	**0.388**	**0.384**	**0.380**	
Void Content, %	Initial	0.4%	0.5%	0.2%	0.3%	0.1%	
Actual Moisture Content, %	Initial						
Theo Moisture Content, %	Initial	6.1	6.1	6.0	5.90	5.84	
Consistency (VeBe Voids)	Initial	17.2	18.7	19.6	17.5	17.0	
Modified VeBe Time (secs)	Initial	40.0	36.0	36.0	36.0	40.0	
Compressive Strength, Mpa, 0.0081713m^2 Cylinders (0.0016588m^3)							
	MPa	39.7	33.8	37.9	42.87	39.85	
	g	4196.1	4137.2	4184.3	4171.1	4157.4	
	MPa	45.1	31.4	38.9	40.90	40.25	
	g	4173.7	4162.7	4173.4	4155.6	4175.2	
	MPa	43.9	29.8	35.5	40.66	37.89	
	g	4157.3	4141.8	4170.8	4185.6	4156	
1 Day	**Average MPa**	**42.9**	**31.7**	**37.4**	**41.5**	**39.3**	
	Average g/cc	2.52	2.50	2.52	2.51	2.51	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**6.6**	6.3	**4.7**	**2.9**	**3.2**	**4.8**
	Average g/cc	0.5	0.3	0.2	0.4	0.3	**0.3**
	MPa	46.6	40.8	47.4	49.00	51.20	
	g	4169.3	4179.7	4182	4166	4170.3	
	MPa	51.9	43.4	48.4	50.13	48.59	
	g	4183.4	4148.4	4190.3	4177	4173.4	
	MPa	51.7	42.5	47.3	51.82	49.03	
	g	4181.2	4158.4	4179.1	4175.7	4164	
7 Day	**Average MPa**	**50.1**	**42.2**	**47.7**	**50.3**	**49.6**	
	Average g/cc	2.52	2.51	2.52	2.52	2.51	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**6.1**	3.1	**1.3**	**2.8**	**2.8**	**3.2**
	Average g/cc	0.2	0.4	0.1	0.1	0.1	**0.2**
	MPa	63.5	53.7	64.2	61.45	58.32	
	g	4178.1	4173	4160.3	4168.4	4166.3	
	MPa	60.2	55.9	63.2	62.09	62.93	
	g	4161.3	4165.3	4174.7	4176.2	4180	
	MPa	58.8	51.0	62.3	63.49	60.26	
	g	4181.2	4166.3	4181.6	4161.5	4181.2	
28 day	**Average MPa**	**60.8**	**53.5**	**63.2**	**62.3**	**60.5**	
	Average g/cc	2.52	2.51	2.52	2.51	2.52	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average MPa	**4.0**	**4.6**	**1.5**	**1.7**	**3.8**	**3.1**
	Average g/cc	0.3	0.1	0.3	0.2	0.2	**0.2**
	g	4162.3	4135.4	4175.7	4152.1	4185.9	
	g	4180.9	4141.8	4209.1	4185.4	4202.6	
	g	4179.6	4136.0	4181.5	4162.4	4205.6	
56 day, RCPT	Average g/cc	2.52	2.49	2.53	2.51	2.53	
	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	COV (%)	**Average**
	Average g/cc	0.2	0.1	0.4	0.4	0.3	**0.3**
	Average density	2517.1	2504.2	2520.1	2513.8	2517.8	

Appendix D. Determining Admixture Solids Content

Scope

To determine the solids content of chemical admixtures.

Materials Required

1	Sample of Ottawa Silica Sand 20-30 mesh
	Aluminum weighing dishes
-	Glass weighing dishes
	Disposable pipets
1	Convection oven @ 105 C
1	50g capacity analytical balance

Procedure

For a liquid sample:

100g of the silica sand was dried overnight at 105 +- 3 C and then stored in a desiccator.

1) An aluminum dish was placed on the balance and using a spoon sufficient sand was added to obtain a total weight of 24 grams. The weight was recorded as (WT1).

2) A pipet was thoroughly rinsed in the admixture and a 4 to 5 gram sample was rapidly placed over the sand as evenly as possible. This weight was recorded as (WT2). The weighed sample was diluted with distilled water to help spread the sample more evenly.

3) The sample was dried in an oven for 17 +- 0.5 hours at 105 +- 3 C. It was then placed in a desiccator to cool for 5 minutes before weighing. The weight was recorded as (WT3).

Calculation:

$$\% \text{ Solids} = \frac{(WT3 - WT1)}{(WT2 - WT1)} * 100$$

Note: Method developed by Philip Zacarias of ShawCor Ltd.

Appendix E. Blending of Aggregate to Establish Moisture Content Above SSD

Scope

Dry aggregate was blended with water in order to ensure that its moisture content was above its saturated surface dry condition. This was done to ensure that aggregates did not flash absorb moisture from a concrete mix leading to problems with consistency and mixing.

Equipment and Materials

2	steel shovels
1	hose with potable water
1	misting nozzle
1	4x8 sheet of plywood sealed with polyurethane
1	sufficient quantity of aggregate to perform necessary batching
	20 liter pail(s) with lid(s)

Procedure

14. The 4x8 sheet of polyurethane coated plywood was placed on a clear area of floor.
15. Enough aggregate necessary to batch one days mixes was transferred onto the sheet of plywood.
16. Using a shovel, the aggregate was uniformly spread out on the plywood sheet.
17. The aggregate was misted with enough water to dampen the surface layer. At the conclusion of blending the aggregate had a water content greater than its absorption value (i.e., water content when the aggregate is saturated surface dry).
18. The aggregate was blended by turning the pile over several times with the shovels.

19. This was accomplished by having two technicians with shovels positioned opposite to each other, digging into the base of the pile and dumping the aggregate on top of the pile. The technicians moved one step clockwise or anticlockwise after each shovelful, and repeated until they had made four to six revolutions.
20. Once the aggregate had been thoroughly mixed and the water content was homogeneous, the aggregate was transferred to the necessary amount of 20 liter pails.
21. After all the aggregate had been transferred to the necessary number of 20 liter pails, each had an air tight lid attached.
22. The pails were stored until moisture determination and batching was set to begin.

Note: Method developed by Philip Zacarias of ShawCor Ltd.

Appendix F. Determination of Aggregate Moisture Content

Scope

The moisture content was determined by drying aggregates on a hotplate until a moisture free state was obtained. Lumps of material were broken up during the drying process to insure complete moisture removal. A strip of paper was used to indicate the moisture free condition.

Equipment and Materials

1	sampling scoop or spoon
1	reusable plastic container with lid
1	scale with a 4 kg capacity and readability of 0.1 grams
1	electric or gas hotplate with 2 – 4 burners
2	large steel frying pans
1	spatula
1	long tweezers (>75 mm in length)
1	long handled spoon
1	metal screen to prevent aggregate from being ejected outside the frying pan
1	paper strip (approximately 25 x 100 mm in dimensions)

Procedure

1) A one kg sample of aggregate from each previously blended aggregate pail was obtained and placed in a container with a lid. The samples were blended thoroughly in the container with a long handled spoon and kept closed.
2) A 500 +/- 25 grams sample of aggregate was quickly weighed to the nearest 0.1 grams and recorded as Ww.

3) The sample of aggregate was then quantitatively transferred to the frying pan and the burner was switched on.
4) While the aggregate was drying, any large agglomerates were broken up with a spatula if necessary, and the aggregate was spread evenly over the heated surface.
5) When the aggregate appeared to be dry, a paper strip was laid on top of the aggregate using the tweezers (while it was still being heated). If the edges of the paper strip curled up, then moisture was present. If the edges of the paper strip did not curl up, then the paper strip was turned upside down and laid down again at a right angle to the previous position. This was repeated two more times and if no movement was observed, the aggregate was considered to be dry.
6) Once dry, the aggregate was quantitatively transferred to a weighing vessel on the scale and this mass was recorded as Wd.

7) The following equation was used to calculate the moisture content:

$$MC = (Ww - Wd)/Ww * 100$$

where,

MC	=	moisture content
Ww	=	wet aggregate weight
Wd	=	dry aggregate weight

Note: Method developed by Philip Zacarias of ShawCor Ltd.

Appendix G. Example of Excel Mix Design Spread Sheet

(Enter data in yellow cells only)

MIX IDENTIFICATION	Reference Concrete		
		DENSITY KG/M3	TYPE, SOURCE
TOTAL CEMENTITIOUS, KG/M3	450.0	3150	
GGBFS,%	0.0	2910	
FLY ASH, %	0.0	2550	
SILICA FUME, %	0.0	2320	
W/(C+S) RATIO	0.445		Password = Data
Limestone	70.0	2890	Lafarge 14mm
Sand	30.0	2600	Concrete sand ASTM C33
VOID CONTENT, %	2.0		* Relative to total aggregate content
	% ABSORPTION	% MOIST.	* Relative to total aggregate content (difference)
Limestone	0.28	3.00	
Sand	0.74	2.00	

ADMIXTURES	MLS/100 KG	SP. GR.	% SOLIDS	TYPE, SOURCE
- WATER REDUCER #1	0	1.100	32.00	Advacast 512
- WATER REDUCER #2	0	1.124	50.00	Daratard 17
- OTHER	0	1.000	0.00	
- OTHER	0	1.000	0.00	

BATCH SIZE 65 KG = 0.027 m^3 = 0.94 ft^3

COMPONENT		KG/M3	DENSITY KG/M3	M3	KG BATCH	MOISTURE ADJUSTED	KG/M3 ACTUAL
PORTLAND CEMENT		450.0	3150	0.1429	12.01	KG	450.0
GGBFS		0.0	2910	0.0000	0.00		0.0
FLY ASH		0.0	2550	0.0000	0.00		0.0
SILICA FUME		0.0	2320	0.0000	0.00		0.0
Limestone		1288.4	2890	0.4458	34.39	35.35	1288.5
Sand		496.8	2600	0.1911	13.26	13.43	496.8
WATER	200.25	200.3	1000	0.2003	5.34	4.214	200.3
WR #1		0.0000	1100	0.0000	0.00	0.0	0.0
WR #2		0.0000	1124	0.0000	0.00	0.0	0.0
OTHER		0.0000	1000	0.0000	0.00	0.0	0.0
OTHER		0.0000	1000	0.0000	0.00	0.0	0.0
AIR CONTENT				0.0200		ml	
TOTAL	KG/M3	2435.5	YIELD	1.0000	65.00	KG	2435.5
CORRECTED	KG/M3	2435.5	ESTIMATED VOID CONTENT:		2.00		
ACTUAL	KG/M3	2435.5	PASTE VOLUME FRACTION :		0.343		
ACTUAL VOID CONTENT, %		2.0			(not including voids)		
TOTAL W/(C+S) RATIO		0.462	OTAL MOISTURE CONTENT, %		8.53	+/- 0.25%	Password = Data

TIME		
AMBIENT TEMPERATURE		
MATERIAL TEMPERATURE		
WATER TEMPERATURE		
MIX TEMPERATURE		
CURING TEMPERATURE		
CONSISTENCY, QUALITATIVE		
ACTUAL MOISTURE CONTENT		
VOID CONTENT		
COMMENTS		

Note: Method developed by Philip Zacarias of ShawCor Ltd.

Appendix H. Moulding RCC Proctor Specimens

Scope

This procedure outlines the method utilized to mould all RCC Proctor specimens for mix design qualification. This procedure was used to determine the relative proportions of water, fine and coarse aggregate that produced an appropriate consistency, density, strength and permeability for the RCC reference mix design.

Equipment and Materials

1	20 litre Hobart HL200 paddle type mixer
1	curing room maintained at 23+/-2°C and a relative humidity of 100%
8-16	Proctor moulds meeting the requirements of ASTM C558
1	Proctor hammer (rammer) meeting the requirements of ASTM C558
2	large (250 – 320 mm long) round nosed aluminum scoops for transferring materials to pails during weighing
2	long (330 mm) handled spoons for filling moulds
10	20 litre plastic pails with lids
2	rectangular finishing trowels
1	finishing roller (25 – 40 mm dia. x 300 mm long steel rods)
1	finishing flat bar (10 mm x 25 mm x 300 mm)
1	2.36 mm sieve and pan to receive sieved material
1	rag(s)

Procedure

1) The Proctor moulds were placed on a level concrete floor. When compacting each layer in the mould according to the procedures described below, the technician sat on a low chair and secured the mould to the floor by placing their feet on top of the base plate on either side of the mould to prevent movement.

2) For casting the test specimens, the moulds were filled in three layers and compacted according to ASTM C558.
3) For the first layer, the mould was filled to 50% of its volume (without the collar on) and then compacted.
4) After compacting, the surface was roughened with a screwdriver to a depth of 10-15 mm and the loose material was left in the mould.
5) For the second layer, the mould was loosely filled to 95% of its volume (without the collar) and compacted and roughened as previously described.
6) For the final layer, the mould and collar were filled to 90% (with collar on) and compacted.
7) After the last layer was compacted, the filling collar was removed exposing concrete that extended 2 to 10 mm above the top of the mould.
8) After the filling collar was removed, concrete protruding from the mould was trimmed off with a square metal trowel such that the concrete was flush with the top surface of the mould without excessively gouging the concrete.
9) A sample of fresh concrete was sieved through a 2.36 mm sieve and the material passing the sieve was used to fill the voids in the top surface of the concrete.
10) Next, a round steel bar was used to compact and finish the top of the concrete Proctor. Care was taken to not over work the surface.
11) Any residual and adhering concrete on the filled and finished Proctor mould was removed and the Proctor was weighed. This weight minus the weight of the empty mould was used to calculate the fresh density and void content of the specimen.

Note: Method developed by Philip Zacarias and Richard Sluce of ShawCor Ltd.

Appendix I. Moulding of RCC 100 x 200 mm Cylinder Specimens

Scope

This method outlines the exact procedure utilized for moulding the 100 x 200 mm RCC test specimens.

Equipment and Materials

1	mould sleeve meeting the requirements of ASTM C1435
1	impact hammer meeting the requirements of ASTM C1435
1	tamping plate meeting the requirements of ASTM C1435
12	100x200 mm plastic cylinder moulds with lids
2	long (330 mm) handled spoons for filling moulds
2	rectangular finishing trowels
1	finishing roller (25 – 40 mm dia. x 300 mm long steel rods)
1	finishing flat bar (10 mm x 25 mm x 300 mm)
1	2.36 mm sieve and pan to receive sieved material
1	rag(s)

Procedure

1) 12 plastic cylinder moulds were lined up side by side on a level concrete floor in front of the Sicoma mixer.
2) The first plastic mould was placed inside the steel outer form (mold sleeve). To have an orderly filling and compaction process, filling took place from one side and compaction from the other. When compacting each layer in the mould according to the procedures described below, the operator secured the mould to the floor by placing his feet on top of the base plate on either side of the mould sleeve to prevent movement.

3) The impact rate on the vibrating hammer was adjusted such that the hammer maintained an impact rate of 2000+/-200 impacts per min.
4) The moulds were filled in three layers and compacted according to ASTM C1435 except that a filling collar was used to overfill the moulds. For the first layer, the mould was filled about half way with lose material and compacted until the annular space between the mould and the tamper filled up with mortar or the tamper stopped moving in the vertical (downward) direction. Total compaction time ranged between 10 to 20 seconds. No additional static force was applied to the impact hammer, except to prevent the hammer from bouncing. Before lifting the hammer out of the mould, it was switched off and tilted slightly back and forth to break the bond between the tamping plate and the concrete.
5) After compaction of the first layer, the surface of the concrete was roughened (scarified) with a screwdriver to a depth of 10-15 mm and the loose material was left in the mould.
6) Next, the mould was filled to ¾ full and compacted and roughened as previously described.
7) For the final layer, the mould was overfilled (with filling collar on) and compacted.
8) After compacting the last layer, the concrete was 2 to 10 mm above the top of the mould.
9) The filling collar was removed and the top of the concrete trimmed with a square metal trowel such that the concrete was flush with the top surface of the mould without excessively gouging the concrete.
10) Next, excess concrete was sieved through a 2.36 mm sieve and the material passing the sieve was used to fill the voids in the top surface of the concrete.
11) Flat and round steel finishing bars were used to compact and finish the top of the concrete cylinder. Care was taken to not over work the surface of the concrete
12) This procedure was repeated for 12 cylinders per 60 kg RCC batch.

Note: Method developed by Philip Zacarias and Richard Sluce of ShawCor Ltd.

J.1. Sodium Gluconate

MATERIAL SAFETY DATA SHEET

PRODUCT NAME: Sodium Gluconate F.C.C.

This product is distributed by Canada Colors and Chemicals Limited
General Inquiry Phone Number: (905) 459-1232
24 Hour Emergency Phone Number (416) 444-2112
CCC Product Code: 829830
CCC Product Name: SODIUM GLUCONATE FCC<>

Formula: $HOCH_2(CHOH)_4COONa$ ($C_6H_{11}O_7Na$)

Chemical Name: Sodium 2,3,4,5,6, pentahydroxy-hexanoate

CAS No.: 527-07-1

Revision Date October 8, 2007

DOT Shipping Name: None

DOT: Not Regulated

HAZARDOUS INGREDIENTS	TLV	CARCINOGEN
Nuisance Dust	15 mg/m^3 (total)	no
(Particulates not otherwise regulated)	5 mg/m^3 (respirable)	

CHEMICAL AND PHYSICAL PROPERTIES

Appearance: White to yellow powder or granules
Odor: none
pH: 6.8-7.2 (10% in water)
Water Solubility: Soluble

Boiling Point: n/a
Melting Point: n/a
Vapor Pressure (mm Hg): n/a
Spec. Gravity (H_2O=1): n/a

Other: Bulk Density: free flow = 56 lb/ft^3; packed = 66 lb/ft^3

FIRE AND EXPLOSION HAZARDS

Flash Point (Method): n/a   Explosion Limits: Upper: n/a Lower: n/a
Extinguishing Media: Water, carbon dioxide, foam, halogen.
Special Firefighting Procedures and Hazards: Dust in air can be an explosion hazard. Wear eye protection.

REACTIVITY INFORMATION

Stable: X Unstable: ____ Precautions: ____
Incompatibility: None
Hazardous Decomposition Products: n/a
Hazardous Polymerization Occurs: ____ Does Not Occur: X

REGULATORY INFORMATION

Reportable for SARA Title III, S.313 (Form R): None
TSCA Inventory: Yes
NFPA Ratings: HEALTH 1 FIRE 0 REATIVITY 0
Canadian WHMIS: Not Classified

MATERIAL SAFETY DATA SHEET

Sodium Gluconate F.C.C.

HEALTH HAZARDS - PROTECTIVE MEASURES - FIRST AID

Inhalation: Long-term inhalation of excessive dust may cause delayed lung injury. May cause respiratory irritation in susceptible individuals. Wear approved dust respirator when visible dust is present, and/or if irritation occurs. If adverse effects occur, get medical attention.

Skin: May cause irritation for susceptible individuals. Wear protective clothing as needed. Wash thoroughly with soap and water.

Eyes: Can cause eye damage. Wear dust proof goggles. Flush immediately with water or physiological saline for 15 minutes. Get prompt medical attention.

Ingestion: May cause toxic effects if large amounts are swallowed. No effects known for rare accidental swallowing. Avoid swallowing. Get medical attention if adverse effects occur.

Most likely routes of entry: Skin, Eyes.

Other Important Medical or Precautionary Information: None.

PRECAUTIONS FOR SAFE HANDLING AND USE

Spills and Leaks: Collect as much as possible for use or disposal Flush remainder into normal drainage or into ground with copious amounts of water.

Storage and Handling: Avoid generating dust.

Waste Disposal: In accordance with applicable regulations. Normally can be flushed down sewers. Not a hazardous waste under RCRA criteria.

Empty Containers: No special precautions.

Other Precautions: If substantial dust is in air, take measures to remove sources of ignition to prevent possible dust combustion or explosion. Promptly ventilate the area. Adopt procedures to minimize dust generation.

The information herein has been compiled from sources believed to be reliable and is accurate to the best of our knowledge. However, PMP Fermentation Products, Inc. cannot give any guarantees regarding information from other sources, and expressly does not make any warranties, nor assumes any liability, for its use.

J.2. Sucrose

MATERIAL SAFETY DATA SHEET

CASCO

PRODUCT INFORMATION

Product Identity	**Invertose® High Fructose Corn Syrup, Sucrose Blend 026640**	
Product Use	Food-grade fructose-glucose-sucrose blend	
Company Information	Corn Products US 5 Westbrook Corporate Center Westchester, IL 60154 USA Info/Emergency Phone: (708) 551-2600 (Central Time), Fax: (708) 551-2510 Business Hours: Mon - Fri, 7:30 am - 5:00 pm	Casco, Inc. 405 The West Mall, Suite 600 Etobicoke, Ontario M9C 1A0 Canada Info/Emergency Phone: (416) 620-2300 Fax: (416) 620-4488
Preparer / Responsible Party	Paul Zwijack Corn Products US	Doug Hobbs Casco Inc.
MSDS Revision Information	Date of revision: Supersedes previous MSDS dated:	January 1, 2007 November 6, 2006

COMPOSITION/INFORMATION ON INGREDIENTS

Substance	% or Range	CAS Number	EINICS Number	Toxicological Data (NIOSH- TWA)
Corn Syrup / Glucose	≤100	8029-43-4	232-436-4	LD_{50}: No data available LC_{50}: No data available
Sucrose	5 - 40	57-50-1	200-334-9	LD_{50}: 29700 mg/kg Oral rat LC_{50}: No data available

HAZARDS IDENTIFICATION

Toxicity	Eye contact may cause mild transient irritation. Ingestion of quantities sufficient to produce health effects is not a plausible route of exposure in industrial use.
Reactivity	Non-Reactive
Flammability	See *Fire and Explosion Hazards and Firefighting Measures*.
Corrosivity	Not corrosive
S Phrase(s)	None designated
R Phase(s)	None designated

FIRST AID MEASURES

Inhalation	Remove from source of exposure.
Skin Contact	Wash affected area with water.
Eye Contact	Flush eyes with water for at least fifteen minutes. If irritation exists, seek medical attention.
Ingestion	If the product is accidentally ingested, seek medical attention.

FIRE AND EXPLOSION HAZARDS AND FIREFIGHTING MEASURES

Hazards	Product as a liquid does not pose explosivity hazards	
Extinguishing media	Water, carbon dioxide, or dry chemical.	
Fire and Explosion Hazards Data	Flashpoint: no data available	Autoignition temperature: no data available
	Lower Explosive Limit: no data available	Upper Explosive Limit: no data available

PREVENTIVE MEASURES

- **Accidental Release Measures**

MATERIAL SAFETY DATA SHEET

Control Measures	Avoid direct release to environmental media. Contain product for disposal. See Environmental Precautions.
Personal Protection	Avoid contact with skin and eyes. Protective equipment for skin is not required unless product temperature is sufficient to require precautions.
Environmental Precautions	Dispose of residues in compliance with applicable national, state/provincial, and local regulations.

- **Handling and Storage**

Handling	Avoid contact with eyes. Use protective equipment appropriate for the product temperature.
Storage	Store in a cool, dry place away from incompatible materials. (see *Stability and Reactivity* for incompatible materials).

- **Exposure Controls and Personal Protection**

Engineering Controls	None required other than preventing direct contact with product.
Respiratory Protection	Not required for the foreseeable conditions of use.
Eye Protection	Wear appropriate eye protection such as goggles or glasses if there is the potential for eye contact with the product
Skin Protection	Skin protection may be required depending on product temperature.

PHYSICAL AND CHEMICAL PROPERTIES

Appearance	Form: viscous liquid	Color/colour: colorless - straw like	Odor/odour: None or faint carmel-like
Physical Data	Melting point: Not applicable	Density: ≈ 11.0 lbs / gal (@ 20°C)	Water Solubility: soluble
	pH Value: 3.8 - 5.0	Odor/odour threshold: not data available	Vapor/vapour Pressure: no data available
	Boiling Point: no data available	Freezing Point: no data available	Evaporation Point: no data available

STABILITY AND REACTIVITY

Conditions to avoid	This product is stable under normal conditions of temperature and pressure.
Materials to avoid	Oxidizing/oxidising agents.
Decomposition products	Carbon monoxide; carbon dioxide, irritant gasses, and smoke.
Dangerous polymerization	Will not occur.
Dangerous reactions	None are known.

TOXICOLOGICAL INFORMATION

Health Hazards	**Routes of Entry:** Ingestion	
	Acute Effects: Eye contact may cause mild transient irritation.	
	Chronic Effects: Adverse effects from chronic ingestion are not known	
Exposure Limits	None	
Carcinogenicity	IARC: No	NTP (USA): No
	ACGIH: No	OSHA (USA): No
Reproductive Toxicity	Fructose-glucose or sucrose are not classified as a reproductive toxin by any authoritative body or regulatory agency.	

TRANSPORT INFORMATION

Shipment of this product is not controlled by ICAO, USDOT, Canadian TDG or Mexican NOM-004-SCT-2000 regulations.

ECOLOGICAL INFORMATION

In its intended manner of use, this product should not be released directly into environmental media.

MATERIAL SAFETY DATA SHEET

REGULATORY INFORMATION

United States	TSCA: All constituents are on EPA's TSCA inventory.
	CERCLA: Contains no reportable quantity (RQ) substances per Sections 302/304 of EPA
	SARA: Contains no chemicals subject to the reporting requirements of Section 311, 312 and 313 of EPA
	FDA: Classified as *Generally Regarded as Safe* (GRAS)
Canada	DSL: All consituents are included.
	WHMIS Classification(s): not applicable
	Food and Drug Act: Fructose-glucose is regulated as a standard foodstuff.
Europe	Exempt from OECD (793/93/EEC) List for Evaluation of High Production Volume (HPV) Chemicals
	EU EINECS Glucose 232-436-4; Sucrose 200-334-9
Elsewhere	Present on Philippines (PICCS) and Australia (AICS) and China's Product Inventory Lists

DISCLAIMER OF EXPRESSED OR IMPLIED WARRANTIES

The attached data has been compiled from sources which Corn Products International, Inc. and its affiliates, believe to be dependable and, to our knowledge and belief is accurate. However, Corn Products and its affiliates cannot make any warranty or representation respecting the accuracy or completeness of the data. We assume no responsibility for any liability or damages relating thereto, or for advising you regarding the protection of your employees, customers, or others. You should make your own tests to determine the applicability of such information to, or the suitability of any products for your specific use. Corn Products International, Inc. and its affiliates expressly disclaims all warranties, expressed or implied, including but not limited to, warranties of merchantability, accuracy, fitness for use or for a particular purpose, and noninfringement. The United Nations Convention on Contracts for the International Sale of Goods shall not apply to sales of products by Corn Products International, Inc. and its affiliates.

J.3. Corn Syrup

MATERIAL SAFETY DATA SHEET

corn products CASCO

PRODUCT INFORMATION

Product Identity	**Invertose® High Fructose Corn Syrup 026550**	
Product Use	Food-grade fructose-glucose	
Company Information	Corn Products US 5 Westbrook Corporate Center Westchester, IL 60154 USA Info/Emergency Phone: (708) 551-2600 (Central Time), Fax: (708) 551-2510 Business Hours: Mon - Fri, 7:30 am - 5:00 pm	Casco, Inc. 405 The West Mall, Suite 600 Etobicoke, Ontario M9C 1A0 Canada Info/Emergency Phone: (416) 620-2300 Fax: (416) 620-4488
Preparer / Responsible Party	Paul Zwijack Corn Products US	Doug Hobbs Casco Inc.
MSDS Revision Information	Date of revision: Supersedes previous MSDS dated:	January 1, 2007 November 6, 2006

COMPOSITION/INFORMATION ON INGREDIENTS

Substance	% or Range	CAS Number	EINICS Number	Toxicological Data (NIOSH- TWA)
Corn Syrup / Glucose	≤100	8029-43-4	232-436-4	LD_{50}: No data available LC_{50}: No data available

HAZARDS IDENTIFICATION

Toxicity	Eye contact may cause mild transient irritation. Ingestion of quantities sufficient to produce health effects is not a plausible route of exposure in industrial use.
Reactivity	Non-Reactive
Flammability	See *Fire and Explosion Hazards and Firefighting Measures* .
Corrosivity	Not corrosive
S Phrase(s)	None designated
R Phase(s)	None designated

FIRST AID MEASURES

Inhalation	Remove from source of exposure
Skin Contact	Wash affected area with water.
Eye Contact	Flush eyes with water for at least fifteen minutes. If irritation exists, seek medical attention.
Ingestion	If the product is accidentally ingested, seek medical attention.

FIRE AND EXPLOSION HAZARDS AND FIREFIGHTING MEASURES

Hazards	Product as a liquid does not pose explosivity hazards	
Extinguishing media	Water, carbon dioxide, or dry chemical.	
Fire and Explosion Hazards Data	Flashpoint: no data available	Autoignition temperature: no data available
	Lower Explosive Limit: no data available	Upper Explosive Limit: no data available

PREVENTIVE MEASURES

- **Accidental Release Measures**

Control Measures	Avoid direct release to environmental media.Contain product for disposal. See Environmental Precautions.

MATERIAL SAFETY DATA SHEET

Personal Protection	Avoid contact with skin and eyes. Protective equipment is not required unless product temperature is sufficient to require precautions.
Environmental Precautions	Dispose of residues in compliance with applicable national, state/provincial, and local regulations.

- **Handling and Storage**

Handling	Avoid contact with eyes and mucous membranes. Use protective equipment appropriate for the product temperature.
Storage	Store in a cool, dry place away from incompatible materials. (see*Stability and Reactivity* for incompatible materials).

- **Exposure Controls and Personal Protection**

Engineering Controls	None required other than preventing direct contact with product.
Respiratory Protection	Not required for the foreseeable conditions of use.
Eye Protection	Wear appropriate eye protection such as goggles or glasses if there is the potential for eye contact with the product
Skin Protection	Skin protection may be required depending on product temperature.

PHYSICAL AND CHEMICAL PROPERTIES

Appearance	Form: viscous liquid	Color/colour: colorless - straw	Odor/odour: None or faint cereal-like
Physical Data	Melting point: Not applicable	Density: ~1.385 - 1.393 g/cc (@ 20°C)	Water Solubility: soluble
	pH Value (50% w/w solution): ~ 4.2	Odor/odour threshold: not data available	Vapor/vapour Pressure: no data available
	Boiling Point: no data available	Freezing Point: no data available	Evaporation Point: no data available

STABILITY AND REACTIVITY

Conditions to avoid	This product is stable under normal conditions of temperature and pressure.
Materials to avoid	Oxidizing/oxidising agents.
Decomposition products	Carbon monoxide; carbon dioxide; irritant gasses, and smoke.
Dangerous polymerization	Will not occur.
Dangerous reactions	None are known.

TOXICOLOGICAL INFORMATION

Health Hazards	**Routes of Entry:** Ingestion	
	Acute Effects: Eye contact may cause mild transient irritation.	
	Chronic Effects: Adverse effects from chronic ingestion are not known	
Exposure Limits	None	
Carcinogenicity	IARC: No	NTP (USA): No
	ACGIH: No	OSHA (USA): No
Reproductive Toxicity	Fructose-glucose is not classified as a reproductive toxin by any authoritative body or regulatory agency	

TRANSPORT INFORMATION

Shipment of this product is not controlled by ICAO, USDOT, Canadian TDG or Mexican NOM-004-SCT-2000 regulations.

ECOLOGICAL INFORMATION

In its intended manner of use, this product should not be released directly into environmental media. However, it is readily biodegradable in the natural environment.

REGULATORY INFORMATION

United States	TSCA: All constituents are on EPA's TSCA inventory.
	CERCLA: Contains no reportable quantity (RQ) substances per Sections 302/304 of EPA

MATERIAL SAFETY DATA SHEET

	SARA: Contains no chemicals subject to the reporting requirements of Section 311, 312 and 313 of EPA
	FDA: Classified as *Generally Regarded as Safe* (GRAS)
Canada	DSL: Fructose-glucose is included.
	WHMIS Classification(s): not applicable
	Food and Drug Act: Fructose-glucose is regulated as a standard foodstuff.
Europe	Exempt from OECD (793/93/EEC) List for Evaluation of High Production Volume (HPV) Chemicals
	EU EINECS 232-436-4
Elsewhere	Present on Philippines (PICCS) and Australia (AICS) and China's Product Inventory Lists

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