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EFFECT OF CURING ON THE DETERIORATION OF RC STRUCTURES IN THE ARABIAN GULF

BY

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ABSTRACT

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Title:Effect of Curing on the Deterioration of RC Structures in the Arabian Gulf

Supervisor of Thesis: Nasser NJ Alnuaimi.

The deterioration of concrete in the Arabian Gulf is responsible for reduced service life of reinforced concrete structures. The reasons for degradation are attributed to the harsh environmental conditions and the prevalence of unruly construction practices. The negligence of moist curing of concrete is an important cause of concrete deterioration. In this thesis, concrete is cast mimicking the exposure conditions in winter and summer of the Arabian Gulf, and the performance of concrete while altering its curing durations by 0 days, 3 days, 7 days and 28 days were studied. The batches of concrete were exposed to three exposures of outdoor sun, sea water and laboratory conditions for 30 days and 90 days durations. The compressive strength and micro-structural analysis were also studied. The hydration process of concrete was compared to the compressive strength and thus suggesting the cause of deterioration to be the incomplete hydration. The chloride content of the concrete was found to measure the potential to reinforcement corrosion. The concrete cast and cured in summer were found to be more degrading compared to the concrete cast and cured in winter. Increasing the curing duration from 0 days to 28 days enhanced the properties of concrete, developing a healthy micro-structure. A relation between the chemistry of hydration and compressive strength of concrete is suggested.

DEDICATION

This thesis is honorably dedicated to my mentor and teacher, Dr Nasser Al Nuaimi who had been a beacon of support and a source of enlightenment throughout my study at Qatar University.

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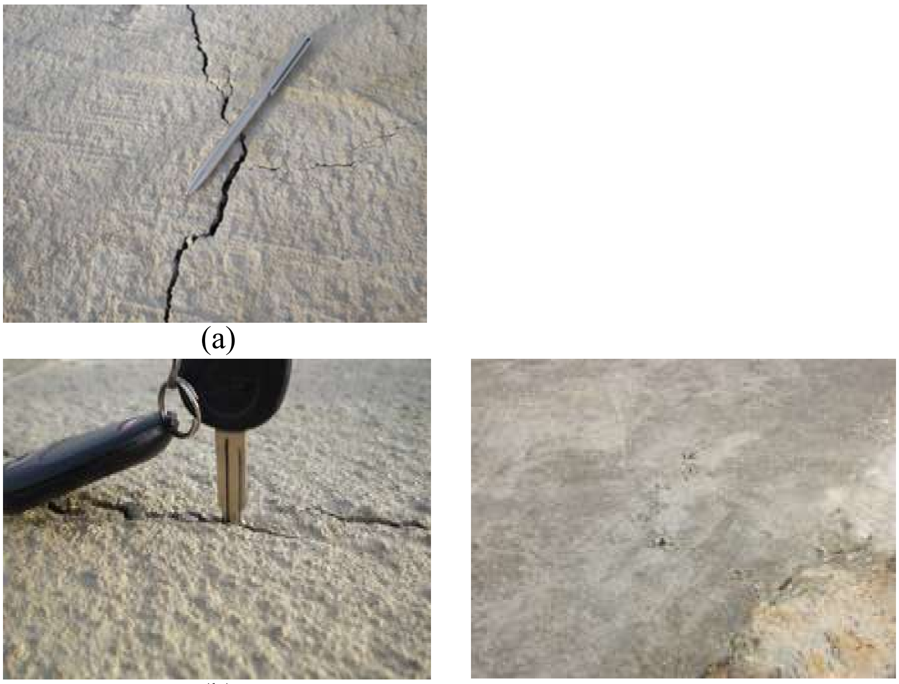
CHAPTER 1: INTRODUCTION

The service lifetime of reinforced concrete (RC) structures in the Arabian Gulf has been reducing at an alarming rate over the past few decades. With a hoard of construction projects lined up, fast completion is the main concern of the construction industry. The quality of construction is compromised with the need to finish construction projects at a fast rate. The deterioration of concrete in the Arabian Gulf is a matter of concern due to the aggressive environmental conditions of the region [1]. Extreme climatic conditions that prevail play a major role in the deterioration of concrete structures, yet, most of the adversities can be mitigated by taking proper precautions during construction. Unfortunately, the investigations on the degradation of reinforced concrete (RC) structures in the Arabian Gulf has been attributed to the adverse climatic conditions without taking into consideration the mitigation strategies to improve the quality of concrete. This statement is validated by the field data developed by Rasheeduzzafar, et al. 1989 [30], indicating that a shallow understanding of concrete behavior under aggressive environmental conditions and poor construction practices lead to early deterioration of RC structures in the Arabian Gulf. Concrete is most vulnerable when it is freshly placed, thus, the curing of concrete at early ages is of extreme importance. Concrete needs to be exposed to a nominal initial curing environment in the first 48 hours with a temperature range of 20°C to 25°C and similar final curing temperatures after demolding, accompanied by external moist curing for at least 28 days, to attain optimum strength and durability properties. The pore-structure of concrete is also affected at early ages by the curing conditions and is considered as one of the pre-eminent criteria governing its durability and performance in aggressive environments [35]. An adequate supply of moisture is necessary to ensure that hydration is enough to reduce the porosity to a level, such that the desired strength and durability can be attained. Researches indicate that a refined micro-structure, with finely divided hydration products in concrete, is the most direct, scientifically appropriate and cost-effective solution to majority of the durability issues of reinforced concrete [33]. Theoretically, there is enough water in concrete to ensure complete hydration without additional water being supplied [2], however, in practice, water is lost from the paste in different ways such as (i) direct evaporation, (ii) water absorption by aggregates, especially when the aggregates have high water absorption ratio as most limestone aggregates in the region, and (iii) water absorption by formwork or subgrade. The casting of concrete during different seasons experienced in the Arabian gulf also has varied effects on the properties of concrete. The concrete cast during summer, while extreme heat and dryness prevails, is prone to detrimental effects than concrete cast in winter when the atmospheric conditions are nominal. There are different ways of providing external moisture content to concrete for its hydration. The effect of curing duration while concrete is exposed to adverse climatic conditions during its initial and final curing stages are studied in this research. The behavioral changes of concrete while casted in different seasons of the year, accompanied by extreme exposure conditions is investigated over a period of 4 months. Further emphasis on these curing techniques is to be extended on concrete infused with cement replacements and chemicals that enhance the properties of fresh concrete, as the importance of curing is more apparent in the case of concrete containing silica fume or other admixture replacements because the pozzolanic reaction is, in general, very sensitive to the curing [3].

1.1 Research Motivation

The Arabian Peninsula is the largest in the world, and in terms of global climatic classification, has an arid (precipitation 5 cm/year, evaporation 124 cm/year) subtropical climate. The coastal flats, where much of the development is founded, are exposed to saline oceanic influences, and the environment is characterized by intense heat often associated with high humidity and strong persistent drying winds [37]. Reinforced concrete structures being constructed in the Arabian Gulf are showing an alarming reduction in service life to about 10 to 15 years [37]. High temperature conditions that prevail in the Arabian Gulf region that reach 50 degrees in summer in the shade, and could reach 60 to 70 degrees in the direct sun are also often associated with hot blowing winds. These conditions are very damaging to freshly poured concrete especially if the exposed surface of concrete is relatively large, as is the case with flat roofs or matt foundations. Thus, attention is to be given to curing done under such conditions [2]. The rate of evaporation of the water from concrete is significantly higher in hot and dry environments than in cool and moist ones [4]. This leads to excessive plastic shrinkages and cracking, reduction in strength and increase in the rate of carbonation and chloride ingress [5]. Unfortunately, plastic cracking of concrete is commonly accepted by most construction contractors in the region, and considered as normal behavior of concrete during summer. These cracks ranges from 18 mm in depth and 4 mm in width in RC buildings as can be seen in the Figure 1. The footprint of birds is seen on freshly placed concrete declaring the negligence of concrete once poured and left to dry under the sun.



(a)

(b) (c)

Figure 1: (a) Shrinkage cracks; (b) Shrinkage Crack Width; (c) Bird Foot Prints on Neglected Concrete

The negligence of curing fresh concrete degrades its durability and ultimately endangers the safety of the structure [4] [6-8]. The high temperature effects on concrete are further aggravated if it is accompanied by combinations of dry weather, direct sunlight and large diurnal winds [4] [8]. Loss of water from fresh and young concrete due to these climatic conditions, accompanied by inadequate curing, can result in detrimental effects on the properties of concrete in the short and long run, resulting in a shorter service life of the structure [4] [9-11].

A visual inspection was done by the research group on a building in the Arabian Gulf, which had been built in the year 1985, to study the early deterioration of concrete. The 30-year-old building is seen to have powdery cement matrix and extensive corrosion in the reinforcement, which had further caused the steel to expand and the concrete cover to peel off.

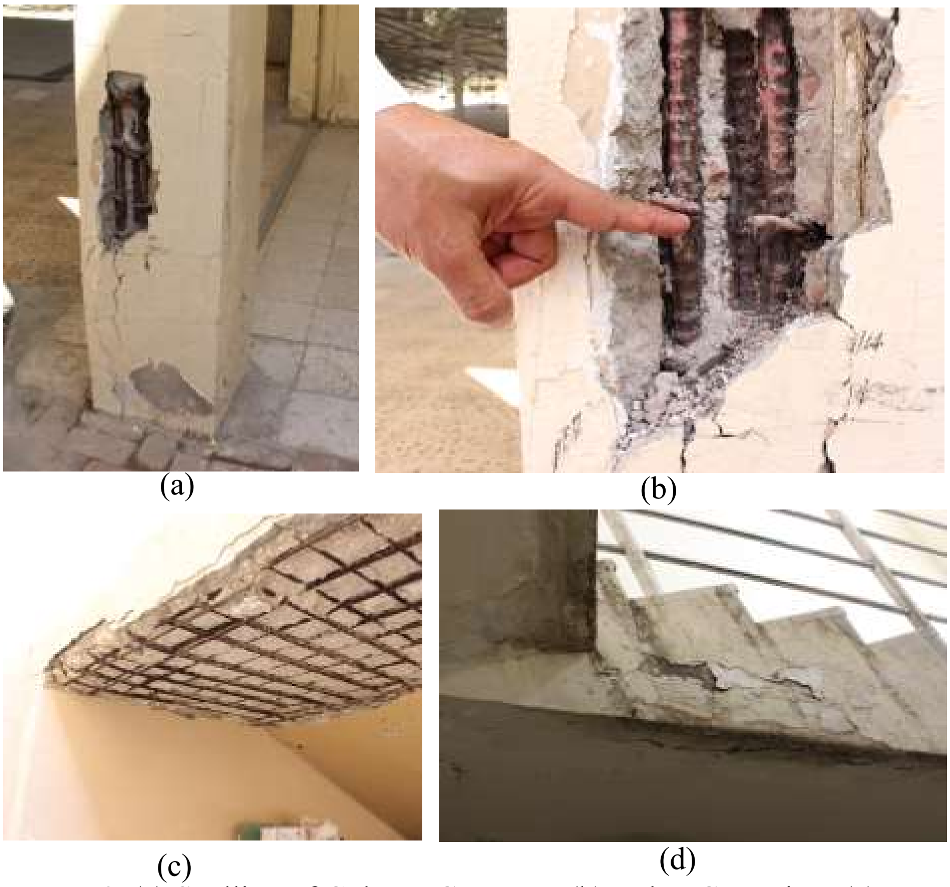


Figure 2: (a) Spalling of Column Concrete; (b) Rebar Corrosion; (c) Loss of soffit Concrete; (d) Spalling of Paint.

The deterioration was observed in locations which were closer to the ground and exposed to direct sunlight. The ingress of chloride ions from the ground through the concrete cover had caused the reinforcement to corrode (Figure 2-a). The cement matrix inside the concrete columns as shown in figure is pulverized and powdery, indicating the lack of proper hydration (Figure 2-b). The spalling of paint from the slabs and joints (Figure 2-d) is due to high water permeability of the concrete, which is another outcome of a coarse pore structure, indicating a lack of proper hydration. Spalling of concrete due to the expansion of corroded reinforcement is prevalent throughout the structure. The concrete matrix is also seen to have sea-shells found in ocean sand. This indicates the usage of ocean sand for construction, without processing or screening. The deterioration of this building can be attributed to the negligent construction practices in the region. The combination of adverse climatic conditions, improper construction practices and inadequate nurturing of concrete in its early ages causes the concrete structures to degrade. Such adverse conditions to which the concrete was exposed to, is recreated in the laboratory and the deterioration of concrete is studied and compared, to concrete cast while optimum climatic conditions prevail. This research article is intended to provide reasoning to such deteriorating structures in the Arabian gulf, and to suggest possible measures to avoid such deterioration in the future.

1.2 Research Significance

The performance of concrete used for construction is measured based on specimens extracted from the concrete batch and cured in ambient conditions for 28 days, which is often different than the concrete exposed to site conditions. The material performance of concrete in the region is apparently controlled by the concrete-environment interaction, thus, specifying concrete merely on strength considerations while ignoring factors related to durability causes a set of problems of varying severity [37]. The curing duration for concrete from a durability point of view is different compared to the strength point of view [5] [12] [24]. Thus, optimum curing durations and techniques are to be deduced for structures to be durable as well as strong. Most concrete structures in the Middle-East were constructed based on building codes developed for other countries, with moderate climatic conditions, due to a lack of local guidelines [5]. Therefore, there is a need to investigate the behavior of the concrete and its response to different environmental factors in such adverse climatic conditions. The response to concrete with different curing durations and adverse exposure conditions for extended periods would be a guideline to deduce optimum curing method to be specified in the construction codes.

1.3 Research Objective

Casting of concrete during different seasons of the year influences the performance of concrete. During the winter season experienced in the Arabian Gulf, concrete is exposed to nominal exposure conditions, whereas, casting in the summer is degrading. The difference in seasons affects the initial curing condition (first 48 hours) of the concrete before demoulding. Since most of the curing regimes start post demoulding, the influence of initial curing conditions in the first 48 hours is seldom investigated. The objective of this research is to distinguish between the performance of concrete while casted in winter and in summer. Further, the effect of initial curing conditions, harsh exposure of heat and extreme salinity for 30 days and 90 days, with varying curing durations are also investigated. The results of compressive strengths of concrete are reinforced with micro-structural analysis of crucial specimens to derive a relation between the chemistry of hydration and the mechanical properties of concrete. The durability aspect is measured in terms of the chloride content of the concrete. The curing method used in the experiment is to immerse in water completely for the designated duration.

1.4 Research Methodology

Following the objective of research, two batches of concrete were cast with different conditions governing the mix. One of the concrete mixes was casted in in summer, simulating the initial curing conditions of summer that is experienced in the Middle-Eastern state of Qatar. The other cast was in winter, simulating the initial curing conditions of winter in Qatar. The characteristics of the two batches, such as number of samples, temperature of the atmosphere, water content of the aggregates, temperature of the wet mix of concrete and the relative humidity of the atmosphere while casting, is elaborated in the experimental programme describing the summer and winter batches of concrete. The summer batch of concrete was named Batch A and the winter batch of concrete was named Batch B. The two batches of concrete were further divided into sub groups depending on their exposure conditions as shown in Figure 3. The main difference between the two batches A and B were the atmospheric exposure conditions during the first 48 hours after casting, which is called the initial curing phase (ASTM C-31/C-31-M-19). Both the batches of concrete were cast reciprocating the usual practices of construction contractors in Qatar. The concrete mixes were casted onto cylindrical concrete specimen to investigate the properties of concrete after the respective curing and exposure conditions. The different curing durations altered were 0 days, 3 days, 7 days and 28 days of moist curing. After their respective fresh water curing periods, the designated cylinders were exposed to three different exposure conditions - outdoor sun exposure, sea water exposure and laboratory exposure. The characteristics of the exposure conditions are outlined in the experimental programme. The matrix of the sample and the experimental design for the summer and winter cast are elucidated in the later subsections as well. The compressive strength of the cylinders is tested after exposure for 30 days and 90 days after casting. The chloride content and micro-structural analysis: XRD and XRF analysis were done after 90 days of exposure.

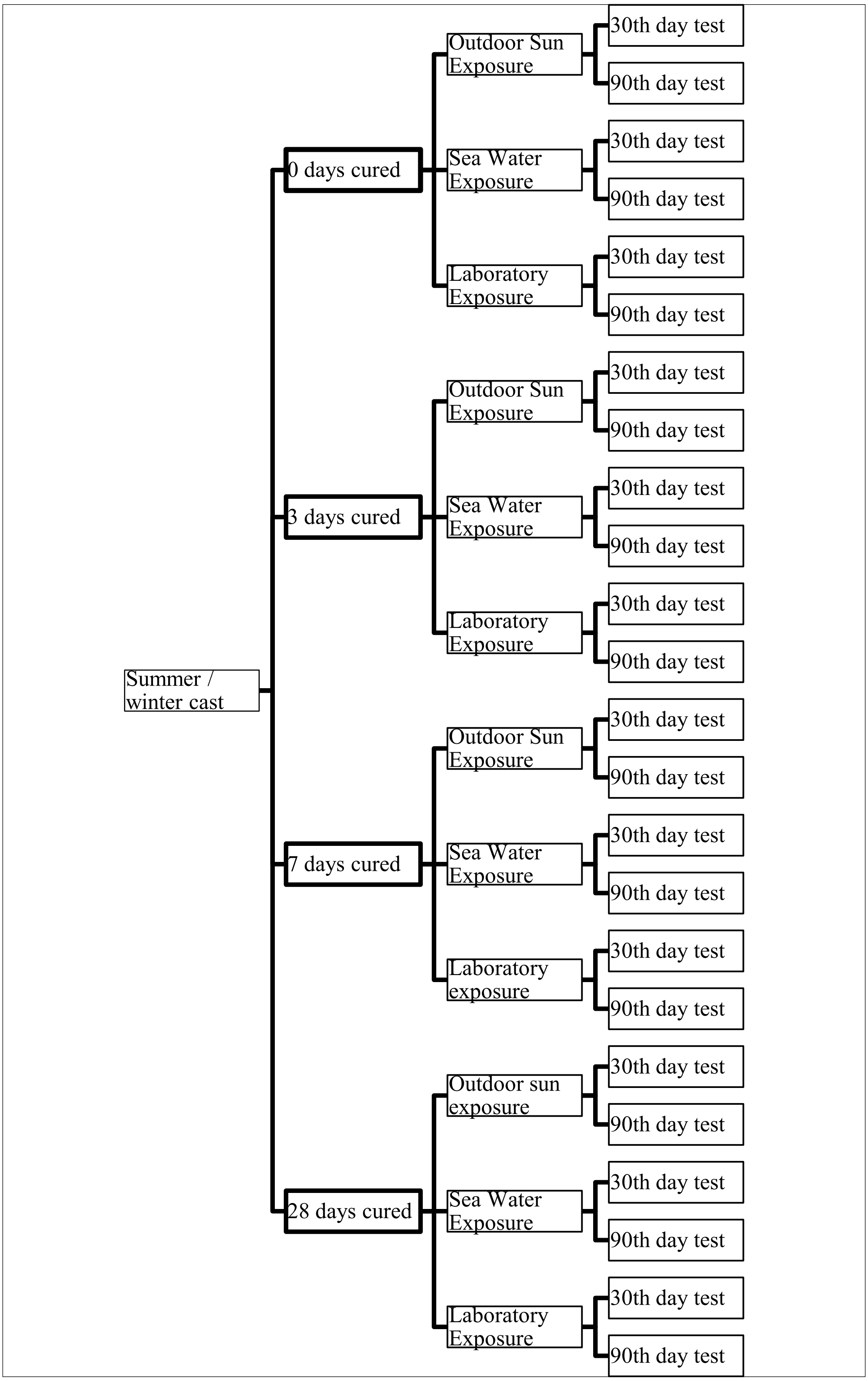


Figure 3: Experimental Design of Specimens

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Hydration of Concrete

The hydration of concrete is a series of chemical reactions that happen when cement reacts with water. The binding agent, cement comprises of Tricalcium Silicate (C_3S), Dicalcium Silicate (C_2S), Tricalcium Aluminate (C_3A), Tetracalcium Aluminoferrite (C_4AF) and Calcium Sulphate Dihydrate (Gypsum). The hydration of cement yields different products as time progresses. The calcium silicates react with water and forms two main components of hydrated cement - Calcium silicate hydrate (C-S-H) and Calcium Hydroxide (CH) [2] [45].

$$2C_3S + 6H \rightarrow \underbrace{C_3S_2H_3}_{\text{C-S-H}} + 3CH$$

$$2C_2S + 4H \rightarrow \underbrace{C_3S_2H_3}_{\text{C-S-H}} + CH$$

The Tricalcium Aluminates react with the sulphate ions, supplied by the dissolution of gypsum and produces ettringite crystals ($C_6AS_3H_{32}$). The primary reaction of C_3A is shown in the equation below.

$$C_3A + 3CSH_2 + 26H \rightarrow C_6AS_3H_{32} \text{ (Ettringite)}$$

The more the gypsum and water content, the more the ettringite becomes stable. The potential of reforming ettringite crystals are based on sulphate attack. Lack of ettringite crystals in the micro-structure could possibly cause sulphate attacks in concrete in the future.

The main hydration product responsible for strength of concrete is the C-S-H cluster (Figure 5-a). It comprises of 50% to 60% of the volume of cement paste. They have a poor degree of crystallinity with variable composition due to its unstable nature. Water plays a major role in its formation and structure. The cement grains are bonded together mainly by the Van-der-Waals forces caused by the C-S-H cluster and its area increases as hydration proceeds. Calcium Hydroxide (CH) comprises of 20% to 25% of the paste volume. They are distinctly large crystals having a hexagonal prism morphology (Figure 5-c) [41]. CH contributes less to the strength compared to C-S-H. 15% to 20% of the paste volume consist of Calcium Sulpho Aluminate hydrates such as ettringite (Figure 5-b). It has a needle like structure and contributes less to strength compared to CH and C-S-H. The absence of water makes the ettringite crystals dry out and subsequently forms second generation ettringite needles which are much smaller in dimensions and indicates the deterioration of concrete. Depending on the degree of hydration, the cement matrix can have un-hydrated clinker grains (Figure 5-d) which are cement particles which didn't receive enough water for hydration. They have the chemical properties of CH, yet the crystalline morphology that mimics the original clinker particles. The timeline of formation of these hydration products are as shown in Figure 6 [2].

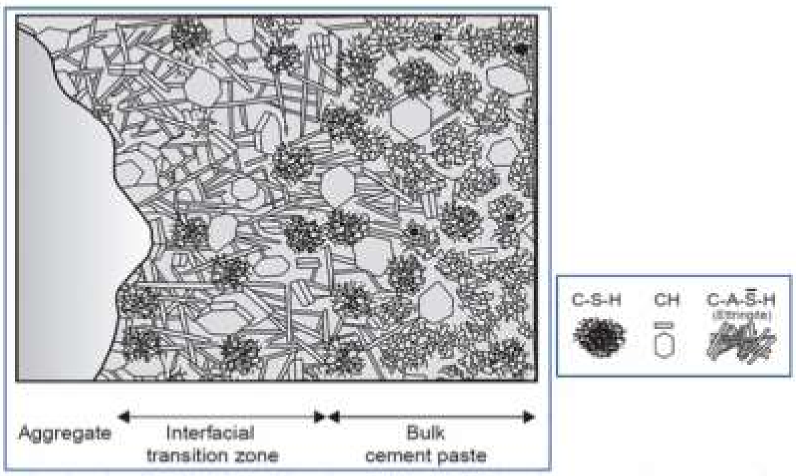


Figure 4: Sketch of Hydration products of concrete [2]

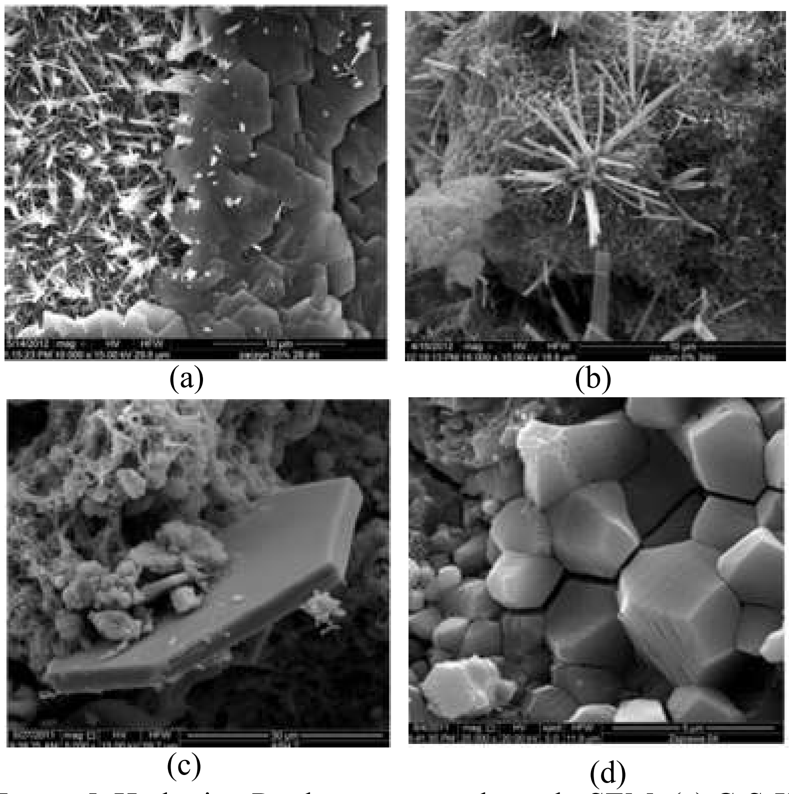


Figure 5: Hydration Products as seen throught SEM; (a) C-S-H cluster; (b) Ettringite crystals; (c) CH platelets; (d) Unhydrated Clinker Particles [41].

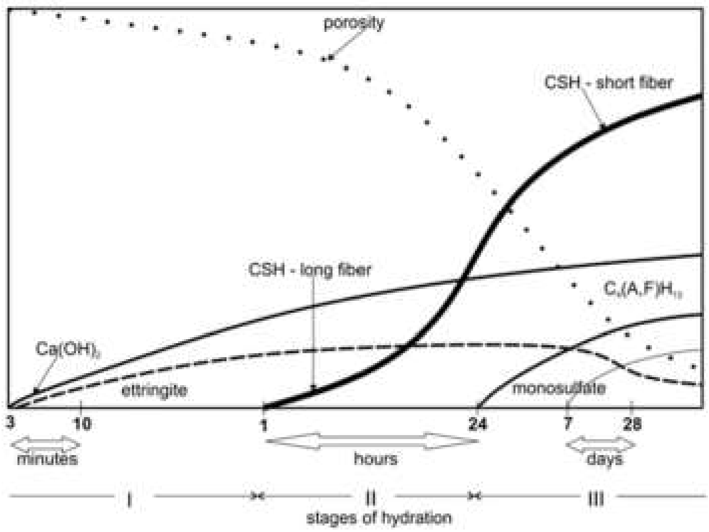


Figure 6: Timeline of formation of Hydration Products.

2.2 Curing of Concrete

According to ASTM C-31/C-31-M-19, the curing of concrete is in two stages, namely initial and final curing. The initial curing stage is the first 48 hours in which concrete is left to harden before demolding. The final curing is the external supply of moisture to aid the hydration process of concrete, which is done until 28 days of casting. Different types of curing techniques are used in the industry and in research, that aids the hydration process of concrete. Curing regimes in experimental studies reflect the ones used in actual construction practices. The curing practices can widely be divided into conventional and unconventional curing techniques. The conventional curing practices include continuous moist curing, curing with wet burlap and surface sprinkling of water. Unconventional practices developed in recent times include the use of polyethene sheet covering, liquid membrane-forming curing compounds and steam curing. Additionally, internal curing practices have been developed, comprising of prewetted light weight aggregates (LWA) and super-absorbent polymers (SAP).

2.2.1 Moist Curing

The most common method of curing among the general construction contractors is the sprinkling of water with wet burlap covering. Moist curing includes sprinkling of water on concrete surface and sprinkling of water on pre-wetted burlap sheets that retain water on them, thus, dampening the concrete surface for extended durations. Wet burlap curing is found to be the best curing method as far as strength, reduced water absorption and permeability are concerned [31]. The minimum duration of water curing required for different types of concrete is variable. Al-Ani & Al Zaiwary [31] recommend 3 days of wet burlap curing for rich mixes and 7 days for lean mixes. Al-Gathani [46], Bushlaibi & Alshamsi [15] and Alsayed & Amjad [5] had studied the effects of sprinkling with water twice a day and sprinkling after covering with wet burlap twice a day, for a duration of 7 days to deduce the best method of wet curing in the region. Alternatively, by changing the moist curing durations from 1, 3, 6, and 27 days, the development process of various properties of concrete with the extension of curing duration are studied, as showcased by Alizadeh, et al [14] and Shattaf, et al. [33]. The conclusions elaborated in the later part of this article indicate the superiority of moist curing while adverse climatic conditions prevail. Even though the general construction contractors use this method of curing, the lack of continuous moist curing for extended periods is one of the causes for concrete deterioration in the region. The minimum curing duration and curing regimes must be optimized with respect to several properties, such as strength, permeability etc.

2.2.2 Curing by Evaporation Inhibition

Another type of curing is the use of chemical membranes in which excessive evaporative loss of water is inhibited by the application of a membrane-forming curing compound to the freshly placed concrete. Some examples of curing compounds used in experiments conducted in the Arabian Gulf include a petro-resin based membrane forming curing compound used by Alizadeh, et al. [14] and an acrylic-based; water-based; bitumen-based; and coal-tar-epoxy based curing compounds used by Ibrahim, et al. [24]. With scientific advancements in the type of curing compounds, this method is seen to be effective and advised only where the scarcity of water is prevalent [24] [27]. It is found that the performance of bitumen-based curing compounds is generally better than that of other curing compounds, followed by coal tar epoxy, and acrylic and water-based curing compounds [24] [27]. Curing of concrete by covering with polyethene sheets is suggested to prevent water from evaporating from fresh concrete as well. This method is found to have an adverse influence on reducing the porosity and the absorptivity of the concrete in adverse climatic conditions. Furthermore, curing using a curing compound could be an expensive procedure due to the high prices of curing compounds. However, these types of curing practices are increasingly used for large scale projects where the extended moist curing of concrete is seen as a time-consuming process. Replacing moist curing with evaporation inhibiting curing processes would also lead to the early deterioration of concrete structures. Using this type of curing techniques while the concrete is exposed to harsh environmental conditions is yet to be studied and verified.

2.2.3 Internal Curing

Internal curing in concrete is a relatively recent idea and is emerging as a promising curing technique. Concrete mixtures are modified by adding suitable curing agents supporting the curing requirements of concrete [12]. Bentz & Stutzman [16] used prewetted LWA as an internal curing medium for three different blended cements, concluding that at third-day testing, internally cured specimens showed reduced strength initially, however showing better performance at later stages. The use of Super Absorbent Polymers (SAP) as an internal curing agent in concrete was studied by Vedhasakthi & Saravanan [17], concluding that in high-performance concrete, compressive strength of self-curing concrete at 28 days was exceptionally higher than conventionally cured concrete. However, the compatibility of such unconventional curing practices is less investigated in regions with hot and arid climatic conditions, thus there is a need to further study such curing practices in hot and arid climatic conditions.

2.2.4 Combined Curing Methods

The use of evaporation inhibiting curing techniques would be more effective if they are combined with water curing. An initial period of moist curing followed by the application of a curing compound or covering with polyethene sheets [15] have shown to improve the performance of concrete while adverse climatic conditions prevail. By varying the initial curing durations, the optimum moist curing duration needed before the application of the curing compound has been suggested to be at least 7 days [24] [27]. This method can be suggested to ensure complete hydration of the cement matrix if time restrictions do not allow the use of extended moist curing. This method could be a possible solution to quicken the construction process without compromising on the quality of concrete.

2.3 Effect of Curing on the Performance of Concrete

The process of curing aids in the development of the micro and macro properties of concrete. The main characteristics of hardened concrete that are effected by the curing of concrete are - compressive strength, pore structure, shrinkage, water absorption, chloride attack and micro-structural properties. The effect of various types of curing on these properties of concrete is reviewed in the following subsections.

2.3.1 Effect of Proper Hydration on the Compressive strength of Concrete

The compressive strength of concrete would be the most appropriate parameter to be considered for evaluating the quality of curing. The complete hydration that ensures the required strength of concrete mix is attained by proper curing of the concrete. Different durations of moist curing and additions of other curing methods have a profound effect on the stress capacity of concrete. These contemporary and traditional curing methods have a different effect on concrete when it is exposed to adverse climatic conditions such as high temperatures, which in turn causes deterioration of concrete due to badly dispersed hydration products [4] [18] [19]. Abdul-Ghafoor et, al. [25] had found that there is a 25% reduction in the compressive strength of concrete if it was cured at elevated temperatures of 45^{o}C, even after following proper precautions for concreting in hot weather. In hot weather conditions, delaying or reducing the process of curing also has detrimental effects on the compressive strength [13] [36]. A good representation of the difference in compressive strengths from concrete cured indoors and in the adverse climatic conditions of the Arabian gulf, is shown in the graph (Figure 7) by Bushlaibi & Alshamsi, [15] in which the authors compare the increase in compressive strengths of concrete samples with increase in curing durations for outdoor and indoor samples. The trends of increase in compressive strengths for samples cured in outdoor conditions are lesser than the ones cured indoors.

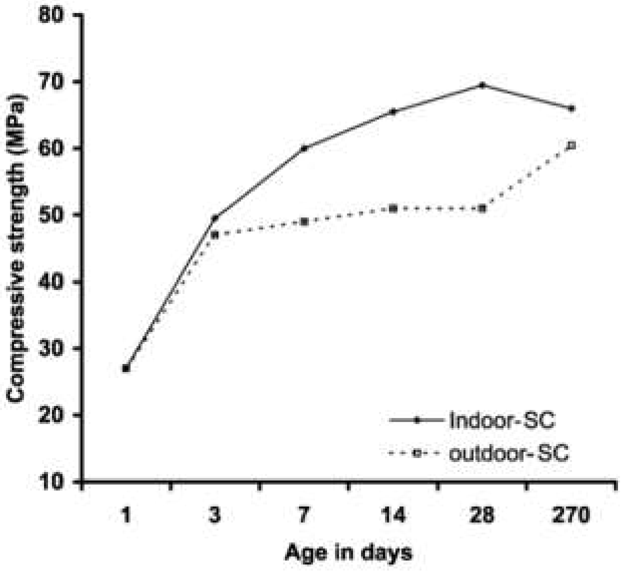


Figure 7: Compressive strength development of concrete - indoors vs outdoors [15]

2.3.1.1 Effect of Curing Methods on Strength

To achieve good quality concrete in regions where adverse climatic conditions prevail, extra importance is to be given to the process of curing, with respect to both duration and curing methods. In an experiment done in the Arabian Gulf, by Alsayed

& Amjad [5] the variations in compressive strength with different types of curing methods were studied. Four different curing methods, including (i) sprinkling with water twice a day; (ii) covering with wet burlap after sprinkling with water twice a day; (iii) covering with a polyethene sheet; and (iv) no curing conditions, were done for 7 days. After 365 days of exposure to hot and arid temperatures, it was found that the specimen cured by sprinkling with water twice a day was 42% stronger than the uncured ones. Interestingly, curing by covering with polyethene sheets reduced the compressive strength by 23% compared to the wet curing process [5]. The polyethene sheet acted as an insulator to the concrete surface, trapping the hydration heat, consequently increasing the temperature and leading to insufficient cement hydration. The increased temperature would have caused cracking in concrete through thermal gradient, thus reducing the compressive strength. Taryal et al. [26], Clark, et al. [20], and Keeley [21] had observed similar results. This shows that use of evaporation inhibitors might decrease the compressive strength of concrete, emphasizing the superiority of moist curing over other curing methods when hot and arid temperature conditions prevail.

2.3.1.2 Effect of Curing Duration on Strength

Furthermore, the duration of moist curing affects the compressive strength development of concrete. As the moist curing duration increases, the degree of cement hydration increases, hence, the compressive strength development. A study done by Alizadeh, et al. [14] altered the duration of moist curing and compared its effects on concrete made with Normal Portland Cement (NPC) and Silica Fume induced Cement (SFC). The curing durations used in the study was 0, 3, 7 and 28 days. It was found that the 28^{th} day compressive strength of the specimen cured for 28 days was 28% higher compared to the specimen that hadn't been cured at all. While comparing the results of Normal Portland Cement (NPC) and Silica Fume induced Cement (SFC), the researchers [14] found SFC to be 32% weaker than normal concrete if curing is not done.

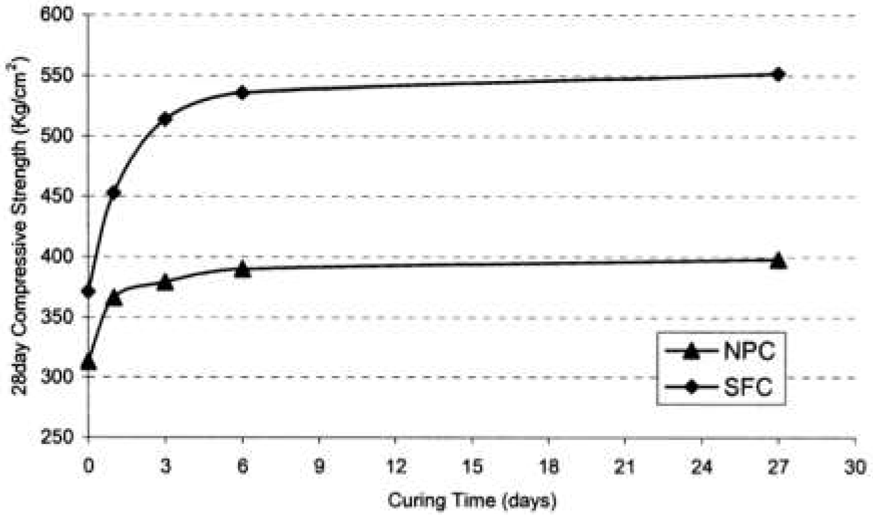


Figure 8-Variation of compressive strength for Normal Portland Concrete(NPC) and Silica Fume induced Concrete (SFC) with different moist curing durations [14]

The effect of curing duration and methods on High Strength Concrete (HSC) while hot and arid climatic conditions prevail, is rarely investigated. Bushlaibi & Alshamsi [15] studied the effect of varying moist curing durations followed by covering with polyethene sheet or wet burlap on different specimens made with HSC. This experiment done in the Arabian Gulf, found out that the compressive strength increases as the duration of moist curing increases. In the case of HSC exposed to arid exposure conditions, compressive strength increased by (i) 5% while sprinkling with water twice a day, (ii) 15% while sprinkling water twice a day and then covering with polyethene sheet, (iii) and 13% by spraying with water twice a day and then covering with wet burlap for the specimens cured for 14 days duration, compared to no curing at all. The improvement in strength increased as the moist curing period is prolonged. This study also outlines the difference in the compressive strengths of concrete exposed to outdoor and indoor conditions, as mentioned earlier, to prove that concrete is to be dealt with differently when exposed to harsh environmental conditions compared to normal exposure conditions (Figure 7).

2.3.1.3 Effect of evaporation inhibitors on Strength

A recent trend in the curing process, is to apply curing compounds as water evaporation inhibiters from the concrete surface so that hydration happens without the need for external moisture. The concrete cured by this method was 28% weaker than 28 days water cured samples as reported by Alizadeh, et al. [14], thus, this method was found to be ineffective while hot and arid exposure conditions prevail. This indicates that the internal moisture content of concrete is not enough to provide necessary hydration in such climates. However, having a period of initial moist curing before the application of certain curing compounds has been suggested as an acceptable curing technique by Ibrahim, et al. [24] in a study conducted in the Arabian Gulf. This experiment conducted in harsh climatic conditions, varied the duration of moist curing from 1, 2, 3 and 7 days, and then applied three different curing compounds on the concrete surface; namely, (i) acrylic based, (ii) bitumen-based and (ii) water-based curing compounds. This study suggests that to attain maximum strength of concrete in hot weather conditions, a minimum initial moist curing of 7 days is required before using the bitumen-based curing compound.

2.3.2Effect of Curing on the Durability Properties of Concrete

The pore structure of the cement matrix is the primary factor controlling the durability properties of concrete such as permeability, water absorption and shrinkage. To remain in service for design life, concrete is expected to resist chloride attack, sulphate attack, carbonation and other harmful elements. For concrete at the micro-level, the primary property to be developed by the process of curing is the pore structure of the cement matrix. Other properties such as permeability, water abruption, chloride ingress and shrinkage. are related to the pore structure. Proper curing of concrete provides a finer siliceous material distribution and reduces the concrete permeability and absorption properties [4]. Like the strength properties, hot and arid weather conditions alter the mechanism of development in the pore structure. Seishi and Della [22] concluded that when concrete specimens are cured at high temperatures, a coarser pore structure and higher porosity is observed. Substantiating this, Cabrera, et al. [32] observed an increase of 10 to 20% in porosity for all curing periods while exposed to adverse climatic conditions outdoors. The permeability and water absorption of laboratory cured specimens were less than the specimens cured in hot and humid environmental fields as observed by Saricimen [32].

It is understood that curing of concrete for longer durations increases the degree of hydration of cement; thus reducing the porosity and permeability of concrete [5] [33]. Alsayed & Amjad [5] mentioned that the use of polyethene sheet method of curing had adverse effects on the porosity, similar to the effect on compressive strength, due to decreased cement hydration.

2.3.2.1 Effect of Curing on the Pore-Structure

The effect of duration of moist curing on the pore structure of concrete for different mix proportions was studied by NR shattaf, et al. [33]. The study conducted in the UAE used 5 different mixes of concrete with different proportions of blast furnace slag and silica fume additives. Four curing durations, which are (i) no curing, (ii) 3 days curing, (iii) 7 days curing and (iv) continuous water curing were done, and the specimens were exposed to hot and arid climatic conditions for 18 months. It was concluded that the reduction of total porosity was in the range of 30 to 50% in the continuously water cured specimen, compared to samples with no curing conditions. The reduction in pore sizes (volume) were in the range of 55% to 75% for samples that were water cured continuously, compared to no curing. The study also found that blended cements are more sensitive to water curing than normal cements. The greater the blast furnace slag content, the greater was the sensitivity to water curing. Subsequently, it is to be noted that if water cured properly, the performance of concrete with blast furnace slag additions are greater than other specimens. These samples with high slag content and water cured continuously, showcased 25% reduction in porosity and 80 to 90% reduction in threshold pore diameter. These results underline the importance of prolonged water curing to attain a well-defined pore structure in all types of concrete, especially when hot and arid climatic conditions prevail, indicating that most of the durability problems of concrete in the region can be reduced by prolonged moist curing.

2.3.2.2 Effect of Curing on the Shrinkage and Water Absorption

Shrinkage of concrete leads to cracks on the concrete, which is undesirable for the durability of concrete. As far as shrinkage of concrete is concerned, even well cured samples showcase rapid shrinkage in normal climatic conditions, however, in the study of Alsayed & Amjad [5] mentioned earlier, it was found that intermittent wet curing process increases the exposure time needed to develop the ultimate shrinkage of concrete. The study further found that none of the four curing techniques could significantly reduce the early shrinkage of concrete in hot and arid climates.

The effect of wet curing after the application of a curing compound, on the shrinkage strain of concrete was studied by Maslehuddin, et al. [27]. Water retaining curing compounds were applied on concrete after moist curing for 1, 2, 3 and 7 days. It was concluded that drying shrinkage strain reduces, as the initial curing period increases. Lower plastic shrinkage strain was also observed in samples cured for extended durations before applying a curing compound. Similar conclusions were reached in a study on the effect of using curing compounds on water absorption done by Ibrahim et al. [24]. Furthermore, in such adverse exposure conditions, Alsayed & Amjad [5] found that water cured samples had 22.5% reduction in water absorption compared to non-cured samples. These studies show that using a curing compound for the processes of curing would be rendered less effective while hot and arid climatic conditions prevail unless an initial period of water curing is done.

The process of wet curing is important in having a well-defined microstructure of concrete which has direct effects on its compressive strength, wear resistance and durability. Thus, the importance of the effect of proper curing on these parameters is not in their values but in their relationship with other properties of concrete.

2.3.2.3 Effect of Curing of Chloride Attack

Due to the saline environment, one of the predominant reasons for concrete deterioration in the Arabian Gulf is the chloride induced reinforcement corrosion. Therefore, it is important to apprise the effect of curing on the diffusion of chloride onto concrete. Initial curing of concrete exposed to aggressive environments plays an important role in the rate of chloride penetration, especially in the early ages. Rasheeduzzafar, et al. [35] has stated that the migration of chlorides into the concrete is greatly dependent upon the duration of curing. In a study by Alizadeh, et al. [14] about the effect of duration of moist curing on the diffusion of chloride onto concrete, the concrete specimens were subjected to three exposure conditions; which were (i) tidal-zone, (ii) submerged in sea water and (iii) arid atmospheric conditions of the Persian Gulf. The different specimens were cured for 0, 1, 3, 6 and 27 days and exposed to the above conditions for three months. The relationship between curing of concrete and diffusivity of chloride ions was quantified using the following equation.

$$D_{curing}=k_{curing} \times D_0$$

Where, D_{curing} is the diffusion coefficient of the cured specimen, k_{curing} is the curing factor and D_0 is the diffusion coefficient of standard cured concrete. It was concluded that the diffusion coefficient of chloride ions decreases as the moist curing time increases (Figure 9). The rate of decrease in diffusion coefficient with the curing duration, reduced from 3 days onwards in normal concrete and 6 days in silica fume induced concrete, indicating the need for more curing time when additives are added to concrete. Furthermore, it was found that the diffusion coefficients are higher in tidal and submerged exposure conditions than in atmospheric conditions. This highlights the need for extended curing duration when the exposure conditions are more aggressive.

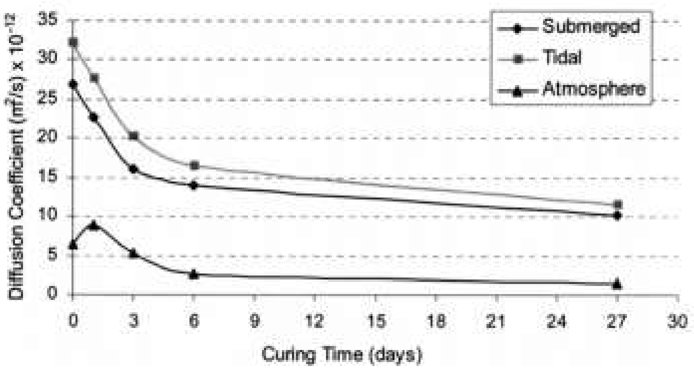


Figure 9: Penetration of Chloride ions to concrete for different zones of exposure [14]

With respect to the issue of chloride permeability, the use of curing compounds is seen to be more effective when the specimens were water cured for at least 7 days [24]. In a similar study [27], the rate of reinforcement corrosion in concrete specimens cured by applying the selected curing compounds, is found to be less than that in the concrete specimens cured by covering with wet burlap.

2.3.3 Effect of curing on the micro-structural developments of concrete

A comparative microstructural analysis based on the hydration process for different curing practices is necessary to establish best curing practices in regions with hot and arid climatic conditions. However, the development process of hydration products with different curing practices and durations is to be investigated further, while concrete is exposed to the arid climatic conditions of the Arabian Gulf. In a study by Khaliq & Javaid [12] the concrete microstructure analysis of the hydration process was done at 3, 7, 14 and 28 days of different curing regimes. Specimens were subjected to microstructure image analysis by Scanning Electron Microscopy, (SEM) and quantitative analysis to determine the concentration of elements by Energy-Dispersive Spectroscopy (EDS).

The SEM micrographs for air-cured specimens (zero moist curing) at ambient conditions indicated the formation of indistinct ettringite crystals on the third day. On the 7th day, formation of C-S-H gel, CH plate-like crystals, and ettringite clearly started to fill the empty spaces and help improve the density. On the 14th day, layered CH crystals were seen with a lesser proportion of C-S-H gel in it, and on 28th day, a similar situation is observed as that on the 14th day, with layered CH crystals existing in a distinct formation. However, as the hydration progressed, the available water in the pores got used by the constituents leaving behind empty pores, increasing the porosity of the air cured samples [12]. Whereas, The SEM micrograph for water-immersed specimens show that they developed a better microstructure, due to the formation of hydration products with distinct ettringite and CH crystals on the third day of testing. On the seventh day, a clear formation of CH plate-like crystals and ettringite crystals in the voids could be seen. The honeycombs of C-S-H gel were also prominent, indicating the hydration products resulting from proper curing. On the 14th day, fine bundles of C-S-H (Type-I C-S-H) and honeycombs of C-S-H gel (Type-II C-S-H) are quite distinctive. Testing on the 28th day illustrated pure layered CH crystals with C-S-H gel identified by its honeycomb formation. Thus, the technique of water immersed curing gave the best results among various other curing methods and conformed to be the better curing practice. Similar studies on the effect of curing on the microstructural analysis of hydration process while the concrete is exposed to hot and arid climatic condition, would provide further insight on the concrete deterioration in the Arabian Gulf.

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 Concrete Casting

Since the number of concrete cylinders to be casted were large in number, plastic cylindrical moulds were fabricated as shown in Figure 10, to accommodate the casting of 52 cylindrical concrete samples at the same time. The inside dimensions of the mould were 200 mm height with 100 mm diameter.

Figure 10: (a) Moulds for Casting; (b) Slump Test

The procedures followed during the casting of concrete were according to ASTM-C 39/C39M-18. Before placing the concrete onto the moulds, the slump of the concrete mix was measured and regulated according to ASTM C143/C143M-159. The cylindrical moulds were lubricated with oil before casting for the easy removal of hardened concrete from their moulds. The temperature of the mix was measured using an infrared thermometer soon after the required workability of the concrete was met. The concrete was poured onto the 52 cylindrical moulds at 3 layers. The specimen was then placed on a vibrating table and vibrated for 2 minutes to ensure the complete compaction of the concrete specimens. The concrete moulds were demoulded after 48 hours by cutting the cylindrical moulds vertically along the height. The constituents of the commercially available cement used for casting concrete was analysed using XRF and is shown in Table 1. The properties of the fine aggregate and coarse aggregates used are mentioned in Table 2.

Table 1:
Constituents of Cement Used

Compound Name	Content Percentage
CaO	66.4%
SiO_2	18.4%
Fe_2O_3	6.1%
SO_3	3.0%
Al_2O_3	2.2%
MgO	1.4%
Na_2O	0.8%

Table 2:

Properties of Aggregates

	Fineness Modulus	Specific gravity	Density (kg/m3)	Water Absorption (%)	Moisture content (%)
Fine aggregates	2.31	2.564	2558.3	1.87	3.00
Coarse aggregates	-	2.581	2574.19	2.72	0.02

The nomenclature of the concrete specimens to identify their characteristics was done according to Figure 11. The first letter denotes the batch, winter or summer; the second letter is the exposure condition, Sun, Lab or Sea Water; the third number is the exposure period before testing; and, the last number is the duration of curing, 0 days, 3 days, 7 days or 28 days.

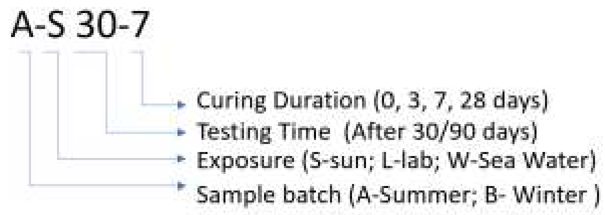


Figure 11: Nomenclature of Samples

3.1.1 Summer Cast (Batch A)

As mentioned earlier, the batch A of concrete was casted in the scorching heat of summer in Qatar and was left to harden in the first 48 hours exposed to sunlight and dry climatic conditions. The casting conditions of winter and summer specimen are compared in table. The mix design of the concrete was done to attain a target strength of 30 MPa and is shown in Table 4. The atmospheric temperature during casting was 47ºC and the relative humidity of the atmosphere was 31% and the windspeed was 15 km/hour (Table 3).

Table 3:

Concrete Cast Conditions

Casting Conditions	w/c ratio required	Atmospheric temp	Mix Temp	Humidity	Wind speed km/h	Initial curing temp
Summer	0.8	45ºC	54ºC	31%	15	47ºC
Winter	0.64	23ºC	35ºC	78%	0	25ºC

The summer batch had to be cast in two trials. The first trial of concrete had to be discarded due to the extremely low workability because of dry and hot atmospheric conditions. The aggregates used for casting were exposed to extreme heat throughout the summer and had been drained out of moisture, making the dry aggregates absorb the water used for the hydration of cement particles. The characteristics of the two trials and the reason for discarding the first trial are elucidated in the following subsections.

Table 4:

Mix design of Concrete

Mix Design for casting 0.2 m^3 of concrete					
Target strength	**Cement (kg/m^3)**	**Water (kg)**	**Fine agg. (kg/m^3)**	**Coarse agg. (kg/m^3)**	**w/c**
30 MPa	69.54	55.63	141.8	215.2	0.8

3.1.1.1 Summer Cast Trial 1

The first trial of the summer samples, even though discarded, are mentioned in this thesis to elaborate a major hurdle faced while casting concrete in hot and dry climatic conditions. The trial 1 was mixed in the above-mentioned climatic conditions according to ASTM C192/C192M-18 and the mix design in Table 4. Unfortunately, the designed water-cement ratio of the mix, 0.58 was not enough to make concrete workable enough to be casted onto the concrete cylinders. After the mixing of concrete the slump obtained was only 5 mm which was unacceptable according to ASTM C143/C143M-159. More water was added to make the concrete a bit more workable and the water cement ratio was increased to 0.65. With slump obtained of 5 mm, even though the concrete was not workable, the mix was proceeded to be casted onto the cylindrical moulds. The mix temperature at the time of casting was 54ºC and the concrete was compacted well despite being unworkable. After demoulding the specimen after 48 hours, it was found that the concrete had lots of voids and uncompacted aggregates which had left holes on the surface of the cylindrical specimens (Figure 12). Due to the excessive surface damage of the cylindrical specimen, the samples were discarded from being mentioned in this thesis. However, the results and discussion of the trial 1 samples of the summer batch would be mentioned. This underlines the major issue of increasing the water cement ratio of concrete while casting in the summer temperatures due to excessive drying. Although the use of superplasticisers can prolong the workability of concrete, construction contractors are seen to be using excessive water to make concrete workable for casting. The adverse effects of increasing the water cement ratio due to low workability would be further discussed in the results and discussion section.

Figure 12: Voids and uncompacted concrete in trial 1

3.1.1.2 Summer Cast Trial 2

Trial 2 of the summer casting was considered as the batch A to be used to compare the properties of concrete while casting in extremely adverse climatic conditions and nominal climatic conditions. The trial 2 was cast with the same atmospheric conditions in Table 3. The water cement ratio of the second batch was increased to 0.8 to improve the workability of the concrete mixture. The slump obtained after the mixing of concrete was 65 mm and was in accordance with ASTM C143/C143M-159. The increased workability had made it easy to cast concrete without air voids and uncompacted aggregates on the surface of the specimen. Later, it was found that the increased water cement ratio had decreased the target strength of the concrete, thus enumerating the hurdles and obstacles of casting concrete while adverse climatic conditions prevail.

3.1.1.3 Summer Cast Specimen Details

After the casting of Batch A, the concrete was in the mould for the first 48 hours exposed to direct sunlight and exposed to temperatures varying from 35ºC to 47ºC (Figure 13).

Figure 13: Batch A specimens (a) Initial Curing; (b)Control Specimens

The initial curing conditions to which the concrete was exposed during the hardening phase of concrete were extremely degrading, thus simulating the existing conditions in which concrete is cast in summer. Four cylindrical specimens were casted as control specimens (Figure 13-b), which were brought indoors; simulating nominal initial curing conditions for the first 48 hours. The control specimens were in the temperature of 20 ºC to 23 ºC, humidity of 50% to 60% and shielded from sunlight. The control specimen was used to control the properties of the summer specimen with optimally cured specimen of the same mix design. Following 48 hours of initial curing, the designated cylinders were cured for 28 days, 7 days, 3 days and 0 days. After their respective curing durations, the cylinders were dried for 24 hours and placed in their respective exposure conditions. The matrix of experimental design is shown in Table 5. 52 samples were cast for the summer specimens; 48 specimens with adverse initial curing and 4 control specimens with nominal initial curing. 26 specimens were for testing the compressive strength after 30 days of casting and 26 of them were for testing after 90 days of casting and

Table 5:

Experiemental Matrix of Summer Cast

Summer cast (batch A)								
Exposure/ curing	0 days curing		3 days curing		7 days curing		28 days curing	
Laboratory Exposed	L3001	L3002	L3031	L3032	L3071	L3072	L30281	L30282
Sun exposed	S3001	S3002	S3031	S3032	S3071	S3072	S30281	S30282
Seawater exposed	W3001	W3002	W3031	W3032	W3071	W3072	W30281	W30282
Total number of specimens for 30th day testing	24 + 2 control specimen							
Total Number of specimens for 90th day testing	24 + 2 control specimen							
Total number of specimens for the summer cast	48+4 control specimen=52 specimen							

exposure. For every condition of specimen, 2 samples were made for quality control. Thus, the specimens cast in summer were further exposed to nominal final curing conditions (laboratory exposure), extreme sun and heat exposure (outdoor sun) and extremely saline conditions (sea water exposure), for 30 days and 90 days.

3.1.2 Winter Cast

The winter cast specimens (batch B) were casted in nominal temperatures of 23ºC and without being directly exposed to sunlight. The aggregates used for the winter cast had been cooled and had adequate moisture content in them. This process was to simulate the condition in where there is high probability of rain and increased atmospheric humidity during the winter season. The winter specimens experienced nominal curing conditions of 18ºC to 25ºC in the first 48 hours of their casting according to ASTM C-31/C-31-M-19. The winter specimens were cast with an atmospheric humidity of 78% which was adequate for the initial curing process of concrete. The concrete mix was casted for a target strength of 30 MPa and the water cement ratio was 0.64 to have a workable slump of 65 mm according to ASTM C143/C143M-159. All other procedures and equipment used to cast the winter specimens were similar to the summer casting. 48 hours after de-moulding, the concrete specimens were cured according to their designated curing durations of 0 days, 3 days, 7 days and 28 days, and then kept in their respective exposure conditions. 32 specimens were made with the winter casting, and the experimental design matrix of the winter casting is shown in Table 6. The number of specimens used for the winter cast is lower

Table 6:

Experiment Matrix of Winter Cast

Winter cast (Batch B)								
Exposure/ curing	0 days curing		3 days curing		7 days curing		28 days curing	
Laboratory	L3001	L3002	L3031	L3032	L3071	L3072	L30281	L30282
Sun exposed	S3001	S3002	S3031	S3032	S3071	S3072	S30281	S30282
Seawater exposed	W3001	W3002	W3031	W3032	W3071	W3072	W30281	W30282
Total Number of Specimens at 30th day test	8 specimens							
Total Number of Specimens at 30th day test	24 specimens							
Total Number of specimens in the winter cast	32 specimens							

than the summer cast. For the winter casting, 30 days testing was done only for the specimens exposed to laboratory conditions with different curing durations, because the outdoor sun was similar to indoor conditions during winter and the necessity was only to study the effect of exposure after 90 days. The specimens dedicated for testing at 90 days were kept in 3 exposure conditions; namely laboratory exposure, outdoor sun exposure and saline sea water exposure. Since the winter specimen were cast while nominal initial and final curing conditions prevail, the control specimen selected is the specimen which was cured for 28 days in lab conditions, for both 30th day and 90th day testing.

3.2 Exposure Conditions

Three exposure conditions selected were outdoor sun, marine sea water and nominal lab conditions. The concrete specimens were exposed to these conditions for 90 days. Various tests were done at the 30th day and the 90th day after exposure, except for the winter samples, which were tested only at 90 days of adverse exposure.

3.2.1 Outdoor Sun Exposure

The outdoor sun exposure is dubbed as the most adverse climatic condition that is experienced by concrete during the initial and final phases of hydration. There is a subsequent loss of water while concrete is exposed to high temperatures, low humidity and dry winds. The outdoor sun exposure had temperature ranges from 40ºC to 50ºC, with a relative atmospheric humidity of 30% to 40% and hot winds of 15 to 20 km/Hour. The outdoor sun conditions simulate the exposure conditions of majority of the buildings and construction happening in the Arabian Gulf. The concrete cylinders were placed in an open area as shown in Figure 13, exposed to direct sunlight and high temperatures. The concrete specimens in the outdoor sun are also made to be in contact with the ground soil to study the effect of the sulphate and chloride rich soil of Qatar.

Figure 14: Outdoor Sun Exposure

The concrete cylinders were made to be in contact with the soil from all directions as time progressed, such that the sulphate and chloride ingress onto the concrete could be from all directions. 48 hours after casting the specimens, they were demoulded and the samples with 0 curing duration was directly exposed to the sun; the 3 days cured samples were exposed to the sun after 3 days of water immersed curing and the same was done for the 7 days and 28 days cured samples. The summer cast (Batch A) was tested after exposure for 30 days and 90 days as mentioned earlier, and the winter cast were tested at exposure to the outdoor sun for 90 days only.

3.2.2 Saline Water Exposure

The designated specimens were immersed in sea water to simulate the effect of fresh water curing on concrete structures that are exposed to marine environments. The structures near the sea, or in the tidal region of sea water or even submerged into sea water risk an early corrosion of steel bars due to the chloride ingress from the concrete cover. Due to the construction of buildings near the sea and the highly saline nature of the ground water of Qatar, it is necessary to study the effect of curing on the ingress of chloride ions onto the concrete. Usually, the corrosion of reinforcements happen after years of exposure to sea water or marine environment. To replicate these extended years of exposure to marine environment in the time period of 90 days, the concentration of NaCl in the water was increased to 30% compared to the salt content in sea water which is only 3% (ASTM D1121). Thus, by immersing the concrete in 30% saline solution, an accelerated damage phenomenon due to exposure is simulated. The main property expected to be studied from this exposure condition was the chloride absorption of concrete with different curing durations. The concrete cylinders with zero curing was directly immersed in the saline solution 48 hours after casting. The concrete with 3 days curing duration was cured for 3 days in fresh water and then dried under the sun for 24 hours and then immersed in the saline solution. Similar procedure was done for the 7 days and 28 days cured samples. The concrete specimens were immersed in the saline solution for 90 days. The tests were done on these specimens at 30 days and 90 days of exposure, except for the winter specimens, on which the tests were done only after 90 days of exposure to sea water.

3.2.3 Laboratory Exposure

The specimens kept under laboratory exposure simulates the nominal temperature and conditions required for the optimum hydration of concrete according to ASTM C-31/C-31-M-19. With a temperature range of 20ºC to 25ºC, relative humidity of 60% to 65% and shielded from direct sunlight, the indoor laboratory exposure provides a suitable environment for concrete to hydrate in its final curing durations. The main objectives of the laboratory specimens are to provide optimal final curing conditions for concrete and for comparison of the characteristics of concrete with different moist curing durations subjected to nominal final curing conditions. Both the summer and winter batches were exposed to laboratory conditions to differentiate between the effects of good and adverse initial curing conditions on concrete, while optimum final curing conditions are prevalent. After their respective moist curing durations of 0 days, 3 days, 7 days and 28 days, the designated samples were kept in the laboratory to be exposed to nominal curing conditions. Both batches A and B, exposed to laboratory conditions were tested at 30 days and 90 days of exposure.

CHAPTER 4: TEST PROCEDURE

To test the effects of moist curing durations, initial and final conditions and the effect of exposure conditions on the characteristics of concrete, the following tests and analysis were performed. The compressive test on the concrete specimens were conducted on the 30th day and 90th day after casting. To justify the results of compressive strength tests, a micro-structural analysis was done using SEM visual inspection, XRD and XRF analysis. To investigate the durability properties of concrete, the chloride content of the samples was analysed.

4.1 Compressive strength procedure

The compressive strength is one of the most important properties to determine the quality of concrete. The compressive strength tests were performed according to ASTM C39/C39M-18. Since the concrete cylinders were cast in unconventional moulds, the concrete specimen was grinded on the top and bottom. This procedure was to make sure that the compressive load applied on the specimen was perfectly perpendicular to the horizontal face of the cylinder. The procedure also made sure that the height of all the cylindrical specimens were uniform. After grinding both sides, the height of the cylindrical specimen was 200 mm and the diameter was 104 mm as shown in Figure 15.

Figure 15: Compressive strength test procedure

Prior to mounting the specimens onto the compressive testing machine, visual inspection of every specimen was done, and the specimens were wrapped in a thin plastic wrapping such that the compressive strength test doesn't destroy the samples before further chemical tests were done. Photographs of all specimens before and after the compressive strength test was taken. The specimen was tested for compression in the machine with a load capacity of 3000kN. Loading pads were inserted at the top and bottom of the cylinders before the test to ensure uniform loading and neglect any undulations in the loading surface. The sensitivity of the compressive strength machine was set to 20%, area of the samples to calculate the was set to 8498.28 mm^2. The failure mode of the compression test was recorded and compared with the standard failure mechanism mentioned in ASTM C 39/C39M-18, to ensure the accuracy of the compressive strength obtained.

4.2 Micro-structural Analysis Procedure

The micro-structural analysis of concrete was done to investigate the variations in the compressive strengths of concrete while exposed to different curing durations and conditions. The Scanning Electron Microscope (SEM) imaging was done to understand the micro-structural formations of the hydration products of concrete. The presence of these hydration products was further validated using the X-Ray Diffraction (XRD) analysis of the samples obtained. Further analysis to find the percentage of hydration products were done using the X-ray Fluorescence (XRF) analysis. The SEM analysis of the concrete samples were done according to ASTM C1723 − 10. The main hydration products which were expected to be found in concrete were Calcium Silicate Hydrates (C-S-H), Calcium Hydrates (C-H), Calcium mono alumino sulphates also known as Ettringite and portlandite clinker particles which may be due to un-hydrated cement particles. The crystalline structures of these particles were carefully studied prior to performing the SEM analysis as elaborated in the introduction section. The micro-structural analysis of the concrete was performed 120 days after casting, after the compression tests were completed. The test was performed on the summer cast exposed to outdoor sun environment to determine reason for the deterioration of concrete exposed to harsh environmental conditions. These results were compared to the micro-structural analysis of winter batch specimens with optimal initial and final curing conditions. Concrete samples of maximum dimension of 1.5 cm were broken off from the cylinders for the SEM analysis (Figure 16).

Figure 16: Gold Plated Sample for SEM analysis

The concrete samples broken off were 0.5 cm from the surface of the cylinder to avoid the presence of external impurities from the atmosphere. The concrete specimens were also placed in air tight packages prior to micro-structural analysis to avoid the disturbance of micro-structure during the compressive tests. According to ASTM C1723 − 10, various types of specimens such as, fractured surfaces, sectioned or polished surfaces, thin sections, or powders can be examined using SEM. For hardened concrete, it is often desirable to examine large specimens or several small specimens concurrently, and chambers are available that can accommodate specimen sizes up to 150 mm. For this thesis, fractured specimen was selected for the SEM analysis as shown in Figure 16. Since concrete specimens are non-metallic and poor conductors, a coating of gold was performed on the samples to obtain images with precision. The summer cast with 0 days, 3 days, 7 days and 28 days; and a control sample with proper initial and final curing conditions were the 5 samples analysed using SEM microscopy. To perform the XRD and XRF analysis, the concrete samples were powdered to a size to pass a sieve size of 150 microns. The powder of the samples was obtained from the surface of the concrete cylinders at 3 different points on the vertical height, such that the powdered samples represent the whole cylinder. The XRD analysis provided a qualitative analysis and the XRF provided a qualitative analysis of the micro-structural constituents of the concrete specimens.

4.3 Chloride Content Test Procedure

The effect of moist curing duration, initial and final curing conditions and the effect of adverse environmental exposure, on the chloride content of the concrete samples were studied by measuring the content of chloride ions as a percentage of cement content of the concrete. The test was performed after 90 days of exposure to the three exposure conditions mentioned earlier. The chloride content of the samples was measured according to BS 1881: Part 124: 1988 (10.2). The reason for using the British standards was to compare the acceptable limit of the chloride content according to Qatar Construction Specifications. To measure the chloride content of the concrete specimens, the concrete is first grinded, and the powder is made to pass through a 150 microns sieve. The powder for the concrete specimens were taken from three different heights of the concrete to have a uniform representation of the chloride content of the concrete surface. The concrete was weighted in a stoppered 500 mL conical flask 5 ± 0.005 g of the analytical sample. The mixture is dispersed with 50 mL of water, and 10 mL of nitric acid is added. 50 mL of hot water is added, and the mixture is boiled for 4 min to 5 min and kept warm for 10 min to 15 min. The sample is then cooled to room temperature and a measured silver nitrate standard solution is added. Subsequently, 2 mL to 3 mL of 3.5.5-trimethylhexanol is added to the solution. The flask was closed with a stopper and shaken vigorously using a shaking machine to coagulate the precipitate. 1 mL of iron (III) indicator solution was added and the solution was titrated with the thiocyanate solution to the appearance of first permanent red colour. The chloride iron content ‘J’ is calculated as a percentage of the cement to the nearest 0.01

% (m/m) from the expression.

$$J = \left\{Vs - \frac{V6m}{0.1}\right\} * \frac{0.36545}{Mc} * \frac{100}{C1}$$

Where,

Mc is the mass of the sample used in grams

Vs is the volume of the 0.2 M silver nitrate solution added in mL

M is the molarity of the thiocyanate solution in mol/L

C1 is the cement content of the sample in percentage

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Compressive strength

The difference in compressive strength of various specimens with different moist curing durations; initial and final curing conditions; and exposure to three environmental conditions are shown and discussed in the subsections. The summer batch and the winter batch, which had a difference in the initial curing conditions were compared, and the results were correlated with the experiments done by previous researches.

5.1.1 Summer Cast Compressive strength

As mentioned earlier, the summer cast was done in two trials. The first trial was discarded, and the second trial was taken into consideration for the experimental process. Although the trial 1 was discarded, to explain the effect of increasing the water content of the concrete mixture a few samples with less imperfections were recovered to test the compressive strength. The maximum compressive strength of trial 1 was 30 MPa as targeted by the mix design.

In trial 2, two samples were taken for each case scenario and the average result of the two cylinders was displayed. The maximum compressive strength of the summer cast at 30^{th} day is 21 MPa and 90^{th} day is 24 MPa. The target strength of 30 MPa was not attained due to the addition of extra water in the concrete mix during casting to improve the workability. The compressive strength results of the summer batch (Batch A), tested at 30 days and 90 days are shown in Table 7 and Table 8.

5.1.1.1 Compressive Strength After 30 Days Exposure

The maximum compressive strength was obtained in the control specimen due to the controlled optimum conditions in which it was cured in the initial 48 hours and the final 28 days. The 30^{th} day compressive strength of the control specimen, 21 MPa, validates the strength of the mix design since it was cast and cured with optimum conditions of temperature and moisture. The increase in compressive strength with

Table 7:

Results of 30th day compressive strength (Summer Cast)

Test	Exposure	Name	Curing time	Stress, MPa		Avg. Stress, MPa
				Sample1	**sample2**	
30 Days	**Control**	**C-30-28**	**28days**	**19**	**21**	**21**
	LAB	A-L30-0	0 days	10.04	11.30	10.04
		A-L30-3	3 days	15.87	11.91	13.89
		A-L30-7	7 days	14.48	16.31	15.1
		AL30-28	28days	16.8	0.00	16.8
	SEAWATER	AW30-0	0 days	12.12	0.00	12.1
		AW30-3	3 days	8.51	15.71	12.11
		AW30-7	7 days	17.56	15.14	16.3
		AW3028	28days	15.85	16.76	16.8
	SUN	A-S30-0	0 days	7.99	5.55	6.77
		A-S30-3	3 days	9.56	8.14	9.56
		A-S30-7	7 days	12.65	8.55	10.60
		AS30-28	28days	-	-	16.76

curing durations of concrete exposed to the three conditions of outdoor sun, sea water and laboratory is shown in Figure 17. The compressive strengths were lowest for the specimens exposed to outdoor sun followed by the laboratory specimen and then the sea water exposure specimens.

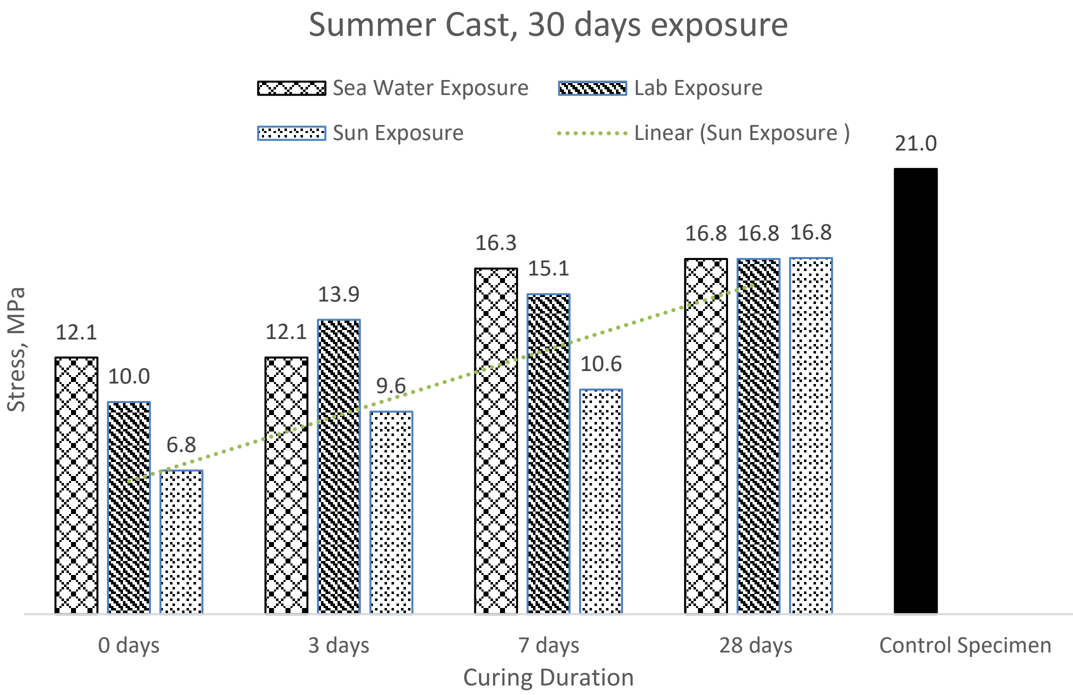


Figure 17 : Comparison of Lab, Outdoor Sun and Sea Water Exposure (30th day tests)

The outdoor sun exposed specimen had compressive strengths were 6.8 MPa. 9.6 MPa and 10.6MPa for the curing durations of 0 days, 3 days and 7 days respectively. The laboratory samples, which experienced nominal exposure conditions after their moist curing durations gave compressive strengths of 10.0MPa, 13.9MPa and 15.1 MPa for curing durations of 0, 3 and 7 days respectively. The apparent increase in strength of the sea water samples is discussed in detail in the later subsections.

5.1.1.2 Compressive strength after 90 days exposure

The 90 days compressive strength results were taken as a better representation than the 30^{th} day test due to the prolonged exposure period of the specimen to their respective exposure conditions. The test results of the compressive strength of the specimens with different curing durations, exposed to the three exposure conditions are displayed in Table 8.

Table 8:

Compressive strength results after 90 days exposure

Test	Exposure	Name	Curing time	Stress, Mpa		Avg. Stress, Mpa
				Sample1	sample2	
90 days	**Control**	**C-90-1**	**28days**	**21**	**24**	**24**
	LAB	A-L90-0	0 days	9.7	12.71	11.2
		A-L90-3	3 days	0.0	15.7	15.7
		A-L90-7	7 days	17.0	0.0	17.0
		AL9028	28day	25.1	22.6	22.6
	SEAWATER	AW900	0 days	19.3	18.5	18.9
		AW903	3 days	16.1	20.9	18.5
		AW907	7 days	20.7	19.3	20.0
		AW9028	28day	10.6	30.2	20.4
	SUN	A-S90-0	0 days	11.1	7.5	9.7
		A-S90-3	3 days	12.5	13.2	12.5
		A-S90-7	7 days	16.1	14.3	14.3
		A-S90-28	28day	17.3	16.1	16.7

There is an apparent increase in the compressive strengths of the specimens tested at 90th day compared to the 30th day testing. This phenomenon is further discussed in later subsections. The control specimens which were casted, cured and exposed in nominal exposure conditions gave a compressive strength of 24 MPa, validating the strength of the concrete cast at 90 days to be 24 MPa. After 90 days of exposure to harsh and adverse climatic conditions, the outdoor sun samples gave compressive strengths of 9.7 MPa, 12.5 MPa 14.3 MPa and 16.7 MPa with curing durations of 0 days, 3 days 7 days and 28 days. The laboratory samples gave a higher compressive strength of 11.9 MPa, 15.7 MPa, 17 MPa and 22.6 MPa for the mentioned durations of curing. The sea water samples exhibited an increase in strength compared to other exposure specimens, yet had a constant strength of 18.9 MPa, 18.5MPa, 20 MPa and 20.5 MPa for the 4 durations of freshwater curing. The increase in compressive strengths of the specimens with the increase in duration of moist curing and favourable exposure conditions is shown in Figure 18.

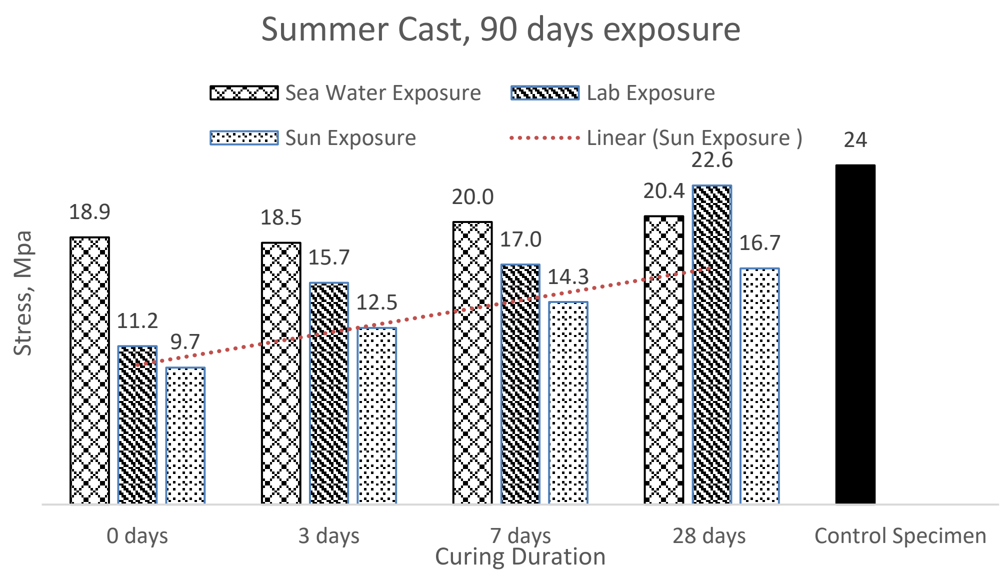


Figure 18: Comparison of Lab, Sun and Seawater samples (90th day)

5.1.2 Winter Cast Results (Batch B)

The difference between the winter cast and the summer cast is the initial curing condition during the first 48 hours after casting the concrete. The maximum 30th day strength of the concrete casted in the winter batch is 24 MPa and the maximum 90th day compressive strength is 32 MPa. The compressive strengths of the winter batch at 30 days and at 90 days are shown in Table 9 and Table 10. The control specimen of the winter cast is taken as the laboratory sample that has been cured for 28 days since it has favourable initial and final curing conditions, and maximum curing duration.

5.1.2.1 Compressive strength after 30 days of Exposure

As mentioned earlier, the compressive strength on the 30th day for the winter cast was done only after exposure to laboratory conditions because, 30 days exposure to winter climate wouldn’t cause accelerated deterioration to the concrete specimens (Table 10).

Table 9:

Winter cast compressive strengths (30th day)

Test	Exposure	Name	Curing time	Stress, MPa		Avg. Stress, MPa
				Sample1	sample2	
30th Day test	LAB	B-L30-0	0 days	15.5	15.9	15.9
		B-L30-3	3 days	20.1	21.3	20.9
		B-L30-7	7 days	21.1	23.1	22.1
		B-L3028	28 days	24.1	24.7	24.1

The compressive strength of the control specimen, B-L30-28 is 24.1 MPa which is the highest due to nominal conditions during the first 48 hours and 28 days of moist curing. The specimens which weren't cured at all gave a compressive strength of 15.9 MPa. The specimen with 3 days and 7 days of curing gave a compressive strength of 21.3 and 22.1 MPa. Even with nominal initial and final curing conditions, the compressive strength decreases as the moist curing duration decreases. The target strength of 30 MPa of concrete was not reached at 30th day testing, this is possibly due to the slow strength gain and the addition of extra water during the mixing of the concrete to increase the workability.

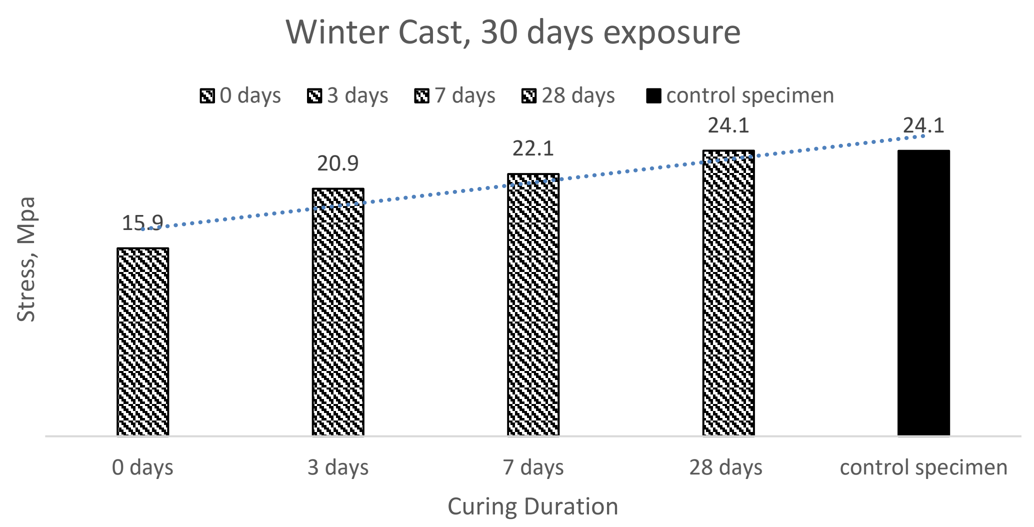


Figure 19: Winter cast, lab exposure (30 days)

5.1.2.2 Compressive Strength After 90 days exposure

The 90th day compressive strength mimics the closest case scenario of concrete after exposure to different conditions for a period of 90 days. Thus, the 90th day compressive strength is taken as an appropriate representation of the compressive strength comparisons of specimens with different curing durations and exposure conditions. The maximum compressive strength was seen in the B-L-90-28, which was the specimen in favourable exposure condition in the laboratory, which was

Table 10:

Winter Cast, 90th day Compressive Strength Results

Test	Exposure	Name	Curing time	Stress, MPa		Avg. Stress, MPa
				Sample1	sample2	
90 days test	LAB	C-L90-0	0 days	14.7	27.3	21.0
		C-L90-3	3 days	23.2	0.0	23.2
		C-L90-7	7 days	24.2	24.3	24.3
		C-L90-28	28 days	34.1	29.1	31.6
	SEA WATER	C-W90-0	0 days	26.7	25.3	26.0
		C-W90-3	3 days	25.0	30.2	27.6
		C-W90-7	7 days	23.2	32.6	27.9
		C-W9028	28 days	29.7	26.9	28.3
	SUN	C-S90-0	0 days	17.5	17.5	17.5
		C-S90-3	3 days	23.2	23.2	23.2
		C-S90-7	7 days	29.3	17.7	23.5
		C-L90-0	0 days	26.6	27.0	25.0

cured for 28 days. With a compressive strength of 32 MPa, this sample was taken as the control specimen for comparing the strengths of other specimens. The 90th day compressive strength of the winter cast concrete with different curing durations and exposure conditions are shown in Table`10. The outdoor sun exposure samples had the lowest compressive strengths of 17.5 MPa, 23.2 MPa, 23.5MPa and 24.2 MPa for the curing durations of 0 days, 3 days, 7 days and 28 days. The laboratory samples had a higher trend in the increase in compressive strength, with 21 MPa, 23.3 MPa, 24.3 MPa and 32 MPa for the four curing durations because of the nominal exposure conditions. As usual, the sea water exposed samples were at constant, yet a higher compressive strength for 0 days, 3 days and 7 days curing compared to the lab and outdoor sun samples (Figure 20).

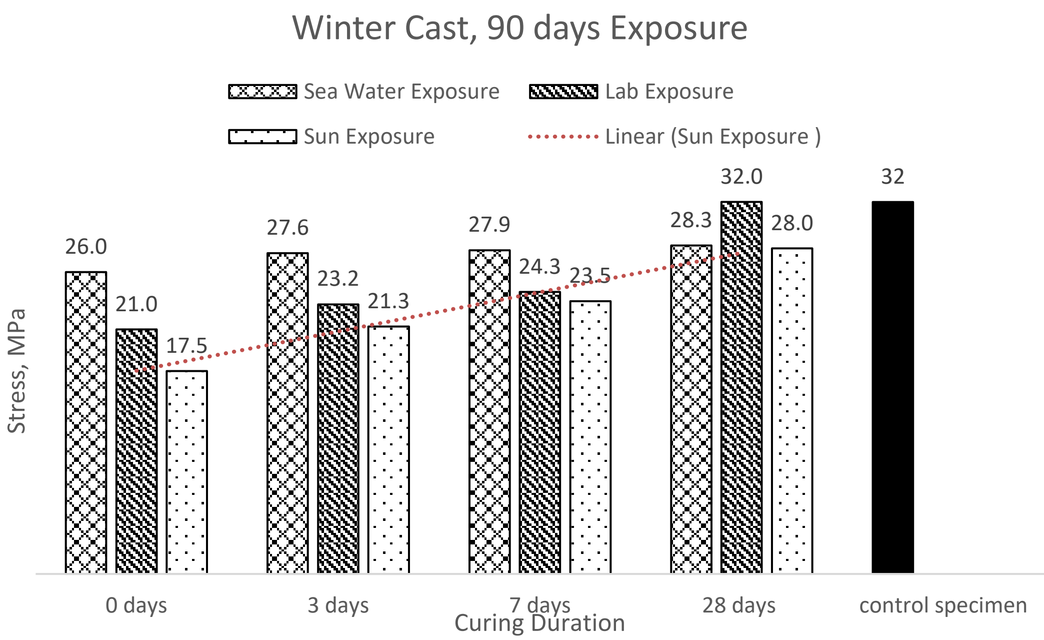


Figure 20: Comparison of Lab, Sun and Sea Water Exposure (90 days)

5.1.3 Effect of Initial Curing

The control specimen experienced favourable initial and final curing conditions during the first 48 hours. Thus, other samples which experienced harsh initial curing and favourable final curing conditions for 28 days are compared to the control specimen to validate the effect of initial curing. The compressive strength of the sample A-30-28 cured for 28 days in fresh water gave a compressive strength of 16.8 MPa which is 20% lower than the control specimen due to the adverse climatic conditions experienced by the concrete during the initial curing phase (first 48 hours). Even though both the control specimen and the specimen A-30-28 was cured for 28 days, the decrease in compressive strength portrays the effect of optimal exposure conditions during the first 48 hours of casting concrete. Excessive drying of water during the initial curing phase decreased the compressive strength of the specimen by 20% at 30th day testing. Similarly, for 90th day testing, the specimen A-90-28, exposed to laboratory exposure and cured for 28 days had a compressive strength of 22.6 MPa which is 6% lower than the control specimen. This is also the result of adverse initial curing experienced by the samples during the first 48 hours. The influence of initial curing in reducing the compressive strength is illustrated in Figure 21.

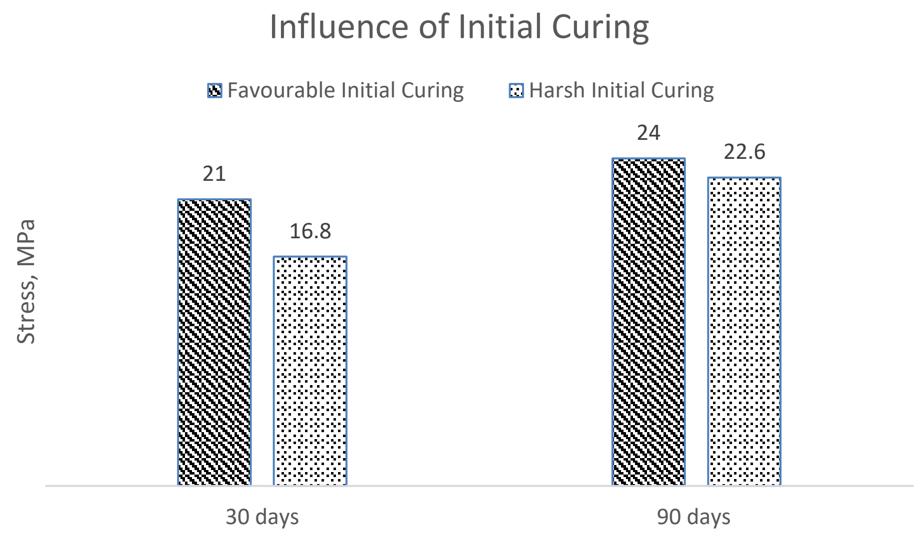


Figure 21: Comparison of favourable/harsh initial curing for samples with favourable final curing

After 28 days of curing, lower compressive strengths of 30%, 15% and 6% for the 3 exposure conditions: outdoor sun, sea water and laboratory of the summer cast, as compared to the control specimen is a combination of the adverse initial curing conditions of concrete in the first 48 hours and harsh external exposure. The nurturing of concrete after casting, in the first 48 hours is crucial in increasing the compressive strength of concrete, no matter which environment the concrete is exposed to in the later stages of its life. Thus, the concrete should be shielded from direct sunlight and maximum care is to be taken such that the casting of concrete is done while the atmospheric temperatures are low, and the relative humidity is high. The effect of initial curing is not applicable for the winter cast because the initial curing phase is favourable for all samples.

5.1.4 Effect of moist curing duration

The damage phenomenon in concrete is denoted as the percentage reduction in compressive strength of the sample compared to the control specimen. The reduction in damage phenomenon as curing period increases for summer and winter specimens are illustrated in Figure 22.

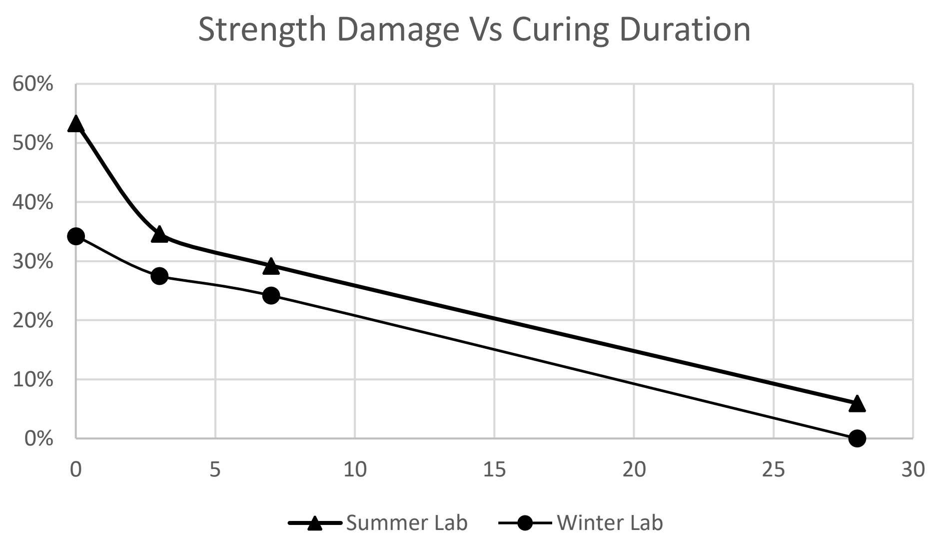


Figure 22: Reduction in damage with increase in curing duration (90 days)

The compressive strength results of the *summer cast specimen* exposed to nominal laboratory conditions are considered for evaluating the effect of increase in moist curing duration. As the duration of moist curing increased, the compressive strengths of the specimens increased. The absence of moist curing decreased the 30th day compressive strength of the lab specimens with zero days curing by 52%. Limiting the moist curing to 3 days and 7 days decreased the 30th day compressive strength by 34% and 28% respectively. The specimens tested after 90 days of casting showcased similar results. Zero cured samples in laboratory exposure was 53% weaker than the control specimen. This emphasizes on the necessity of moist curing even when the environmental conditions are favourable. For curing duration of 3 days and 7 days, the decrease in compressive strength is 35% and 29% respectively. The results of the laboratory specimens outline the necessity of moist curing for extended durations of 28 days even though the concrete is exposed to favourable environmental conditions, as the proper hydration of concrete wouldn't be possible without the influence of external moisture.

The damage in strength of the *winter cast specimens* due to short moist curing is less, due to the favourable initial curing experienced. For the samples tested at the 30th day, the specimen with zero days of moist curing was 34% weaker than the control specimen, implying the fact that even with nominal initial and final curing conditions, the hydration of concrete is not complete without the addition of external moisture content to the hardened concrete. The loss of strength for the limited curing periods of 3 days and 7 days isn't significant compared to the summer cast, yet there was 13% and 8% loss in compressive strength, respectively. In the 90th day compressive strengths of the winter cast, with all conditions favourable to concrete, the lack of moist water curing (0 days) had decreased the compressive strength by 34%. This loss of strength indicates that the relative humidity of the atmosphere and the initial water content of the fresh concrete mixture is not enough to develop the necessary compressive strength of concrete. Limiting the curing of concrete with water for 3 days and 7 days had reduced the compressive strength by 28% and 24% respectively. Complete 28 days of water curing along with nominal and favourable exposure conditions like temperature and humidity helped the concrete reach its target strength of 32 MPa. Thus, concrete needs favourable conditions of exposure and moist curing duration to reach the necessary compressive strengths for which it was designed. Similar strength reduction of 25% was found by Alizadeh, et al., 2008 and Khaliq and Javed 2017 when concrete was cured for zero days in nominal exposure conditions.

5.1.5 Effect of Outdoor Sun Exposure

The damage to strength of outdoor sun exposed samples for different curing durations are shown in Figure 23. The percentage reduction in strength compared to the control specimen are taken as the extent of damage. The most favourable condition experienced by the concrete is the winter lab condition, a comparison is made in Figure 23 to visually differentiate the level of damage caused by the exposure to extreme hot and arid conditions.

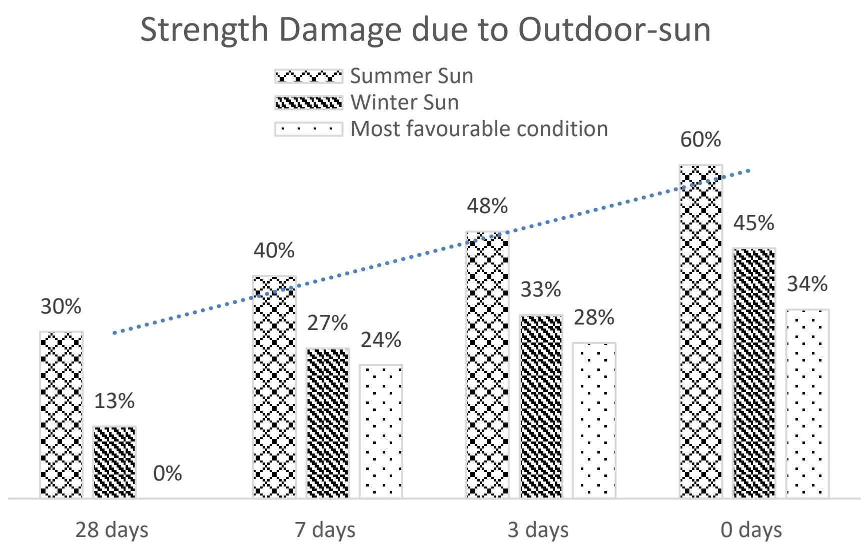


Figure 23: Increase in strength damage due to outdoor sun exposure and short curing durations for winter and summer sun samples (90 days)

For the *summer cast*, the combination of the outdoor sun exposure with zero days moist curing, and harsh initial and final curing, is the most deteriorating condition. In 30^{th} day testing, there is a 68% loss in the concrete samples which are casted and exposed to extreme outdoor sun combined with zero moist curing. This loss of compressive strength can be attributed to the absence of water required for the proper hydration and increased temperature of the concrete matrix. Consecutively, the outdoor sun exposure samples which were cured only for 3 days and 7 days experienced 54% and 50% loss in 30^{th} day compressive strength due to high temperatures and inadequate moist curing durations. For the specimens tested after 90 days of exposure to outdoor sun, due to severe heat and low relative humidity exposure for longer durations, the loss in compressive strength was 60%, 48%, 40% and 30 % for the curing durations of 0 days, 3 days 7 days and 28 days respectively, compared to the control specimen. The excessive drying of the sample being exposed to outdoor sun and extreme temperatures reduced the compressive strength of the A-S-90-28 by 30% even though it had been cured for 28 days in water. The reduction in strength of 30% in A-S-90-28 (sun exposure) to 6% in A-L-90-28 (lab exposure) shows the degrading effect of the harsh environmental exposure to concrete even after 28 days of moist curing is performed. As a validation of the above results of concrete cured and exposed to high temperatures, Abdul-Ghafoor et al., 1992 had also found that there is a 25% reduction in the compressive strength of concrete if it was cured at elevated temperatures of 45°C. Similarly, results on the comparison of outdoor and indoor samples were reported by Bushlaibi & Alshamsi [15] where the specimen cured outdoors was 13% weaker than the specimens cured indoors. This underlines that concreting in high temperatures and low humidity regions drastically reduces the compressive strength of the specimens even though proper moist curing for 28 days is provided.

For the winter cast specimens, even after having an optimum exposure condition during the first 48 hours of initial curing, the exposure to high temperatures and low humidity had decreased the strength of the 28-day cured outdoor sun exposure samples by 13%. The hot and arid exposure combined with zero water curing had decreased the compressive strength of B-S90-0 sample by 45%. Further, reduction of 33% and 27% was seen in the compressive strengths of samples cured for 3 days and 7 days, and then exposed to the outdoor sun. Thus, even though the concrete is cast in favourable winter conditions, exposure of the concrete to harsh environmental conditions can degrade its compressive strengths especially if it isn't cured with water for extended durations.

5.1.6 Effect of Sea water Exposure

The exposure to sea water didn't have much degrading effects on the compressive strength compared to outdoor sun and laboratory exposure. The damage in strength for the summer sea and winter sea are compared in Figure 24. As calculated earlier, the damage is the percentage reduction of strength from the control specimen.

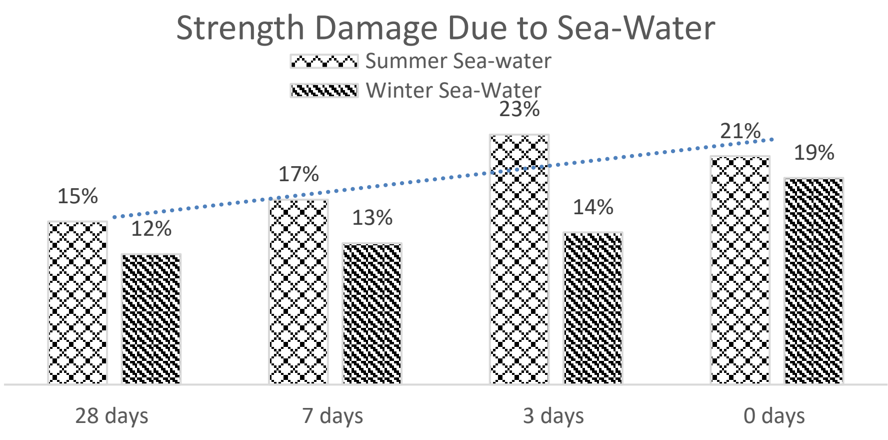


Figure 24: Damage in strength due to exposure to sea-water (90 days)

The sea water samples of the summer cast had exhibited higher strength compared to the outdoor sun and laboratory samples. Yet, due to the lack of fresh water curing, 30th day exposure samples had a decreased strength of 42%, 42% and 22% compared to the control specimen. For 90 days of exposure to sea water, the specimens had 21%, 23%, 17% and 15% lower compressive strength compared to the control specimen.

The sea water samples of the winter cast had a decrease in compressive strength of 19%, 14%, 13% and 12% for the 90th day test for samples cured for 0, 3, 7 and 28 days. The seemingly constant values of compressive strength for different curing duration is the effect of hydration of concrete by saline water. Yet, the samples cured for extended duration in fresh water has still given a higher compressive strength than other samples exposed to sea water during the initial days of curing. It is noted that the increase in strength is only in the 0 days, 3 days and 7 days cured samples and not for the 28 days cured samples. The water molecules in the sea water helps in the hydration of concrete and makes it seem like a case where concrete is cured by using sea water. The effect of using sea water for the curing of concrete was studied by Weigan [38] and a similar phenomenon of the initial increase in the first 30 days, and later decrease in compressive strength was observed in the research done. Wegian [38] observed that concrete specimens cured with sea water had showcased an increase in strength in the first 90 days of casting, yet, after 90 days the strength gain of the concrete specimen began to fade away. The effect of chloride ions in accelerating the initial hydration process of concrete is also mentioned by Hansson, et al. [47]. Thus, it can be deducted that the exposure to saline water with high concentration of chlorine accelerates the compressive strength gain in concrete, but it doesn’t reach the target strength of concrete. Further, the compressive strength of samples exposed to sea water is likely to decrease over time due to the attack of chloride ions on the concrete as studied by

Wegian [38] and Hansson et. al [47].

5.1.7 Effect of Casting Season (Summer/Winter)

One of the main objectives of this study is to outline the difference between the compressive strengths of concrete which is cast in summer, with adverse climatic conditions and winter, with nominal climatic conditions. The 90th day compressive strength tests are considered for this comparison as the samples are exposed to various exposures for a longer period. The most damaging combination, which is the summer sun and the next damaging condition, summer lab is compared with the most favourable condition, winter lab in Figure 25. To quantify the values, comparison is made as the percentage loss in strength of the summer cast specimens compared to the winter cast specimens (Table 11).

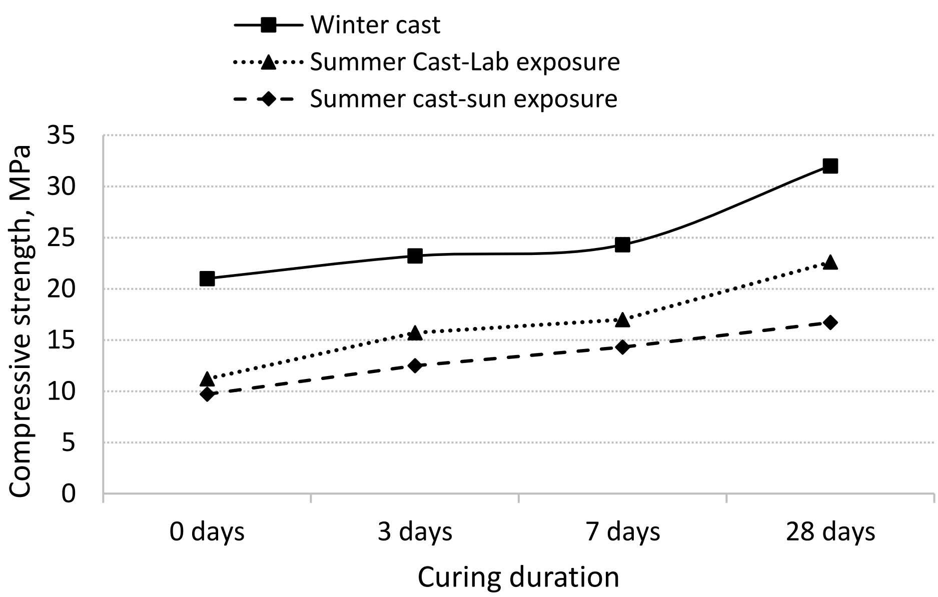


Figure 25: Comparison of Summer Lab and Summer Sun to the Winter Lab exposure

Table 11:

Winter Cast, 90th day Compressive Strength Results

	Percentage Reduction in Strength	
Curing Time	Winter to Summer Sun	Winter to Summer Lab
0 days	54%	46%
3 days	46%	32%
7 days	41%	30%
28 days	48%	30%

Primarily, to examine the effect of initial curing condition at the first 48 hours of casting alone, the comparison of the compressive strengths of summer and winter cast specimens which were exposed to laboratory exposure for 90 days is done as shown in Figure 20. For laboratory exposure, after 28 days of curing, the summer samples are 29.5% weaker than the winter samples at the 90^{th} day testing. If the process of moist curing is completely ignored, the zero cured summer cast samples are 46.8% weaker than the winter cast. Subsequently, a loss of 32.4% and 30% was observed for the samples cast in summer and cured for 3 days and 7 days respectively, compared to the samples cast in winter. These losses in strength are completely attributed to adverse exposure during the initial 48 hours of casting, as the laboratory samples were exposed to favourable conditions for the rest 90 days. These results underline the importance of nurturing fresh concrete soon after its casting. The first 48 hours after casting, which is called the initial curing duration is extremely important for the increased service-life and quality of concrete.

The next scenario considered is the influence of combined effects of adverse initial and final curing conditions of concrete on its compressive strength. The outdoor sun exposure samples of the summer cast are compared with the laboratory samples of the winter cast to examine the extent of damage done to concrete while cast and cured in extreme summer conditions. Figure 25 compares the compressive strengths of the outdoor sun samples of the summer cast and the laboratory samples of the winter cast. It is revealed that the outdoor sun samples of the summer cast are 48% weaker than the laboratory samples of the winter cast while both samples were cured for 28 days with water. The combination of adverse exposure conditions during the initial and final curing periods is found to have detrimental effects on concrete up to 48% compared to concrete with nominal exposure condition in the initial and final curing periods of concrete. If the curing of concrete is completely neglected, the zero cured samples exposed to outdoor sun of the summer cast is 54% weaker than the laboratory exposed samples of the winter cast. However, there is a lower decrease in strength of 46% and 41% for the summer samples cured for 3 days and 7 days. For the outdoor sun samples of the summer cast, the increase in strength from 7 days to 28 days curing is 14.3 MPa to 16.7 MPa, indicating that extending the curing duration by 21 days didn't increase the compressive strength compared to the increase of strength from 24.3 MPa to 32 MPa in the laboratory samples of the winter cast. This is the reason for the 28 day cured samples of the summer cast to be 47% weaker than the winter cast, and the 7 days cured samples to be only 41% weaker than the winter cast. This indicates that 28 days of curing increases the compressive strength of concrete to a greater extend when a favourable combination of initial and final curing conditions exists than adverse initial and final curing conditions.

Climatic conditions to which fresh and hardened concrete is exposed to, plays a vital role in the development of compressive strength throughout the lifetime of concrete. The nurturing of concrete in the initial 48 hours of casting can reduce the detrimental effects of adverse exposure conditions, further, curing the concrete for extended durations of 28 days can negate the ill effects of adverse exposure conditions. It is necessary that casting of concrete during extremely adverse climatic conditions be avoided as much as possible, as it can decrease the quality of concrete and in turn reduce the service life of the structure. Leaving the fresh concrete exposed to direct sunlight can dry out the required water content of the mixture and in turn reduce the compressive strength of concrete up to 53% even though 28 days of proper curing is performed. Thus, it is recommended to cover concrete soon after casting to prevent the moisture escaping from the mixture. Negligence of water curing can reduce the compressive strength of concrete even while favourable climatic conditions exists as elaborated in section. Thus, while casting concrete in adverse climatic conditions, the detrimental effects on the compressive strength can be reduced by improving the initial curing conditions (first 48 hours), shielding and covering the concrete from direct sunlight and heat exposure, and prolonging the moisture curing period to 28 days.

5.1.7 Difference in 30th and 90th Day Compressive Strength

Another notable observation in the compressive strength tests was the increase in 90th day strength compared to 30th day strength. The difference in compressive strengths of the 30 days exposure and 90 days exposure to outdoor sun is compared in Figure 26.

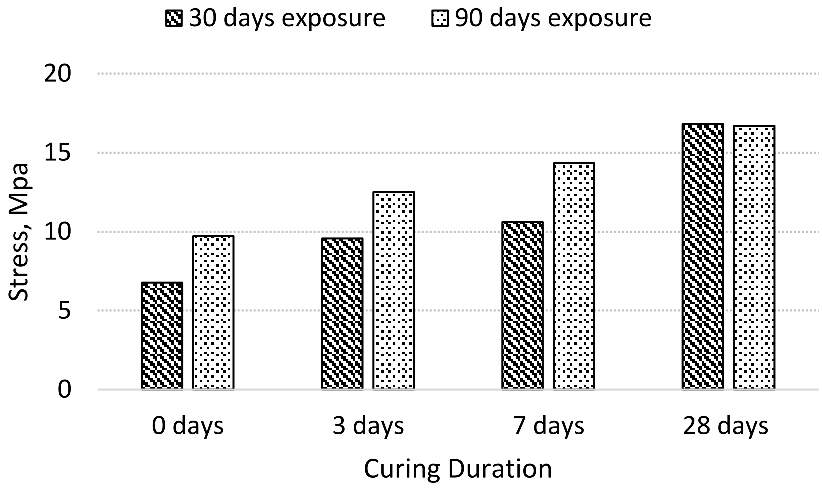


Figure 26: Comparison Between 30 days and 90 days exposure

For the summer cast, there is an average increase of 11% for the laboratory samples and 27% for both outdoor sun exposure and sea water exposure samples, compared to the 30th day testing. For the winter cast, there is an average increase of 13% in 90th day strength compared to the 30th day strength. The 11% and 13% strength gain in the laboratory samples of summer and winter cast is the normal gain of concrete in 90-day time. Similar observations were reported by Kayyali [48]; 8.5%, Chao Zou [49]; 11.29%; and M. Shariq [50]; 8%. The gain of 27% for both outdoor sun exposure and sea water exposure samples in 90 days indicates the delay in strength development of the specimens due to exposure to adverse climatic conditions. Thus, exposure to adverse climatic conditions can delay the strength gain in the early ages of concrete. Similar observation of a gain of 27% was seen in the outdoor cured samples of Al-Gahtani [46]. Further exposure to adverse climatic conditions could cause a detrimental effect on the compressive strength of concrete. Bushlaibi, et al. [15] found that the compressive strength of concrete decreases after 270 days of exposure to hot and arid climatic conditions. Thus, the strength gains or loss of concrete exposed to adverse climatic conditions is to be further studied while exposed to 270 days and more.

As a summary of the compressive strength tests for summer and winter, Table 12 outlines the percentage loss of strength of all combinations of effect of season, exposure and curing, compared to their respective control specimens.

Table 12:

Summary of damage Phenomenon Due to Exposure, Curing and Season of Casting w.r.t the Control Specimens

Sl.No	Exposure Condition	Curing Duration	Summer 30	Summer 90	Winter 30	Winter 90
1	Lab	0 days	52%	53%	34%	34%
2		3 days	34%	35%	13%	28%
3		7 days	28%	29%	8%	24%
4		28 days	20%	6%	0%	0%
5	Sun	0 days	68%	60%	-	45%
6		3 days	54%	48%	-	33%
7		7 days	50%	40%	-	27%
8		28 days	20%	30%	-	13%
9	Sea Water	0 days	42%	21%	-	19%
10		3 days	42%	23%	-	14%
11		7 days	22%	17%	-	13%
12		28 days	20%	15%	-	12%

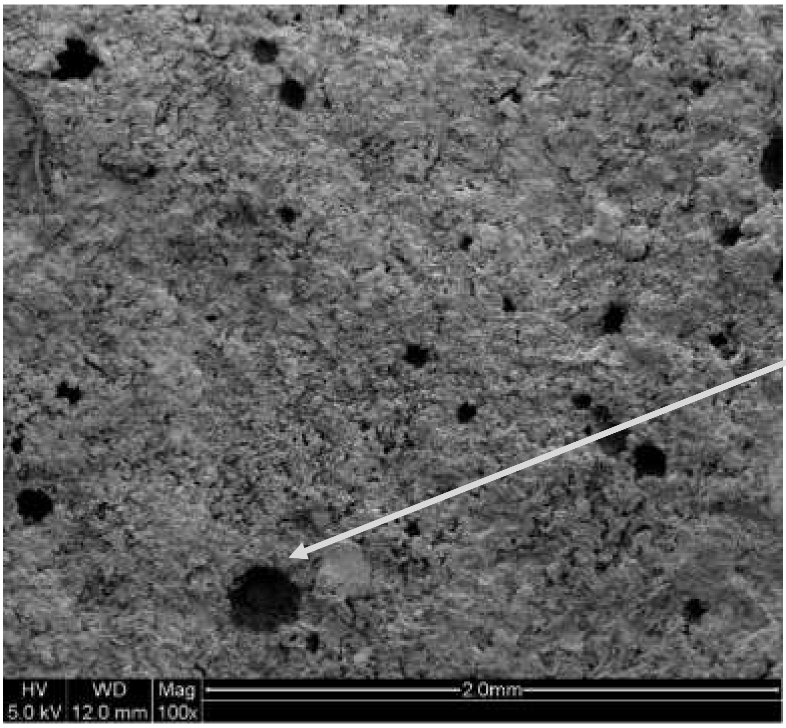
5.2 Micro-structural Analysis

The micro-structural analysis is done after 120 days of casting to aid and provide scientific evidence to loss in compressive strength of the specimens effected the most by harsh environmental conditions. The micro-structural analysis of the specimens is divided into three. Primarily, the concrete is observed through a Scanning Electron

Microscope (SEM). Then the concrete is analysed using XRD to identify the main constituents of the microstructure, qualitatively. The sample is then quantitatively analysed using XRF to identify the percentage of components in the structure. The SEM image is accompanied by the compressive strength of the sample to correlate the loss of compressive strength.

5.2.1 Scanning Electron Microscope Visual Examination

The SEM provides a visual representation of the micro-structure of concrete matrix. Although concrete is highly heterogenous in nature, the micro-structural elements assumes details of the degree of hydration depending on the size, shape and presence of various hydration products. The primary specimen examined was the control specimen of the winter cast, which has been nurtured in favourable initial and final curing conditions, along with 28 days of curing. The specimen which had reached a compressive strength development of 32 MPa, is used as a representation of optimally developed micro-structure of concrete. Figure 28-a shows the terrain of the fractured concrete sample to be viewed under the SEM at 100x magnification.

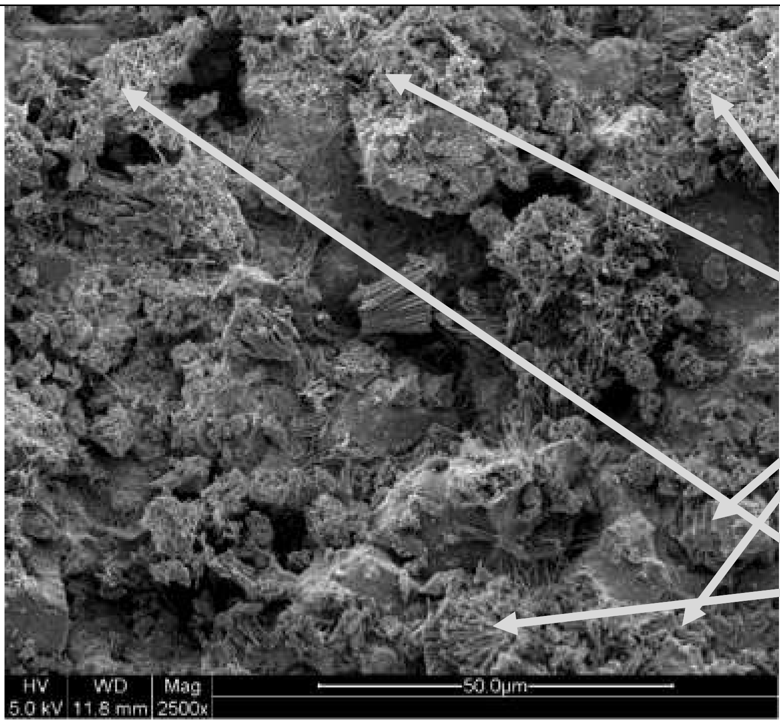


(a) BL90-28

f’90=32MPa

100x Mag

Air Voids



(b) BL90-28

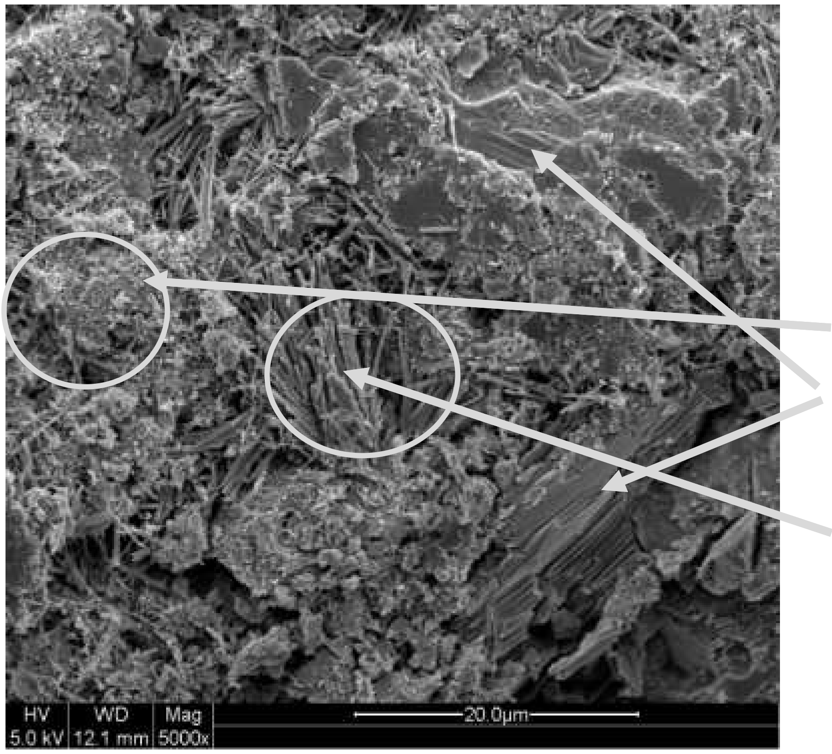
f’90=32MPa

2500x Mag

C-S-H

C-H

Ettringite



(c) BL90-28

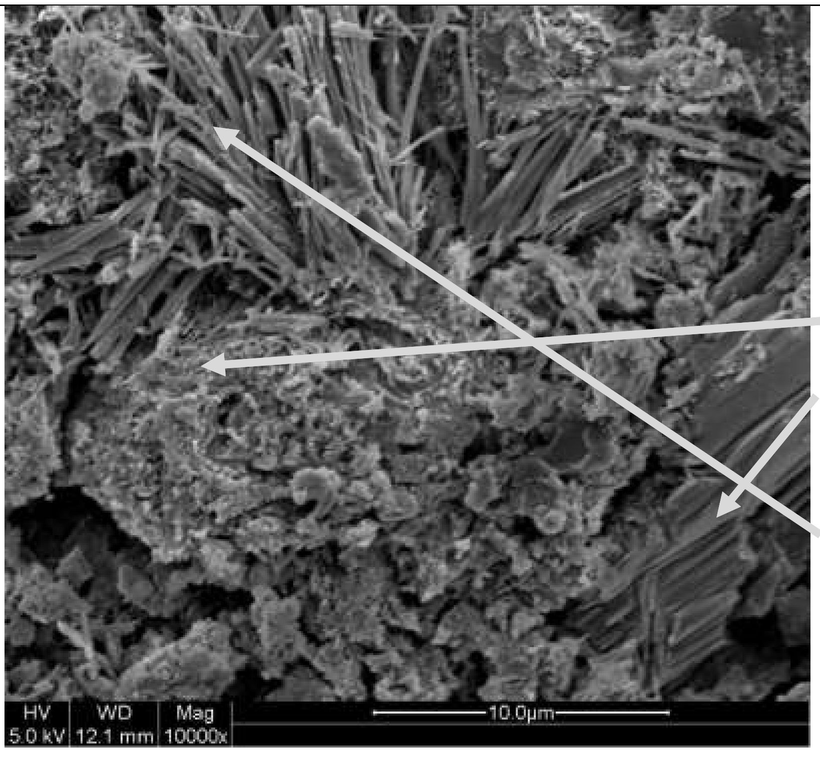
f'90=32MPa

5000x Mag

C-S-H

C-H

Ettringite



(d) BL90-28

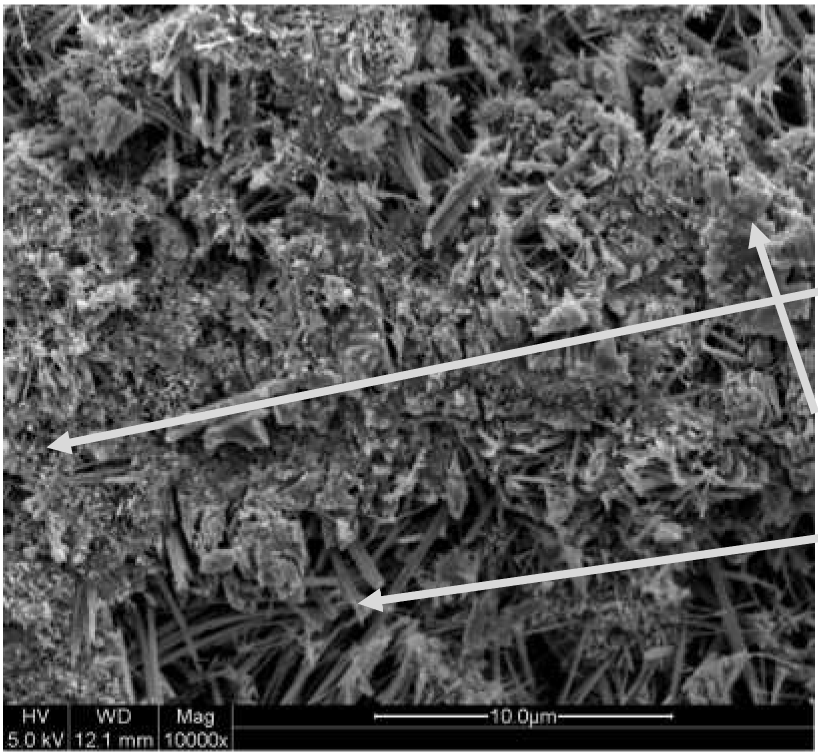
f'90=32MPa

10000x Mag

C-S-H

C-H

Ettringite



(e) BL90-28

f'90=32MPa

10000x Mag

C-S-H

C-H

Ettringite

Figure 27: SEM Images of Control Specimen

At this magnification, the air voids and the grainy particles of the cement and sand components are visible. Further magnifying the samples 2500x, Figure 27-b shows the terrain with the distributed particles hydration products. The needles of ettringite, the C-S-H matrix in the background, the CH platelets, grainy particles of sand and a more detailed look at the air voids are visible. It is revealed that all the hydration products of concrete are dispersed in equal proportions and the micro-structure seems to be densely packed with all the three major hydration products.

A magnification of 5000x shows the terrain of the micro-structure at 20 microns. The main component of the micro-structure that contributes to the strength of concrete, C-S-H is found in abundant in the background. The presence of 60% to 50% of well-formed and dense clusters of C-S-H is an evidence to the apparent increase in the compressive strength of the concrete. Water plays a major role in the formation of C-

S-H crystals thus, its presence in well cured concrete samples. The ettringite needles which helps in the Van-der-Vaal forces between the elements is also revealed to be in abundance. The length of the crystals in found to be 20 microns and with substantial widths as shown in Figure 28-d. The well-formed ettringite crystals signal towards the healthy mix of concrete, as the absence or ill-formed needles indicates the susceptibility of concrete to deteriorating effects such as sulphate attack and loss of strength [45]. The platelet like formations of CH which is a by-product of the reaction of C3S and C2S, is the component that contributes the least to the strength. Usually, CH occupies 20% to 25% of the concrete matrix and grow in the capillary pore space. The development of hydration products with 28 days of curing was observed by Khaliq and Javed [12] as shown in Figure 28. The research explains the formation of all hydration products such as C-S-H, CH and ettringite uniformly and giving a higher compressive strength. Continuous water curing for 28 days prevents the water in the crystalline structures of the hydration products from drying excessively.

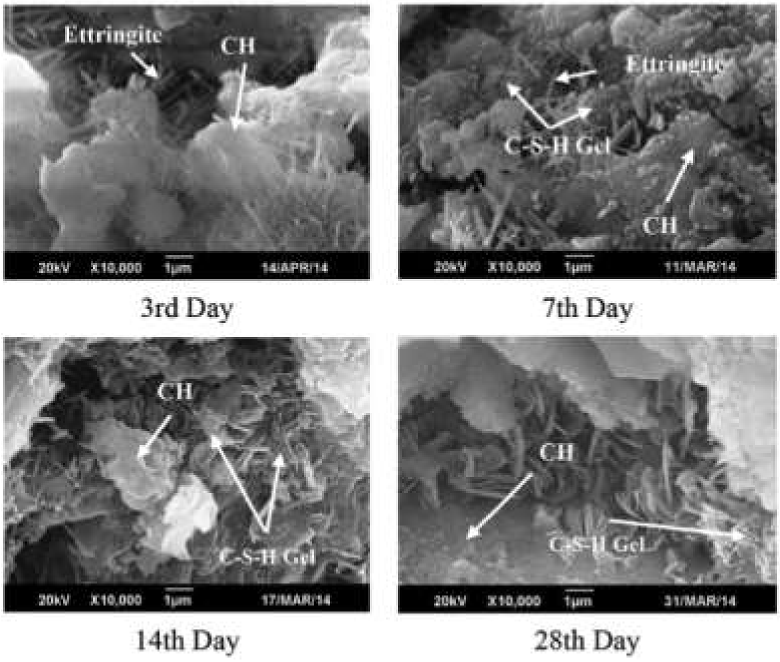
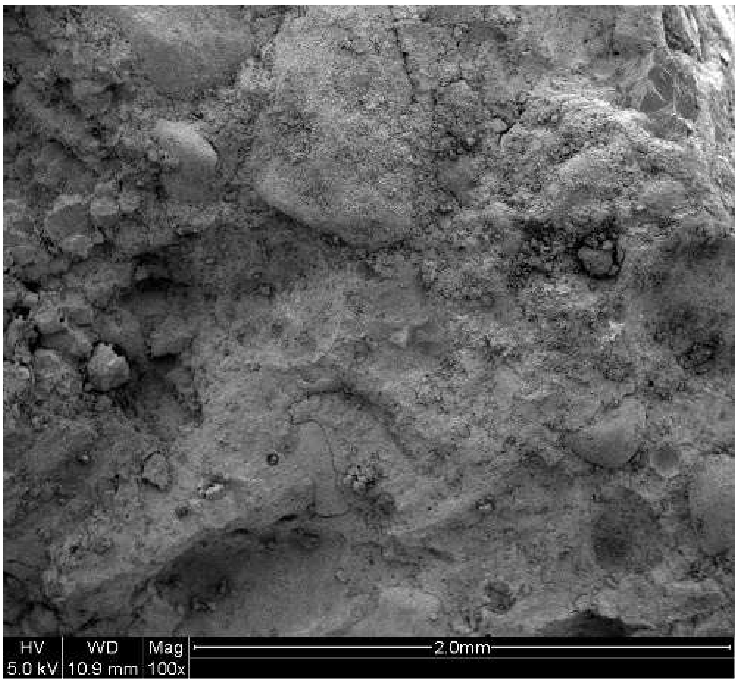


Figure 28: SEM images of 28 days cured specimens of Khaiq & Javed [29]

The hydration products in the micro-structure of outdoor sun samples of the summer cast appears to be completely different, when compared to the control specimen. Evaluating the microstructure explains the low compressive strength of 9.7 MPa in the outdoor sun samples of the summer cast. Figure 30-b shows the 100x magnified image of the zero cured sample. With zero hydration of the cement paste after hardening, the 5000x magnified image of the zero cured sample shows the clinker shaped particles of CH which appears like the structure of un-hydrated clinkers of cement (Figure 30). The clusters of un-hydrated clinkers of portlandite, as explained by some researchers [2] [45], is formed due to the unavailability of water for proper hydration of concrete.

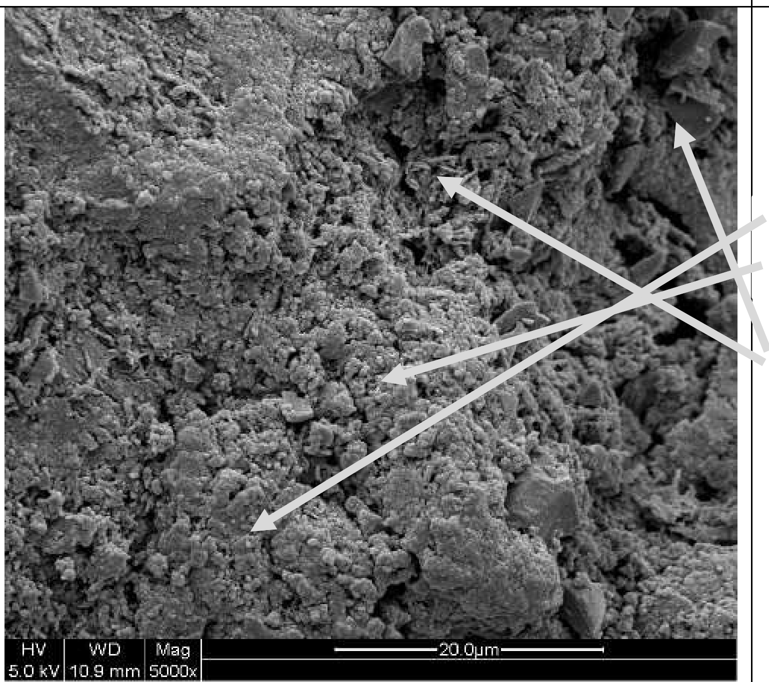


(a) AS90-0

f’90 = 9.7 MPa

100x Mag

Zero days curing



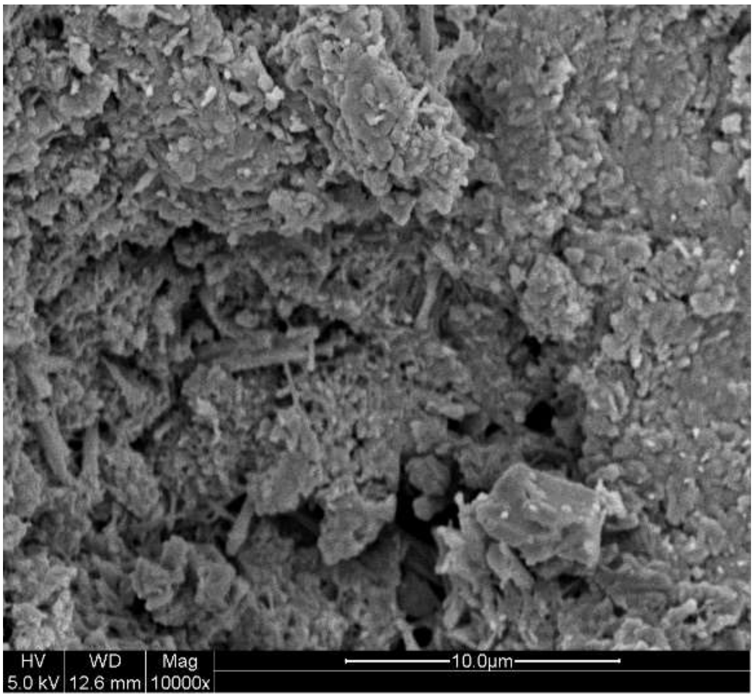
(b) AS90-0

f’90 = 9.7 MPa

5000x Mag

Un-hydrated Clinker

C-H

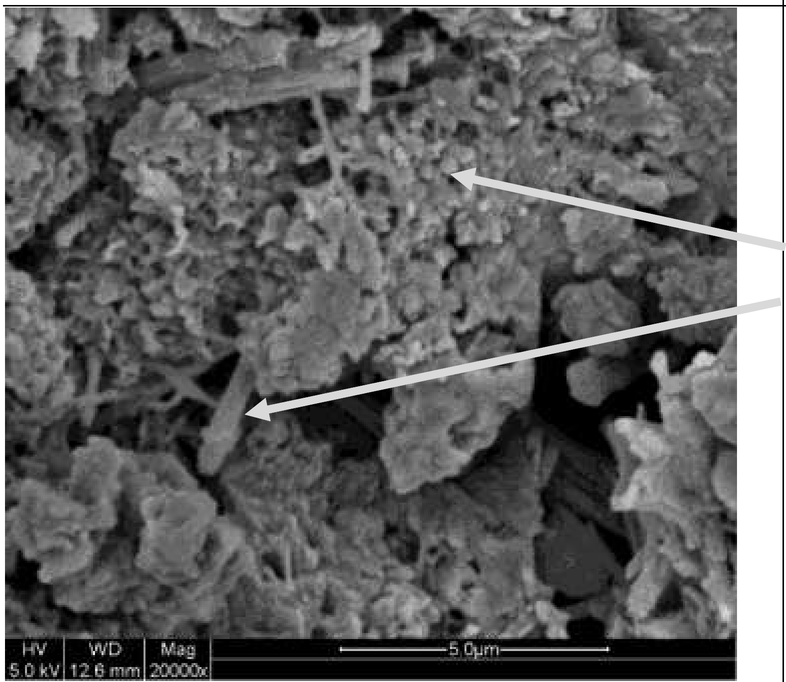


(c) AS90-0

f'90 = 9.7 MPa

10000x Mag

Zero days curing



(d) AS90-0

f'90 = 9.7 MPa

20000x Mag

C-S-H

Ettringite

Figure 29: SEM Images of zero cured sun samples

Though majority of the micro-structure is made up of un-hydrated clinker like particles, there appears to be platelets of CH and ettringite in the background. Figure

30-d shows the presence of CH platelets and second generation of ettringite needles, which are formed when the water from ettringite dries out. There isn't much visual evidence to the appearance of C-S-H which explains the excessive loss of strength in the concrete sample.

The un-hydrated clinker particles have lower bonding capacity than well hydrated C-S-H and ettringite, thus, reducing the concrete strength. This unproportioned distribution of hydration products is mainly due to the lack of water for hydration. The existing water in the mix design had evaporated due to the exposure of the concrete to severe heat. The hydration products of this specimen would have been formed while mixing the concrete during the first 48 hours. Due to the excessive loss of water from the mix and the lack of external water for hydration, the strength gaining hydration products such as C-S-H and ettringite have changed their crystalline structure and disappeared from the concrete matrix as observed by Khaliq and Javed [12]. (Figure 29) shows the micro-structural developments of concrete with zero moist curing over the course of 28 days [12]. It is evident that the hydration products were formed in the initial period and later disappears due to the lack of water.

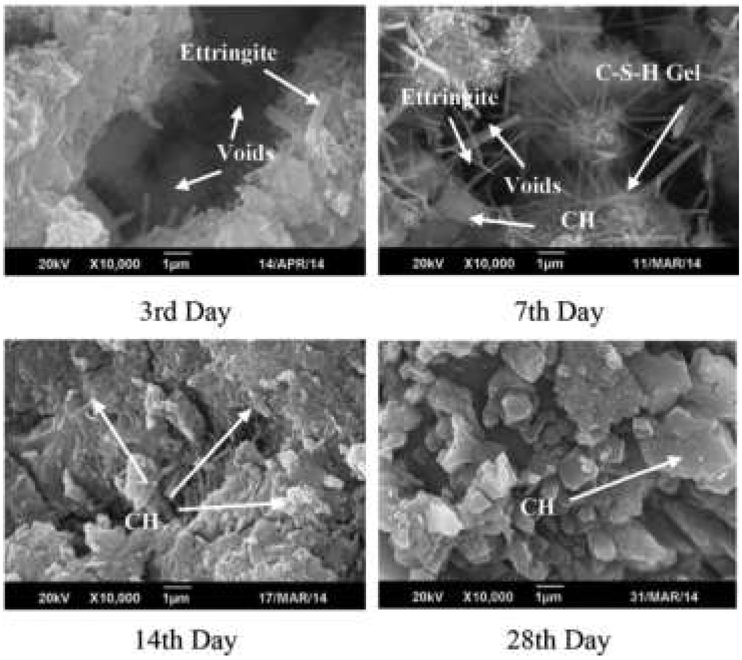
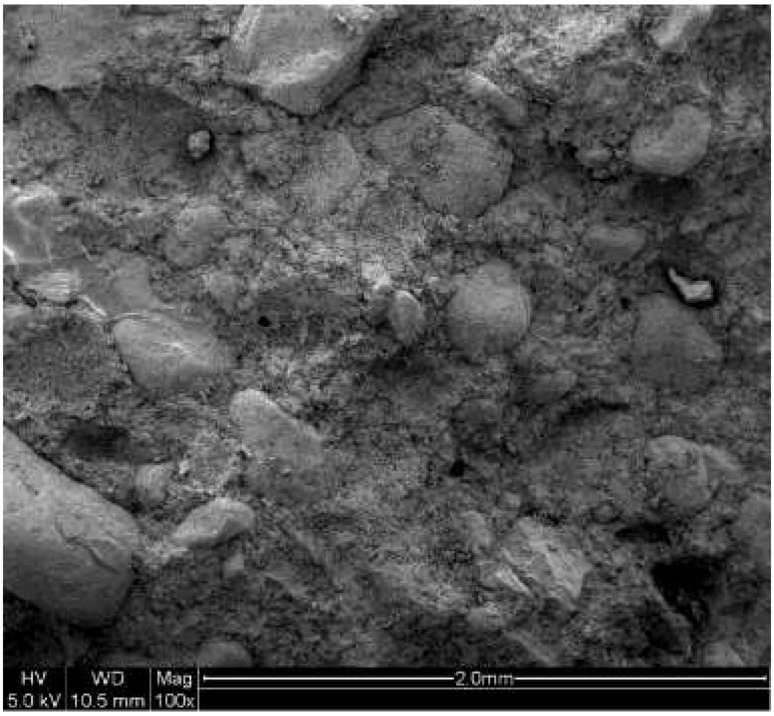


Figure 30: SEM images of zero cured specimens as observed by Khaliq & Javed

The minimal curing duration of 3 days and 7 days also effects the outcome and structure of the hydration products of concrete. As shown in Figure 31, in the micro-structure of concrete cured for 3 days with moisture and then exposed to outdoor sun (A-S90-3), the hydration products are different compared to the control specimen. The specimen is recorded to have a compressive strength of 12.5 MPa. The 5000x magnified image shows the formation of C-S-H clusters in the background, CH platelets, un-hydrated clinker particles and second generation of ettringite formations.

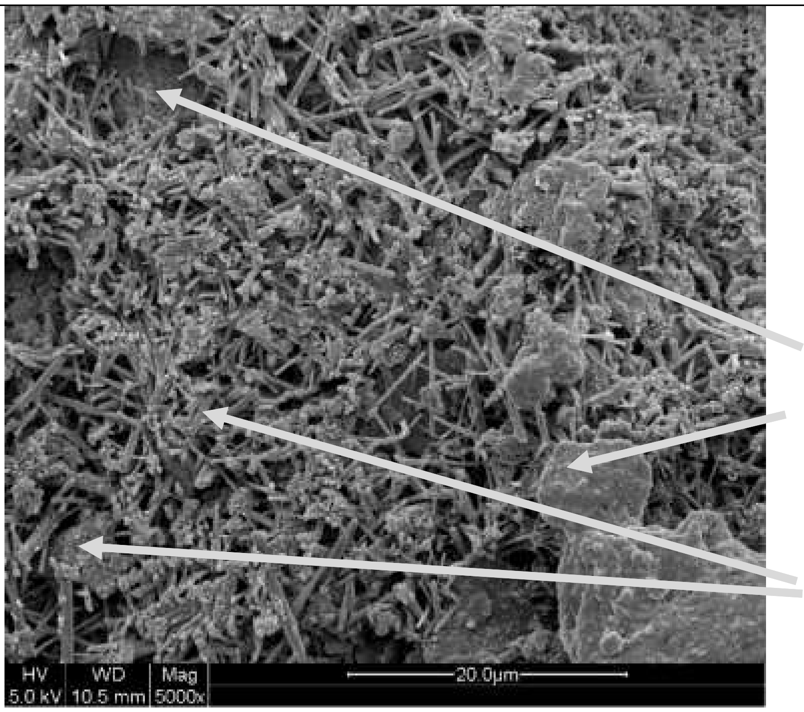


AS90-3

f'90 = 12.5 MPa

100x Mag

3 days curing



f'90 = 12.5 MPa

5000x Mag

AS90-3

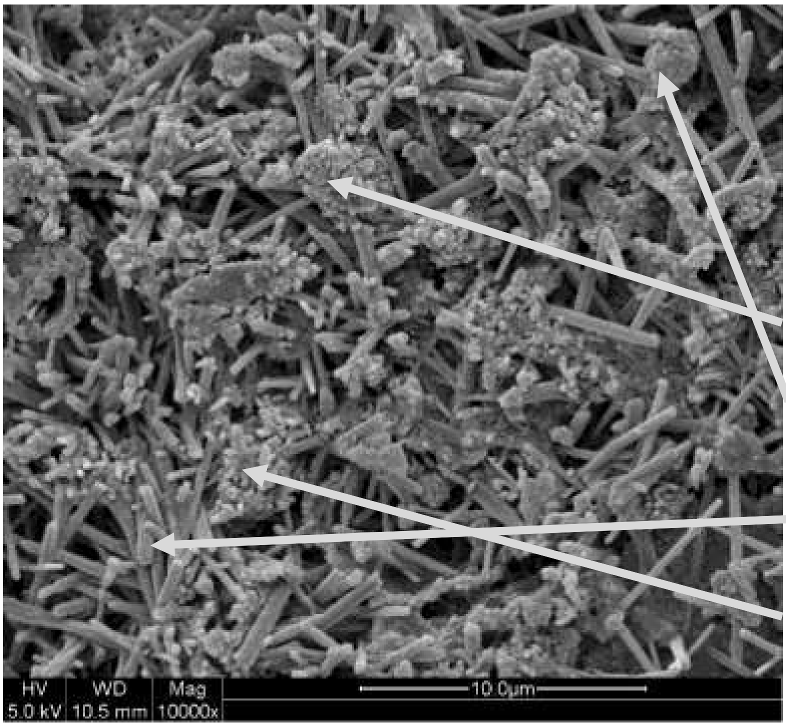
3 days curing

C-S-H

CH

2nd generation ettringite

Unhydrated clinker



f'90 = 12.5 MPa

10000x Mag

AS90-3

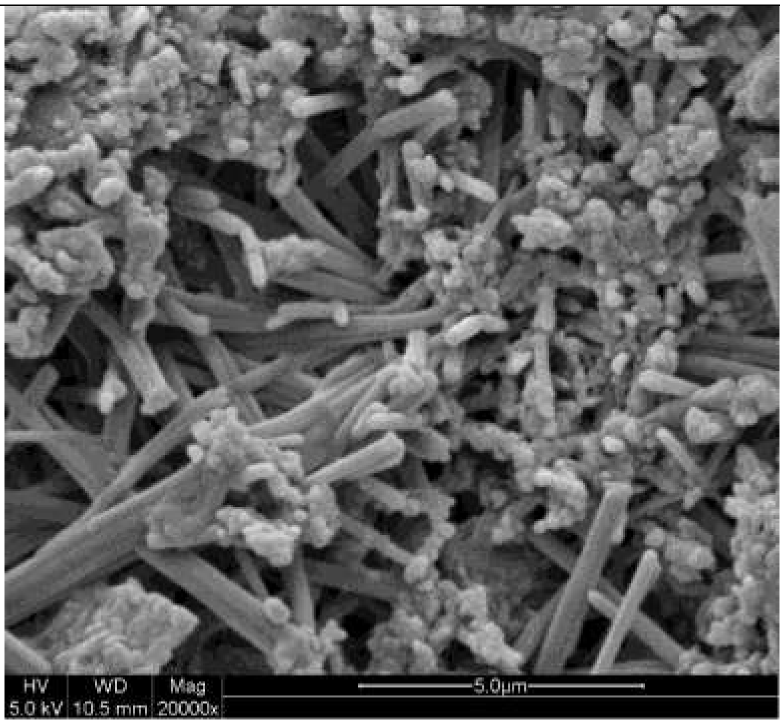
3 days curing

C-S-H

CH

2nd generation ettringite

Unhydrated clinker



f'90 = 12.5 MPa

20000x Mag

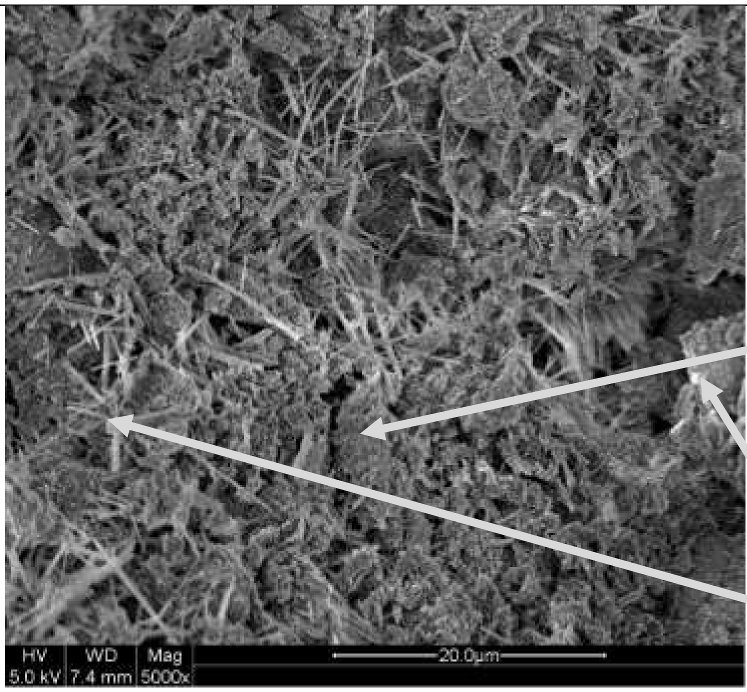
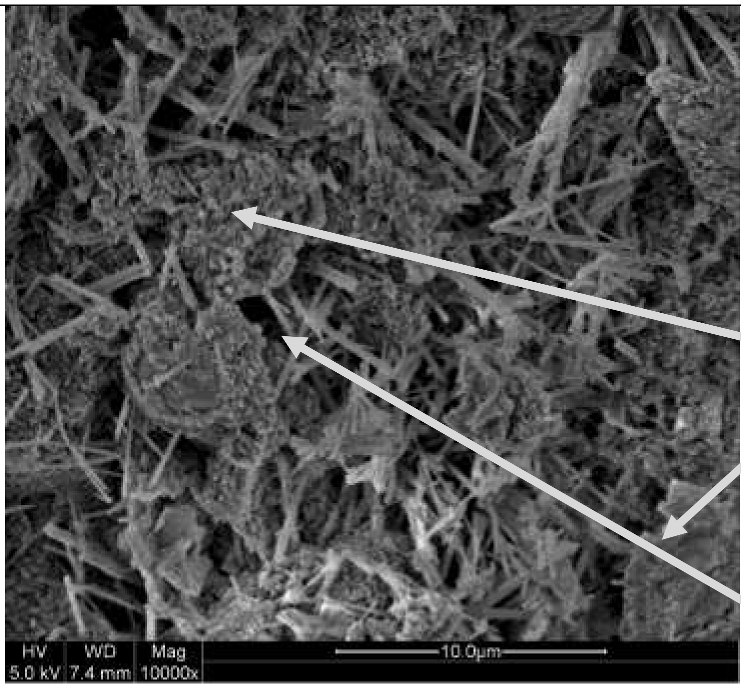
AS90-3

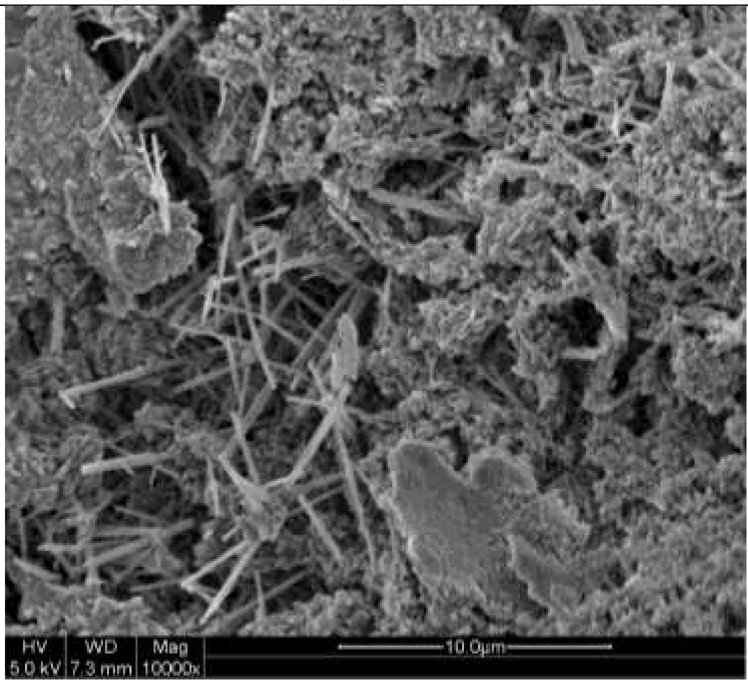
3 days curing

Figure 31: SEM Images of 3 days cured specimen

The C-S-H cluster isn't dense enough to provide adequate strength to the concrete and the CH platelets are accompanied by un-hydrated clinker. The most interesting phenomenon on the 3 days cured samples is the small sized ettringite needles. Due to the excessive drying of water from their crystal lattices, the ettringite loses water from its crystal lattices and forms second generation ettringite, which is smaller and thinner in size [45]. Thus, it suggests that 3 days of water curing is not enough to complete hydration of the micro-structure of concrete. The un-hydrated clinker particles also point towards the lack of water in the micro-structure.

The 7 days cured specimen had a micro-structure that resembled the 28 days cured sample. Figure 31 shows the micro-structural terrain of specimen cured for 7 days before exposure to hot and dry atmospheric conditions. The C-S-H cluster is more densely packed in the background, and the other hydration products - CH and ettringite - are more evident in the visual inspection of the sample. The presence of un-hydrated clinker particles is less and negligible. The healthy appearance of the micro-structure helped the concrete reach better strengths of 14.3 MPa. The thickness of the ettringite needles appears to be lesser than the ettringite needle formations of the 28 days cured sample. These images indicate that 7 days curing of the sample is necessary to form the basic hydration products in concrete, yet, it isn’t enough to develop the compressive strength to the target required.

	**AS90-7** f'90 = 14.3MPa 5000x Mag 7 days curing C-S-H C-H Ettringite
	**AS90-7** f'90 = 14.3MPa 10000x Mag 7 days curing C-S-H C-H Ettringite



f'90 = 14.3MPa

10000x Mag

Figure 32: SEM Images of 7 days cured Specimen

5.2.2 X-Ray Diffraction (XRD) Analysis

To validate the results of the SEM visual micro-structure analysis, the outdoor sun concrete samples of the summer and winter cast were tested by XRD to determine the qualitative composition of the compounds and XRF analysis to determine the qualitative examination of the percentage of compounds in the micro-structure. The major peaks found in the XRD analysis were similar for all the samples of concrete as there wasn't any addition of foreign materials into the mix design. The intensity of the peaks indicate the prominence of these compounds in the micro-structure. The peaks of all the sun exposure samples for different curing durations are shown in Figure 33. Only the peaks relevant to the study of this thesis are mentioned in the graphs. The relevant peaks were recognized to be of portlandite ($Ca(OH)_2$), dolomite, ($CaMg(CO_3)_2$), silica-dioxide (SiO_2) and minor peaks of compounds which were irrelevant for the comparison of the degree of hydration. The only difference in the peaks between all the samples were the intensity of the peaks. Even though calcium hydroxide is found in both C-S-H and CH, portlandite is seen to be an indication of the formation of CH, as calcium hydroxide is the major component of CH. The presence of C-S-H is indicated by the presence of silica-dioxide as it is the major component of C-S-H. The presence of ettringite is measured by the percentages of magnesium oxide (MgO) and aluminium oxide (Al_2O_3) as they are the major components of ettringite crystals, as explained in the introduction. It can be observed from Figure 33 that as curing duration increases; the intensity of the C-S-H peak is higher.

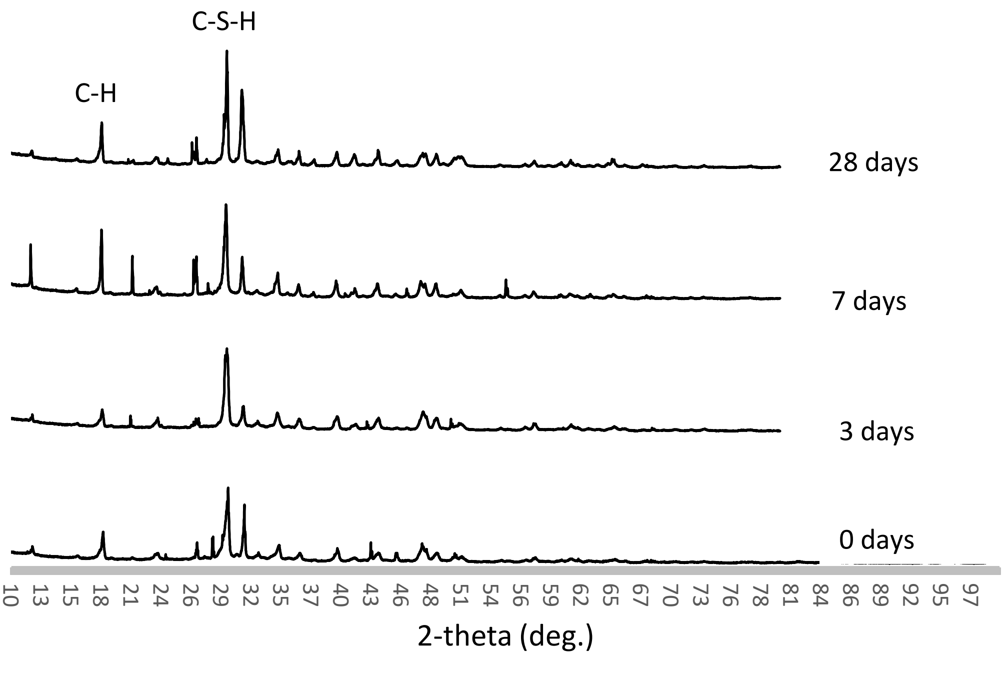


Figure 33: Peaks of X-ray Diffraction of Outdoor Sun Specimens for different curing durations

5.2.3 X-Ray Fluorescence (XRF) Analysis

After the indication of the various compounds in the concrete, to measure the percentage of their presence XRF analysis was done on the outdoor sun samples of the summer and winter cast. Table 15 shows the composition analysis of the concrete samples with moist curing duration of 0 days, 3 days, 7 days and 28 days.

Table 13:

Percentages of constituents by XRF For Summer and Winter Specimen

	0 days cured		**3 days cured**		**7 days cured**		**28 days cured**	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
CaO %	74.2	74.1	69.6	69.4	65.7	68.5	61.8	67.4
SiO2 %	17.2	15.6	20.1	18.9	20.3	19.8	30	21
Fe2O3%	5	4.3	5.5	4.4	5.3	4.4	3.6	4.8
SO3%	2.4	3.3	2.9	3	3	3	3.4	3.1
MgO%	2.2	1.9	1.8	1.9	1.7	1.9	1.4	1.1
Al2O3%	1.7	1.5	1.7	1.5	2	1.6	2.5	1.6

The trend in results were such that as curing duration increases, The CaO percentage decreased and the SiO_2 percentage increased. This indicates the reduction in CH and replacement of C-S-H as the moist curing duration increases. To compare the quality of hydration, the CaO/SiO_2 ratio is considered with different curing durations. A lower ratio describes the equal proportional distribution of the two hydration products and vice-versa. Figure 34 describe the reduction in CaO/SiO_2 ratio as the curing duration increases.

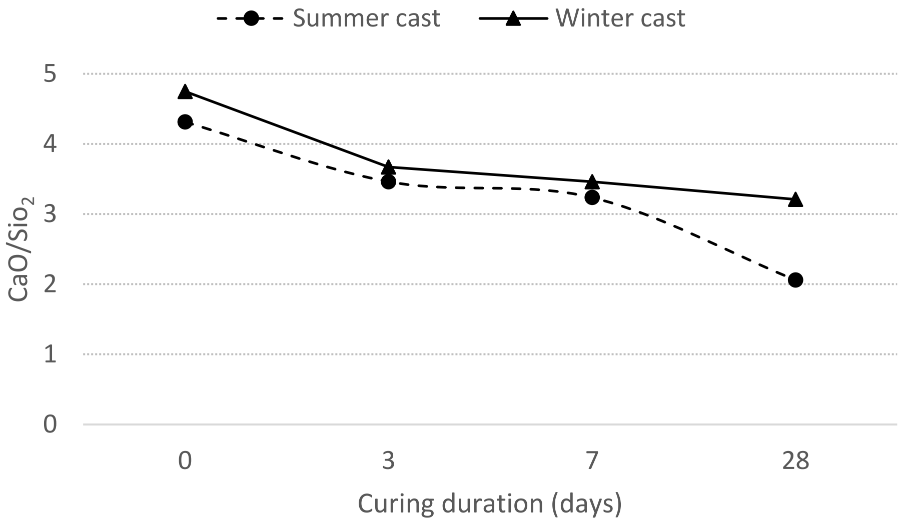


Figure 34: Reduction in CaO/ SiO_2 Percentage

Similar findings were reported by Khalid and Javed [12] where the CaO/SiO_2 ratio was 17.2 for uncured samples and 2.38 for water cured samples. The increase in CaO percentage is due to the abnormality in the production of CH. It was reported that the presence of CaO is attributed towards the unavailability of internal water that would have converted it into $Ca(OH)_2$, which is a source of unsoundness in concrete. The lower ratio of CaO/SiO_2 signified the appropriate quantities of C_3S and C_2S in the micro-structure, leading to good development of strength and durability [12]. The increase in Al_2O_3 and MgO as curing duration increases indicates the increase in the formation of ettringite crystals similar to the findings of SEM images. The variation in XRF results of the winter cast are minimal as the increase in compressive strengths are less significant due to the favourable initial curing conditions. Though SEM imagery is an approximate representation of concrete micro-structure, the XRF analysis facilitates the findings of the SEM image analysis. Even after performing the three micro-structural analyses, due to concrete being highly heterogeneous in nature, a solid conclusion cannot be attained before repeated tests as well as performing EDS analysis. Table 14 summarises the important findings of the micro-structural analysis of concrete with different curing durations. As the moist curing duration increases, distribution of the important hydration products of C-S-H, CH, and ettringite increases. As curing increases, the C-S-H clusters are more, the ettringite crystals are well formed, and thick un-hydrated clinker particles reduces, and the compressive strength increases. The CaO/SiO_2 ratio decreases as curing duration increase and the percentage of Al_2O_3 and MgO increases, indicating the increase in ettringite formation.

Table 14:

Summary of Micro-structural Analysis

Curing Duration	**CaO/SiO_2**	**Micro-structure remarks**	**Strength (MPa)**
0 Days	4.3	High Un-hydrated clinker, High CH and low C-S-H, presence of low 2nd generation ettringite	9.7
3 days	3.5	Low Un hydrated clinker, Low C-S-H, High CH, small and under formed 2nd generation ettringite.	12.5
7 days	3.2	Evident formation of C-S-H dense cluster, CH platelets and ettringite needles of good structure.	14.3
28 days	2.1	Healthy micro-structure with dense C-S-H clusters, well-formed CH plates and thick ettringite needles.	32

5.3 Chloride Content Examination

The chloride content of the concrete samples give an idea about the pore structure of the concrete, as the absorption of chlorine into the concrete depends on the pore structure of the matrix [33]. The chlorine content of the concrete is crucial in finding the corrosion initiation time of concrete. If the chloride content increases beyond the threshold chloride value, the corrosion in the steel rebars are initiated. The chloride content of the concrete with different curing durations exposed to various exposure conditions, for the summer and winter cast is shown in Table 17. The acceptable chloride content of chloride according to Qatar Construction Specifications (QCS) 2010 is 0.3% of the cement content of concrete. The high values of chloride content in the sea water samples are due to the high exposure concertation to carry out accelerated tests.

Table 15:

Chlorine Content of Specimens

Summer Cast			Winter Cast		
Curing Duration	**Name**	**Chloride Content**	**Curing Duration**	**Name**	**Chloride Content**
0 days	AS90-0	1.18	0 days	BS90-0	0.4
3 days	AS90-3	0.52	3 days	BS90-3	0.26
7 days	AS90-7	0.52	7 days	BS90-7	0.21
28 days	AS90-28	0.39	28 days	BS90-28	0.12
0 days	AL90-0	0.39	0 days	BL90-0	0.3
3 days	AL90-3	0.34	3 days	BL90-3	0.21
7 days	AL907	0.26	7 days	BL907	0.26
28 days	AL90-28	0.21	28 days	BL90-28	0.17
0 days	AW90-0	4.21	0 days	BW90-0	2.15
3 days	AW90-3	1.84	3 days	BW90-3	2.1
7 days	AW90-7	1.62	7 days	BW90-7	1.66
28 days	AW90-28	1.53	28 days	BW90-28	1.58

It is observed that the highest chloride content is in the sea water samples with zero curing durations. As curing duration increases, the chloride content decreases. As seen in Figure 35, for the summer cast, the sea water exposed sample has a chloride content of 4.21% of the cement content. This is due to the exposure to 30% saline solution soon after casting, before the capillary pores of the concrete is properly formed. During the initial curing period of 48 hours, the exposure to hot and dry exposure made the concrete more porous, thus accelerated the ingress of chloride onto the concrete. The subsequent curing durations of 3 days, 7 days and 28 days had a chloride content of 1.84%, 1.62% and 1.52%. Due to the high concentration of chloride in the sea water, and the adverse initial exposure, even the 28 days cured sample had exceeded the acceptable limit. The outdoor sun exposure samples also had a high chloride content due to the ingress of chlorine from the saline rich soil of Qatar. The high values of 1.18%, 0.52% and 0.52% for 0 days, 3 days and 7 days exceeded the acceptable limit of chloride content. Further, the high temperatures to which the outdoor sun concrete was exposed to, increased the chloride ingress. According to a study by Hussain, et al. [51], the chloride content in concrete can increase up to 5 folds when exposed to temperatures from 20ºC to 70ºC. The chloride content of the specimen exposed to laboratory conditions were in the acceptable limit for all curing durations.

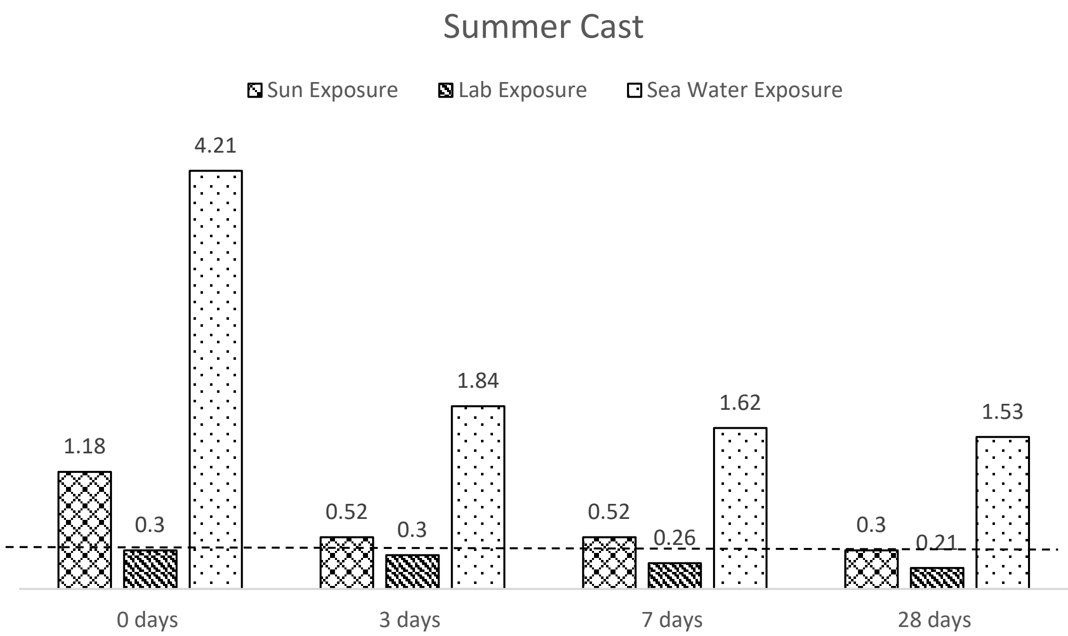


Figure 35: Chlorine content of the summer cast

The winter cast samples had a lower chloride content compared to the summer cast. Due to the favourable exposure conditions during the first 48 hours of concrete casting, the pore structure of the concrete was well formed and decreased the chloride ingress onto the concrete. The sea water exposed concrete with 0 curing duration had a chloride content of 2.15% of the cement content. Following curing by 3 days, 7 days and 28 days, the chloride content was 2.1%, 1.66% and 1.58% for the specimens exposed to 30% saline solutions. All these values were lower than the summer cast due to the comparatively well-formed pore structure of the winter cast. The chloride content of the outdoor sun exposed sample with zero curing was 0.4%, the only value above the acceptable chloride content. All other values of chloride content for the outdoor sun and laboratory samples with different curing durations were in the acceptable range of chloride content.

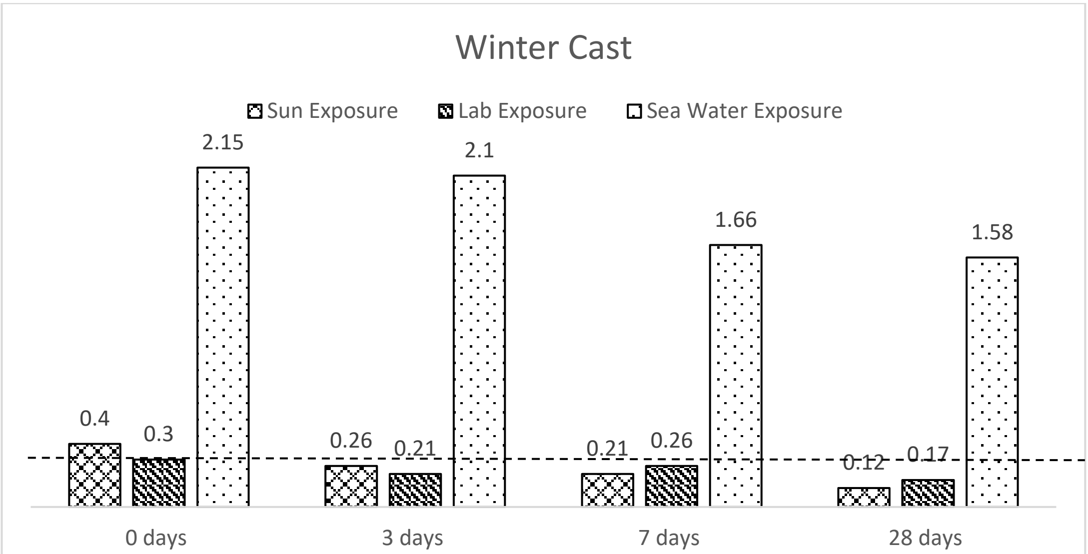


Figure 36: Chloride Content of the Winter Specimens

The lower values of chloride content in the winter cast reflect the nature of the pore structure when casted in adverse climatic conditions and in favourable conditions. The increase in chloride content as the curing duration increases also shows the refinement of pore structure as concrete hydration proceeds. Similar results were reported by Hansson et. al. [47], reporting that test specimens in laboratory atmosphere three days after casting, causes a reduction of 2 to 3 times in the critical chloride concentration and in the initiation time, compared to specimens that has been hardened in 100% RH for 31 days. As reported by Khanzadeh, et al. [52], wet curing extension decreases the difference between initial and long-term diffusion coefficients of chloride due to improvement of concrete cover quality and blocking the ingress of aggressive substance in initial ages. The reduced values of chloride in concrete prevents or delays the corrosion of reinforcement steel in the Arabian Gulf.

CHAPTER 8: CONCLUSION & RECOMMENDATIONS

The effect of curing on the performance of concrete casted during winter and summer, further exposed to varied exposure conditions were experiment. Comparison was made between concrete exposed to nominal initial and final curing conditions and adverse initial and final curing conditions. The compressive strength loss due to detrimental curing practices, its correlation to the micro-structural properties and the absorption of chloride were investigated.

- Concrete to be cast during summer and winter should have different mix designs to compensate for the loss of water due to climatic variations.
- Concrete cast in summer and exposed to outdoor sun without any curing was 60% weaker; and the ones cured for 28 days and then exposed to sun was 20% weaker, than the concrete cast and cured in optimal curing conditions for 28 days, outlining the damage caused by exposing fresh concrete to extreme sun and heat in the first 48 hours and neglecting the initial curing process.
- Concrete cast in winter and then exposed to extreme heat of the outdoor sun was 45% weaker with zero curing, and 13% weaker while cured for 28 days, than concrete cast and cured nominally; expressing the importance of moist curing even though the casting temperatures of concrete is favorable.
- Casting and curing concrete during summer reduces the strength of concrete by 48% compared to casting and curing in winter, along with 28 days of curing.
- The absence of C-S-H clusters, ettringite needles, well-formed CH platelets and the over population of un-hydrated clinker particles in concrete with zero curing and adverse exposure, fortifies the reason for loss of strength of concrete being the lack of proper hydration in concrete. Formation of second

generation ettringite and ill-formed hydration products in the 3 days cured concrete emphasizes the need for prolonged curing durations for complete hydration.

- Higher concentration of chloride in concrete cast in summer and neglecting the curing process spreads light on the lack of durability of concrete in saline environments and accelerated reinforcement corrosion.
- The results and conclusions in this research emphasize the need for extended moisture curing for at least 28 days such that concrete reaches its target strength. Maximum effort is to be taken to cast concrete while the environmental factors are favorable to concrete. The fresh concrete cast should be covered and the moisture in fresh concrete is to be restricted from drying.
- Since the hydration of concrete is a series of chemical reactions that is highly influenced by the presence of water, curing of concrete plays a major role in enhancing the strength and durability properties of concrete.
- Similar research on the properties of concrete is recommended to be carried out on concrete with chemical admixtures such as super-plasticizes and sulphate resistant chemicals. The influence of cement replacements such as Fly-ash, Silica fume and Slag content in concrete on the curing procedure is to be examined further. The effectiveness of other curing methods such as covering with wet burlap, evaporation inhibiting agents and internal curing agents are to be further studied and compared with moist curing.

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