Prediction Of 28 Days Compressive Strength of High Slag Concrete by Establishing Accelerated Oven Curing Regimes for Rapid Quality Control

Sudin Mohan[1,*], Mohammad Ajma[2], Michal P. Drewniok[3]
[1] Qatar Beton LLC, Doha, Qatar
[2] Doha Technical Laboratories, Mesaieed, Qatar
[3] School of Civil Engineering, University of Leeds, Leeds, UK
***Corresponding author,E-mail: sudin.m@hotmail.com**

Abstract

High Slag Concrete (HSC) offers substantial benefits in terms of durability and reduced carbon footprint, but its late strength gain delays accurate 28-day strength prediction from early strength. This study aims to develop accelerated oven curing regimes to predict 28-day compressive strength of HSC accurately. The research focuses on the fundamental question of whether the application of accelerated curing at specific temperatures would help estimate High Slag Concrete's long-term strength. To achieve this, a series of concrete specimens were subjected to accelerated oven curing at 50°C and 70°C. The compressive strength development was observed and correlated with standard curing conditions. Additionally, the hydration kinetics of the cementitious paste under these elevated temperatures were examined by using the Isothermal calorimetry method. This research will produce a predictive model correlating accelerated curing data with 28-day strength. The findings ofthis study will provide a reliable method for estimating the strength of High Slag Concrete at an early age, enabling more efficient construction planning.

Keywords: Calcium Silicate Hydrate Gel (C-S-H). Calcium Hydroxide (Ca $(OH)_2$). Calcium Alumina (Aft). Monosulphur Calcium Sulphoaluminate Hydrate (AFm). Delayed Ettringite Formation (DEF)

1. Introduction

There was a time when Portland cement (OPC) was considered the sole binding material in concrete. The Portland cement exhibits higher carbon emissions in traditional concrete and it became a persistent challenge before engineers and architects, therefore the concrete technologists , researchers, contractors etc. were looking for alternative materials to replace Portland cement and addition without losing the properties of cement. Supplementary cementitious materials in concrete like Pulverized Fly Ash (PFA), Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF), etc. were introduced and widely used from the mid of 20th Century in the construction industry for a variety of reasons including cost-effectiveness, enhanced durability properties, and its lower carbon dioxide emissions.

GGBFS is a by-product of iron production in blast furnaces and is similar to cement which has hydraulic properties(1). Compared to OPC, GGBFS has lower embodied carbon, approx. 1/10 compared to of 79.6 Kg CO_2e/tonne (2). Concrete with cement as a binder, is a fundamental building material used globally in the construction industry, therefore replacing cement with GGBFS is considered to be one of the strategies to decarbonise cement and concrete. It is possible to reach higher replacement rate (36%-80% (3)) at the same time improving ability to resist aggressive agents from penetrating into concrete(4).

In the precast industry, it is extremely difficult to achieve very early age strength especially within 24 hours from pouring for a high GGBFS concrete mix (5). The mold turnover is the main profit factor for precast concrete industry; therefore, it is mandatory to facilitate accelerated curing method in order to achieve the desired compressive strength for de-shuttering and lifting the precast elements. The higher the curing temperature, the faster the heat of hydration of the concrete (6), which is sufficient enough to produce a significant increase in the early age strength of slag cement concrete (7).

Compressive strength is one of the most critical mechanical properties that determine the load-carrying capacity and durability of concrete (8,9) . The strength of concrete is assessed based on 28 days results. The reason to consider the 28 days compressive strength as a parameter is based on the maturity of the concrete. The strength development of concrete depends on both time and temperature. The concrete strength is a function of the summation of product of time and temperature. This is called maturity of concrete.

$$\textbf{Maturity} = \Sigma\ \textbf{(time x temperature)}$$

The temperature is taken from an origin lying between -12 and -10°C because hydration of the concrete stops when the temperature of the concrete reaches above -12°C. However, -11°C is usually taken as a datum line for calculating maturity. The curing temperature of concrete specimen is 20°C±2 (10). For instance, A fully matured concrete cured at 18oC for 28 days will be 19,488oC h, however in standard calculations, the maturity of the fully cured concrete is taken as 19,800oC h, this discrepancy should be attributed to the datum value used for the calculation. Hence, compressive strength at 28 days is considered in the industry as a standard to determine the mechanical property of the concrete (11). As a rapid quality control procedure Its crucial for concrete Quality Control Engineer, to predict desired strength at early age. According to the maturity model using OPC, cube strength results should achieve 46% of characteristic compressive strength in 3 days and 70% in 7 days (12). This assures that the cube will achieve desired compressive strength in 28 days. Whereas in the case of mixes with higher percentage of GGBFS etc., the slower the early strength gain compared to OPC due to reduced availability of CaO in (5). Nevertheless, slag cements exhibit more strength development at later stages(13). The reduced availability of CaO in GGBFS is a key factor for slowing down the hydration process(5) By increasing the temperature during the curing time, we can increase the early age strength, so with increasing the GGBFS content and decreasing the embodied carbon, we might achieve satisfactory early age strength. Nevertheless, there are no models predicting long term strength for concretes with high GGBFS exposed to high temperature curing. Knowing the relationship between early age and 28 days compressive strength for concretes with high OPC replacement with GGBFS cured in high temperatures allow precast concrete producers to optimise their production with minimising associated embodied carbon.

2. Literature Review:

Mixes that contain GGBFS, particularly in low ambient temperature conditions, demand an extended period of curing in order to achieve sufficient strength development (14). Regourd states that the determined activation energy for slag cements exhibits a higher value compared to the activation energy of their corresponding OPC, specifically 50 and 46 J.mol-1 respectively (15). Therefore, thermal treatment is advantageous for slag cement as it serves as an efficient source of activation energy for the hydration process of slag, thus it can be regarded as a latent cementitious material as specified above.

When GGBFS is mixed with OPC, the suspension of slag is activated by the elevated pH of the solution, which is attributed to the presence of calcium hydroxide and alkali ions in the pore solution. Both the clinker and the slag undergo reactions simultaneously, resulting in the formation of calcium silicate hydrate (C-S- H), which contributes to the development of strength. The hydration process of GGBFS generally occurs more slowly compared to Portland cement. Furthermore, during the initial stages of hydration, slag can partially function as an inert filler. This filler effect enhances the nucleation and growth of C-S-H by increasing the effective water-to-cement ratio and providing additional nucleation sites (16).

Enhancing the basicity of slag results in increased hydration of the slag over a specific time period. However, higher replacement levels result in decreased slag hydration, partly due to the reduced availability of portlandite caused by the lower cement content. For comparison, over 80% of the cement in each system had hydrated after 7 days(17).

The degree of C_3S hydration increases with the addition of slag after 1 and 3 days; however, over a longer period, it remains comparable to that without slag addition. This phenomenon is thought to result from the crystallization of calcium silicate hydrate (C-S-H) on the slag particles (Fig 1). Additionally, the reduction in calcium ion concentration in the liquid phase plays a prominent role, especially in the case of very finely ground slag.(17)

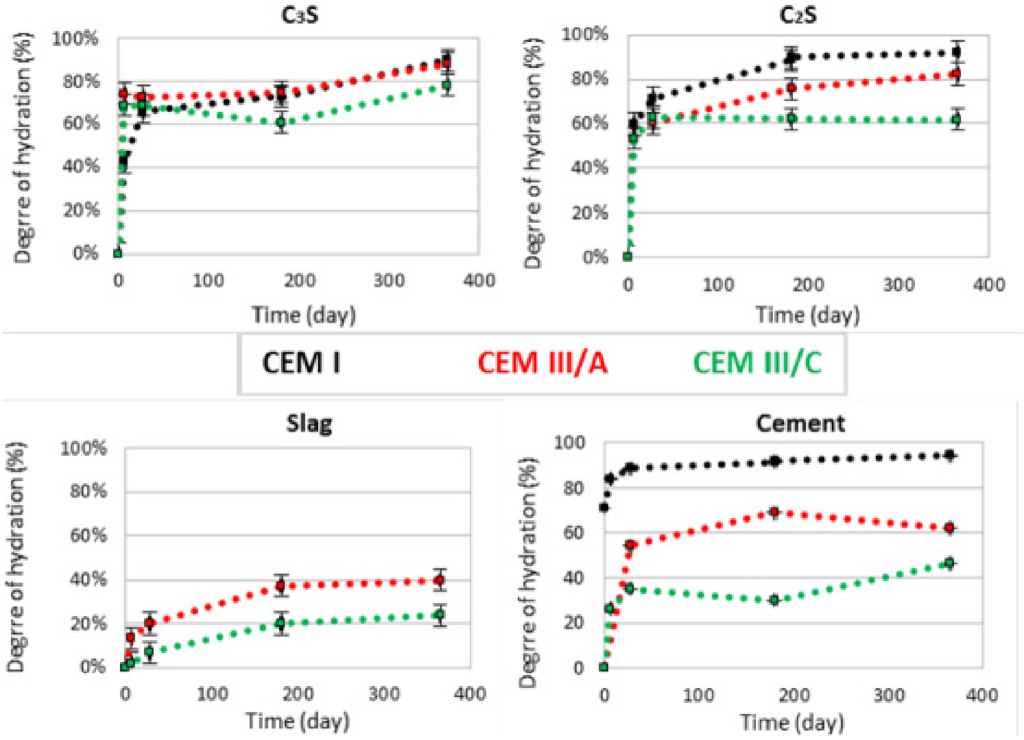

Fig 1. Example of graph showing degree of hydration (%) with respect to time of C3S, C2S, Slag and Cement for CEM I, CEM III/A, CEM III/C Cement. [Adapted from (18)]

The influence of slag on the hydration of C_3A and C_4AF is minimal, as the concentrations of Ca^{2+} , Al^{3+}, and SO_4^{2-} ions in the liquid phase are not significantly altered by the presence of slag. However, since calcium aluminate hydrates and ettringite are well-crystallized and tend to form a porous rather than a compact microstructure, it can be inferred that the hydration rate will be somewhat reduced. Conversely, some calcium hydroxide and SO_4^{2-} ions are adsorbed on the slag glass surface and incorporated into the pozzolanic reaction, which may accelerate the reaction of aluminates (18).

There is a strong correlation between the degree of slag hydration and cement strength. However, as noted by Fierens, varying strengths can be observed at the same hydration degree of different slags, indicating that other factors, such as the microstructure of hydrates and the conditions of their crystallization, also influence strength development (19).

2.1 Accelerated Curing

Accelerated curing can be conducted in various methods namely Warm Water method, Autogenous curing method, Boiling water method (20)etc. The accelerated curing techniques used for this experiment is Oven Curing method which is explained below.

Oven curing method is preferred due to its easiness in performing the accelerated test as no sophisticated setup is needed because every lab will be having a thermostatically controlled oven which fair enough for conducting accelerated test by oven curing. Moreover, it is convenient for high slag concrete [(HSC) due to its efficiency in providing actual control of curing parameters. This can be achieved by meticulously regulating temperature, a critical factor influencing the hydration of GGBFS, oven curing facilitates faster strength development without compromising the hardened concrete properties(21).

Furthermore, oven curing ensures uniform environmental conditions, minimising the variations in curing outcomes and enhancing the consistency of strength prediction. This method effectively protects concrete from external influences, ensuring unswerving quality and performance. The accelerated strength gain facilitated by oven curing is advantageous for construction projects demanding pressing timelines(22).

TNW Akroyd has conducted an exceptional study on oven curing method. He performed the oven curing 30 minutes after mixing the cubes and it was covered with base plate once the cube is placed inside the oven, temperature is brought to 85°C within 1 hour, and maintained the same temperature for a period of 5 hours. After 5 hours, the cubes are removed from the oven, stripped and allowed to cool for 30 minutes. Then it is transferred for compressive testing. Akroyd had concluded that the compressive strength test results for cubes cured normally for a period of 7 or 28 days may be predicted by accelerating the curing of the cubes and testing them 29 hours after casting (23).

2.2 Effects of Accelerated Curing on Concrete

This section examines the complex mechanisms by which accelerated curing processes influences the fundamental characteristics of concrete. Through a comprehensive analysis of these factors, this study aims to explain the potential advantages and disadvantages of accelerated curing for high-slag concrete, providing valuable insights for optimizing construction practices and achieving desired performance outcomes.

2.2.1 Microstructure

During the accelerated curing process the elevated temperature and humidity conditions contributes to shorten the induction period of cement hydration(24) . There is no change in the main products of hydration like Calcium Silicate Hydrate Gel (C-S-H), Calcium Hydroxide ($Ca(OH)_2$),Calcium Alumina (AFt), and Monosulphur Calcium Sulphoaluminate Hydrate (AFm) (25). Accelerated curing techniques change the morphology, density, atomic ratio, and chain length of C-S-H gels. Under rapid increase in curing temperature changes the bulk density of the ionic structure. The curing temperature affects the atomic distribution and changes the atomic proportions (26).

2.2.2 Delayed Ettringite Formation

Ettringite is a mineral composed of hydrous calcium aluminate sulphate, which undergoes formation within concrete during the process of curing under ambient conditions. However, in situations where concrete is exposed to high temperature curing, such as in accelerated curing or in the case of mass concrete, the excess heat produced during the process of cement hydration cannot be easily dissipated. As a result, ettringite formation can be delayed. When the concrete is set, it may lead to expansion and results in internal cracking this phenomenon is called Delayed Ettringite Formation (DEF) (27). Nevertheless, prolonged periods of elevated curing result in significantly decreased expansions, which align with documented chemical alterations that may involve the formation of ettringite following heat treatment (28).

2.2.3 Compressive Strength

This parameter requires further elaboration as it is the pivotal property being analysed in this paper. The compressive strength of concrete refers to the ratio of the maximum uniaxial load that can be sustained by the concrete at a specific rate, to the cross-sectional area of a specimen(29). Some of factors effecting the compressive strength of a concrete specimen are noted below (30).

- Porosity

The relationship between water cement ratio and porosity is a significant factor influencing the compressive strength because it affects the porosity of both the cement mortar matrix and the interfacial transition zone between the matrix and the coarse aggregate(31)

- Water Cement Ratio

Water cement ratio has direct relation on strength of concrete due to its natural behaviour of awakening of the matrix when increasing the water cement ratio due to increase in porosity of mix whereas it behaves vice versa when water cement ratio is lowered.

- Degree of Compaction

The strength of concrete is significantly affected by the increased energy applied during compaction. A portion of this strength enhancement may be attributed to unhydrated cement particles being encapsulated by thinner layers of hydrated cement. Additionally, it is plausible that high-pressure-compacted concrete derives its strength from a combination of particulate interlocking, sintering processes, and the hydration of cement. (31)

- Temperature

The influence of temperature on concrete strength depends on time – temperature history of casting and curing which means the three possibilities concrete cast and cured at same temperature, concrete cast at different temperatures but cured at a normal temperature and concrete cast at normal temperature but cured at different temperatures.(31)

It has been claimed (32) that the addition of gypsum to the mix could significantly lessen the adverse effect on strength at later ages after initial high temperature curing. Normally gypsum dosage is around 3-5% (42). This is most likely due to the gypsum interfering with the hydration phases (C_3A and C_4AF) that readily form in the presence of heat. As a result, the later hydration of slower-acting phases (C_2S and C_3S) does not disturb these phases, reducing microstructural damage and enhancing long-term strength.

Many researches have conducted research on 28 days compressive strength of concrete estimation based on early age strength. Nurse (1949) introduced steam curing, observing inconsistency due to cement composition and hydration rates. Akroyd and Smith-Gander (1956) developed the boiling method, with their modified approach (24-hour normal curing + 33-hour boiling) which closely aligned with 28-day strengths, eliminating the need for correlation graphs. Ordman and Bondre (1958) highlighted the influence of oven temperature inconsistencies, causing significant under-predictions in high-strength concrete. Neville (1957) demonstrated that smaller cubes tend to over-predict strength, particularly at high compressive levels. Emtroy (1958) presented the Cement and Concrete Association (C.C.A.) curve, providing a standardized and reliable framework for early strength predictions, especially for strengths below 28 MPa. In that Prof. Kings method of accelerated oven curing (Fig.2) is considered to be more accurate and easier for adoption (11,23). For instance, accelerated oven curing strength of 42MPa has been increased to more than 65MPa at 28 days, when it is cured under normal conditions (33). Prof. Kings cured the cubes at 93°C temperature for a period of 5 hours, and total time spend for the accelerated curing was 7 hours only. Moreover, the aforementioned research was carried out on 100% OPC mix cubes. Whereas over here we have performed the accelerated oven curing on high slag concrete and the duration of curing time is more than 24 hours.

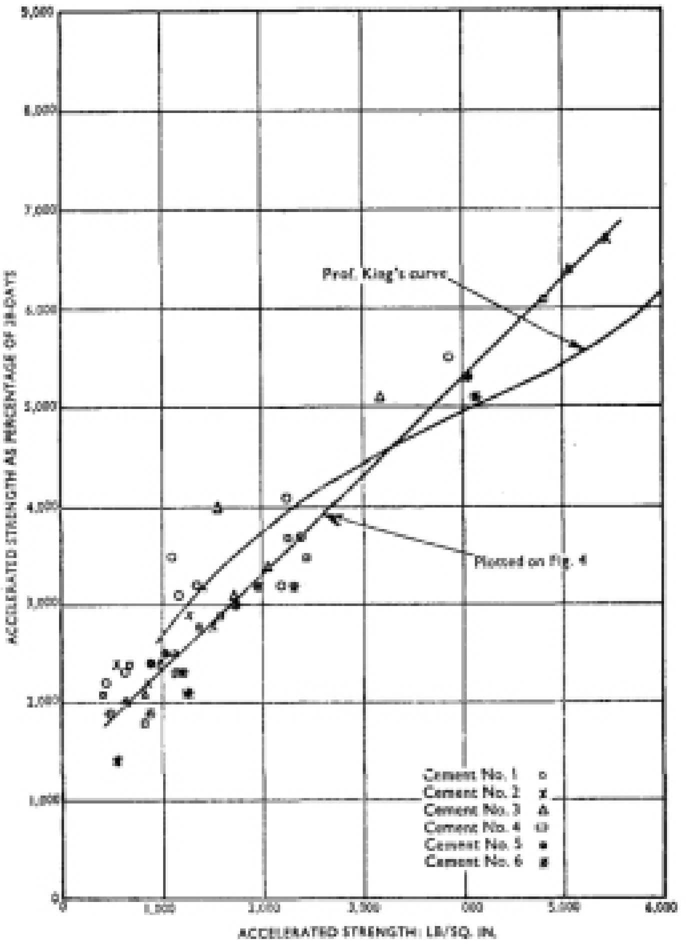

Fig.2 Prof King's prediction curve for accelerated strength as percentage of 28 days with respect to the accelerated strength [Adapted from (23)].

As previously stated, there exists a range of methods for forecasting the strength of concrete by employing diverse accelerated curing protocols. However, when it comes to concrete with a higher percentage of GGBFS composition, there is a need for further investigation into the effectiveness of accelerated curing using a thermostatically controlled drying oven. The concrete's early strength can be significantly influenced by the increased content of GGBFS. Consequently, it is necessary to thoroughly investigate the correlation between the early strength achieved through accelerated oven curing at various temperatures.

The majority of international standards pertaining to conventional accelerated curing methods have been withdrawn or replaced by other standards, resulting in a lack of a standardised protocol for conducting these tests. Ensuring the precision of forecasts derived from accelerated curing is of utmost importance in order to ascertain the dependability and feasibility of quality control protocols. This can be accomplished by juxtaposing these predictions against the concrete's real-world performance over extended periods of service life.

The potential limitations of current predictive models for estimating the 28-day compressive strength in high slag concrete under accelerated curing regimes may pertain to their accuracy and scope. There is a lack of research in the field of developing and validating reliable predictive model that consider the unique hydration characteristics of slag and its interactions with accelerated oven curing method. Knowing this relationship allows precast concrete producers to optimise their production with minimising associated embodied carbon

3. Materials and Methods

In this section we have meticulously analysed the properties of all constituent materials i.e., OPC, GGBFS, coarse aggregate and fine aggregate, admixture and water in order to assure that constituent materials conform to BS EN 206(34) . The testing of constituent materials performed based on international standard (listed in next sections) . The Quality Control testing and properties of constituent materials are explained below in detail.

3.1. Cement

Cements are classified into number of types based on their application, environment, availability, etc. The most common types of cement used in the Middle East are (I) Ordinary Portland Cement (OPC) (ii) Sulphate Resistance Cement (SRC). For this research the OPC was adopted due to its availability and consistency in Qatar, where the research took place. The chemical composition of OPC is analysed in an accredited third-party laboratory and it complies with BS EN 197-1 (35). The OPC (CEM I) used for this study is 42.5R grade. The chemical composition is given below in Table 1.

Table 1: Chemical Composition of CEM I (OPC) & GGBFS

Chemical Components	**CEM I Test** Results (%)	**BS EN 197-1 Limits** (%)	**GGBFS test** Results (%)	**BS EN 15167- 1 Limits** (%)
Magnesium Oxide (MgO)	3.2		4.9	Max.18.0
Aluminium Oxide (Al_2O_3)	3.6		13.5	
Silicon Dioxide (SiO_2)	20.85		34.21	
Sodium Oxide (Na_2O)	0.18		0.16	
Potassium Oxide (K_2O)	0.4		0.4	
Calcium Oxide (CaO)	63.03		42.90	
Loss of Ignition	2.6	Max 5.0	0.9	Max 3.0
Ferric Oxide (Fe_2O_3)	1.8		0.9	
Insoluble Residue (IR)	0.5	Max 5.0	0.5	Max 1.5
Chlorine (Cl)	0.004	Max.0.1	0.004	Max.0.1
Sulphur Trioxide (SO_3)	2.2	Max.3.5	0.5	Max.2.5
CaO/SiO_2 Ratio	3.02	Min.2.0		
Titanium Oxide (TiO_2)			0.19	

Table 2. Clinker Compounds of CEM I (OPC)

Clinker Compounds	CEM I Test Results (%)
Alite(C3S)	65.1
Belite(C2S)	10.7
Aluminate(C3A)	6.5
Ferrite(C4AF)	5.47

The clinker compounds were calculated as per ASTM C 150 (ref) and displayed in Table 2. Furthermore, C_3A content in this cement is 6.5% which makes this cement as moderate sulphate resistance cement even though it is marketed as OPC. The reduction of C_3A content is being pursued in Qatar as a result of the elevated levels of sulphate found in the soil.

There are three main parameters which are considered by manufacturers for assessing the quality of cement are listed below

$LSF(\%)= CaO/(2.8SiO_2+1.2Al_2O_3+0.65Fe_2O_3)$

$SR\ (\%)=SiO_2/(Al_2O_3+Fe_2O_3)$

$AR(\%)=Al_2O_3/(Fe_2O_3)$

The first one is lime saturation factor (LSF) and it is determined by the ratio of lime to silica, alumina , and Iron Oxide and governs the relative proportions of C_3S and C_2S. Typical values for LSF is between 92%-99%(36) .

The second parameter is Silica Ratio (SR) which is otherwise called silica modulus. A high silica ratio means that more calcium silicates are present in the clinker and less aluminate and ferrite. Whereas the final parameter Alumina Ratio (AR) determines the potential relative proportions of aluminate and ferrite phase in the clinker.AR is usually between 1 and 3 (6). The aforementioned parameters for the cement used for this research is tabulated in Table 3.

Table 3. Cement Parameters

Lime Saturation Factor (LSF) (%)	**93**
Silica Ratio (SR) (%)	**3.86**
Alumina Ratio (AR) (%)	**2**

Winter found that in order to achieve enhanced early strength of cement, it is necessary for the values of SR (Silica Ratio) and LSF (Lime Saturation Factor) to be elevated (6). Nevertheless, there are certain disadvantages associated with the use of high LSF (lime saturation factor) and SR (silica ratio) mixes in kilns. These mixes pose significant challenges in terms of achieving the desired reactions, as they are more resistant to combustion and hard to combine. The observed phenomenon is categorized by elevated levels of carbon dioxide (CO_2) emissions, which can be associated to the augmented calcium oxide (CaO) concentration in the cement as well as an enlarged demand for fuel.

3.2 Ground Granulated Blast Furnace Slag (GGBFS)

The physical and chemical properties of GGBFS used is meticulously analysed by an accredited third-party laboratory. The measured basicity ratios for GGBFS reactivity are tabulated in Table 4.

Table 4. GGBFS Basicity Ratios

Chemical Components	Test Results (%)	Limits (39) (%)
P1= CaO/SiO_2	1.25	**>1.0**
P2= $(CaO+MgO)/SiO_2$	1.4	**>1.0**
P3= $(CaO+MgO)/(SiO_2+Al_2O_3)$	1	**1.0-1.3**
P4= $(CaO+0.56Al_2O_3+1.4MgO)/SiO_2$	1.67	**> 1.65**
P5= $CaO+MgO+Al_2O_3\ /\ SiO_2$	1.79	**>1.0**

3.3 Mix Proportions

A single grade of mix with three different cementitious combinations is considered for this study. The primary objective of adding different GGBFS proportions was to comprehensively investigate the influence of a wide range of GGBFS additions on concrete properties. All the mixes are designed to be C50 grade. The different cementitious combination of the mixes used for this study is given below

I. C50-OPC 100%

II. C50-OPC+50%GGBFS

III. C50-OPC+70% GGBFS

The mix designs are designed in SSD (Saturated Surface Dry) condition for each cementitious combination. Mix designs are displayed in Table 5 with the yield calculations to ensure that concrete is designed for 1m^3 . Herein, air content in the mix is calculated according to ACI 211.1 (37) which is 2% when the maximum aggregate size is 20mm. The yield of the mix may be slightly kept higher however in reality the air content would be less than the designed value hence yield would be around 1.02 m^3.

Table 5. Mix designs

Mix Grade	Mix Name	OPC (Kg/m^3)	GGBFS (Kg/m^3)	Water (Kg/m^3)	10/20mm (Kg/m^3)	4/10mm (Kg/m^3)	0/4mm (Kg/m^3)	HP 540 A (Kg/m^3)	Air (%)	W/C Ratio	Theoretical Density (Kg/m^3)
C50 OPC	Mix A	410	-	144	778	382	800	4±1.5	2%	0.35	2510
C50-OPC+50% GGBFS	Mix B	210	210	147	771	385	771	4±1.5	2%	0.35	2490
C50-OPC+70% GGBFS	Mix C	129	301	151	759	380	759	4±1.5	2%	0.35	2480

The quantity of admixture in the latter mixes are subject to have a tolerance of ±1.5 kg/m^3 due to ambient conditions and presence of moisture in the fine aggregate.

3.4 Mixing Procedure

The cube specimens were made in accordance with the BS EN 12390-2 (10). Consequently, the demolding of the cubes was carried out within this specific timeframe. The cubes were stored within the laboratory for a duration of 22 hours subsequent to their casting, after which they were deemed suitable for transportation to a third-party laboratory for the purpose of conducting tests. During the transportation process, gunny bags were utilized to cover the concrete cubes in order to mitigate moisture loss. The Fig 3 depicts Activity Vs Time to understand the timeline of sampling until testing.

The 27 cubes were subjected to standard water curing regime specified by BS EN 12390-2(10). The temperature of the water used for curing in the tank was adjusted to 20°C. Within the set of 27 cubes, there are 9 cubes designated for each of the three age groups: 7 days, 14 days, and 28 days respectively. These cubes are specifically allocated for the purpose of conducting compressive strength tests in accordance with BS EN 12390-3(38). The schematic flow of complete trial mix procedure is depicted below.

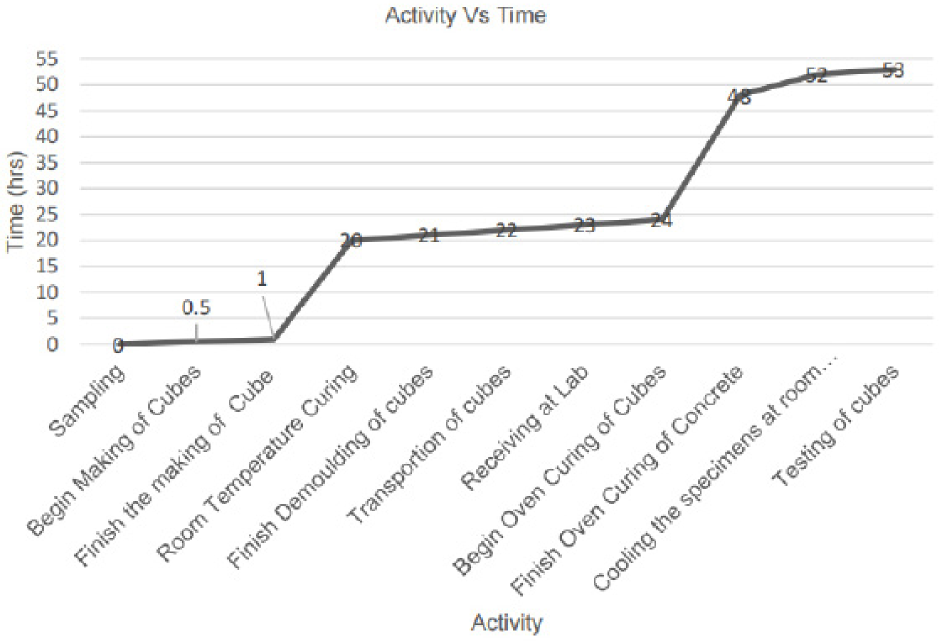

Fig.3: Schematic Flow of Trial Mix from Beginning to End

3.5 Isothermal calorimetry

The isothermal calorimetry test was conducted to study the hydration of cementitious the relationship between accelerated oven cured strength and concrete subjected to water curing at different ages has been well studied in the project. Calorimetry test was performed on accelerated oven cured mixes to monitor the hydration kinetics. The Isothermal calorimeter has to be placed in an environment with a constant temperature, typically a high-precision thermostat, in order to accurately measure heat. It is crucial to verify the accuracy of the thermostat's temperature setting. The calorimetry tests have got several applications like determination of heat of hydration, estimating the activation energy, cement admixture interactions, etc.(39).

3.6 Accelerated Oven Curing Procedure

The remaining 18 cubes were subjected to oven curing in two distinct thermostatically controlled electric drying ovens, with each oven accommodating 9 cubes. The drying oven was calibrated and can conduct a heat up to a range from 20°C to 250°C.

The ovens were set to different target temperatures, 50°C and 70°C, and the oven curing was restricted to 24±0.5 hours. In the experiment involving specimens with a target curing temperature of 50°C, the cubes were initially cured at a temperature of 30°C for a duration of 2 hours. Subsequently, the curing temperature was raised to 50°C for the remaining duration of the oven curing process. Whereas in the case of 70°C oven curing setup, the specimens were initially cured at a temperature of 30ºC for a duration of 2 hours. Subsequently, the temperature was raised to 50ºC and maintained for 1 hour. Finally, the specimens were subjected to the desired curing temperature of 70ºC for the remaining curing period, which lasted for 24±0.5 hours. The temperature time flow for 50ºC was depicted below in Fig.4. The time-temperature relation was similar to the 70ºC Curing regime except temperature progression style as stated in previously.

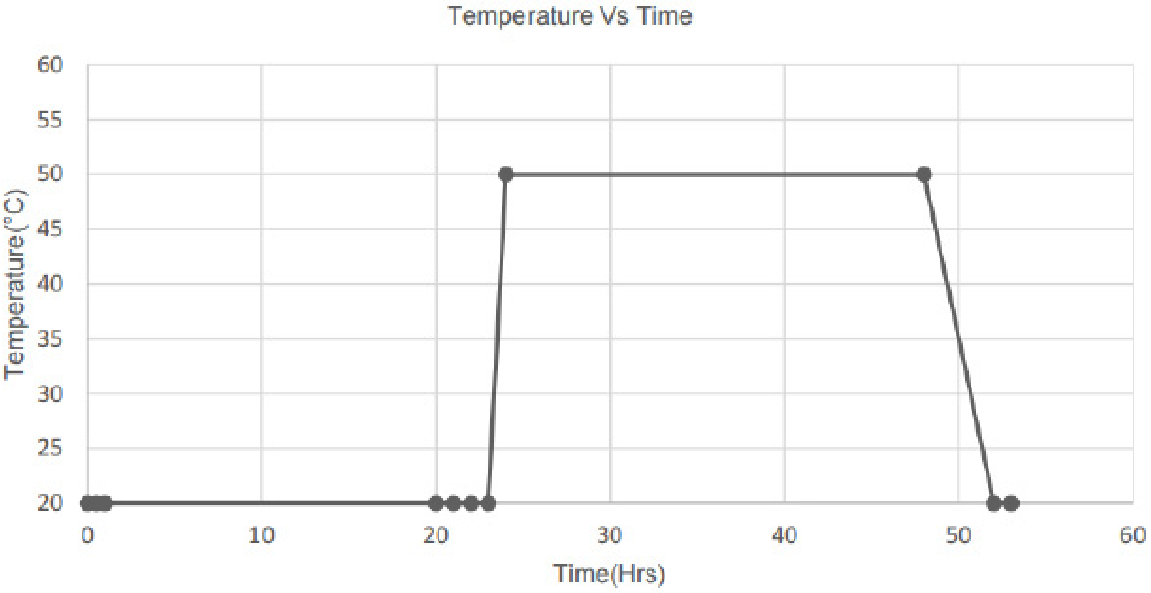

Fig.4. Time- Temperature Flow of Experiment for 50°C

Following the removal of the cubes from the oven, a designated cooling period of approximately 4 to 5 hours was observed, and the cubes were subjected to compressive testing of concrete as per BS EN 12390- 3 (38). The results of compressive strength of cubes are reported separately for cubes cured at different accelerated oven curing regimes that is 50°C and 70°C.

4. Results

The three mixes with fourth generation high range PC admixture with a solid content more than 35 is used for high workability for pumping. Initially, elevated pumping pressures are necessary to overcome the frictional resistance between the concrete and the pump tube. Once this initial resistance is mitigated and a smooth interface is established, the required pumping pressure can be reduced. A sustained decrease in pumping pressure relative to the initial value signifies satisfactory flowability characteristics of the High-Performance Concrete (HPC) mix containing the slag. Hence the target slump of 200±40 mm for better workability due to high GGBFS replacement and maximum target temperature is 35°C (40). The higher slump was proposed the cube specimens were made in accordance with the BS EN 12390-2 (10). It was observed that the concrete had achieved final setting within a period of 17-20 hours after casting. Subsequently the aforementioned curing regimes of the specimens, calorimetry and compressive strength test were conducted. The results have been elaborated below.

4.1 Conduction Calorimetry

The heat flow of the OPC + GGBFS mixes are presented below. For 50°C, the highest first peak was for OPC, lower for 50% GGBFS and the lowest 70% GGBFS cement replacement. It was noticeable, that for the highest cement replacement, the first peak was delayed. For 50% OPC replacement delay was not noticed (Fig.5).

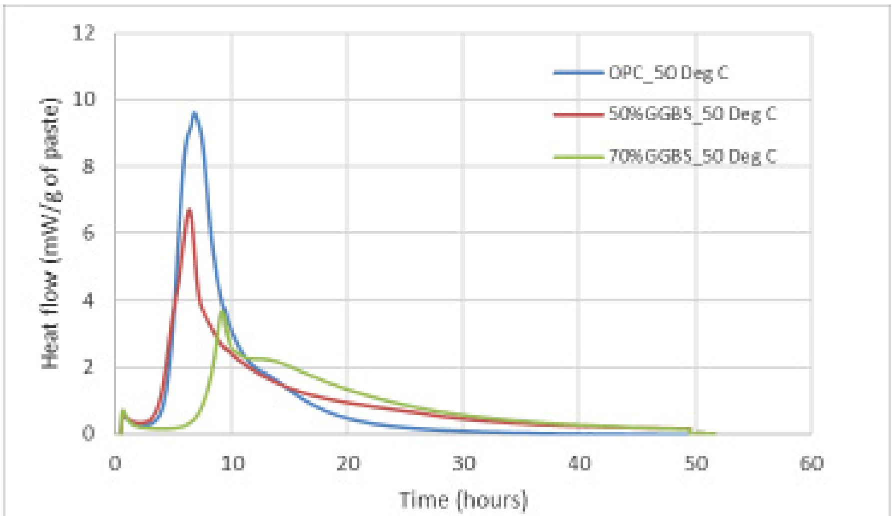

Fig.5. Calorimetry Graph at 50°C

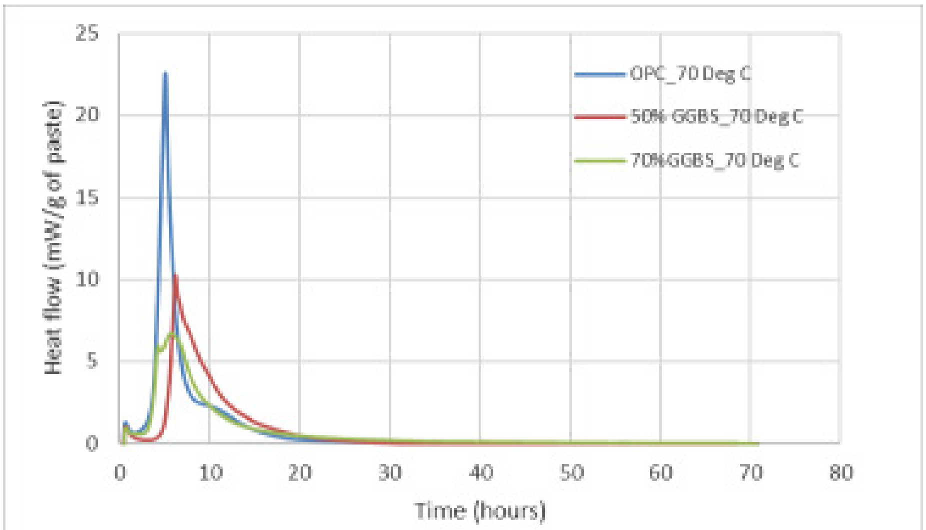

Fig.6. Calorimetry Graph at 70°C

For 70°C, the highest first peak was for OPC, lower for 50% GGBFS and the lowest 70% GGBFS cement replacement. For both 50% and 70% OPC replacement with GGBFS the first peak was slightly delayed compared to 100% OPC (Fig.6).

4.2 Compressive Strength Results

The main aim of this study was to find the relation between accelerated oven cured specimens and water cured specimens for establishing a prediction model. In order to establish a prediction model, monitoring of compressive strength of specimens were inexorable.

The compressive strength of all cube specimens which has undergone the accelerated oven curing regimes and cubes cured under water curing regime as per BS EN 12390-2 (10) were consolidated and tabulated in Annex B and their respective few test reports are attached in Annex A. The cubes cured under water curing has been tested for different ages that is 7 days,14 days and 28 days.

A comparison has been made between the compressive strength of average accelerated oven cured specimens at 23 hours from casting and 28 days water cured specimens (See Fig.7and Fig.8). This was done by creating two bar graphs to analyse the trend of strength gain for each mix at two different curing temperatures. The two bar graphs are depicted below. All mixes, no matter on OPC replacement, achieved 68MPa+-8 after 28 days of curing in ambient temperature (See Fig.7and Fig.8). The highest compressive strength for concrete cubes cured in 50°C was for the highest OPC replacement with GGBFS. Concretes with OPC replacement with GGBFS had slightly higher compressive strength compared to OPC when cured in 50°C (Fig.7). The same trend was for curing in 70°C, however there was no difference in the compressive strength for both 50 and 70% cement replacement. The difference between strength at accelerated curing and curing in ambient condition was higher for curing in 50°C and smaller for curing in 70°C, and was noticed as in Table 6.

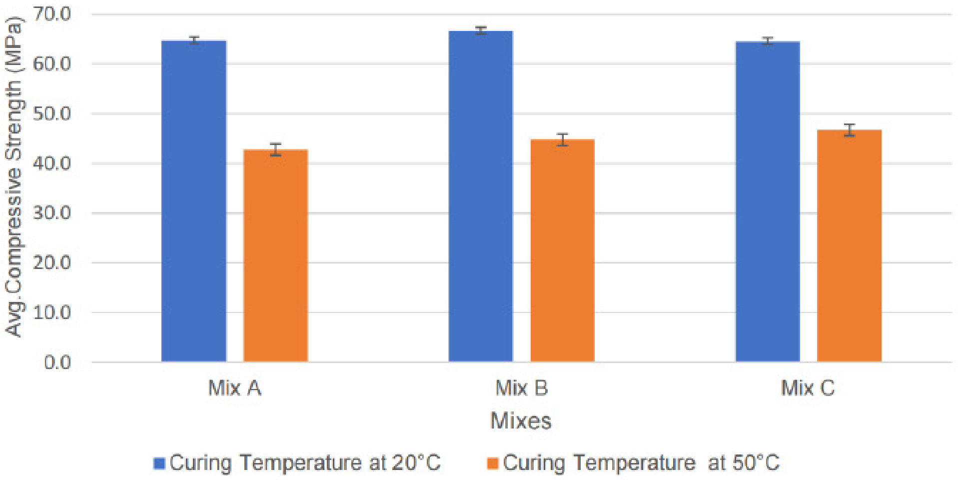

Fig.7. Comparison between 28 days Compressive Strength Vs Accelerated Oven cured Strength at 50°C

(Mix A - C50 OPC, Mix B - C50-OPC+50%GGBFS, Mix C - C50-OPC+70%GGBFS)

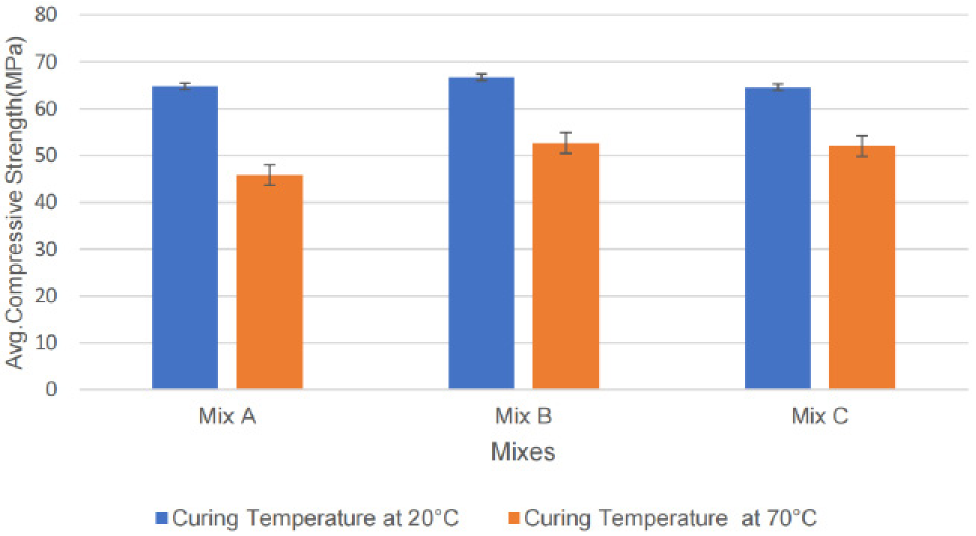

Fig.8. Comparison between 28 days Compressive Strength Vs Accelerated Oven cured Strength at 70°C

(Mix A - C50 OPC, Mix B - C50-OPC+50%GGBFS, Mix C - C50-OPC+70%GGBFS)

5.Discussion

The discussion of our results has been divided in two main sections. In the first part we emphasize on the hydration kinetics in different curing regimes is discussed based on the Isothermal Calorimetry, while the second part focuses on prediction of actual compressive strength from accelerated cured concrete strength results.

a. The Isothermal calorimetry was conducted on all mixes at two distinct temperatures namely 50 degrees and 70 degrees. It was noticed that the heat flow rate is higher in full OPC mix and as the slag content of the mix is getting higher the heat flow is also decreasing. It is clearly depicted on Figure 3 and 4. That is the main reason in mass concrete in order to reduce the core temperature of the structural element with the higher cement replacement with SCM's are recommended. The GGBFS hydrates at a slower rate than OPC which produces a lower temperature rise. (41)

b. After the initial reaction, there is an induction period which is otherwise called dormant period. The gypsum in cement is used to prevent flash set, it is usually added 3-5% with respect to seasonal changes and retarders are used to prolong the setting time. Hence the induction period of GGBFS mixes is higher than the OPC mixes. The induction period would be also higher in mixes containing retarders.

Acceleratory period where you can notice a spike indicating C3S and C2S hydration. Here comes the deceleratory period where hydration slows down, in our case its happening after 10 hours in GGBFS mix at 50 degrees However, in elevated temperature the hydration slows down for around six hours for GGBFS mixes. In the case of OPC mixes deceleration is almost similar, even though in high temperature sudden deceleration is observed. The deceleration period in cement hydration is a complex process influenced by mineral composition, temperature, and its water-cement ratio. C3S hydrates rapidly initially, leading to acceleration, but slows down as water decreases and products accumulate. C2S hydrates more slowly and contributes to later-age strength. Elevated temperature accelerates initial C3S hydration but can also decrease product solubility, leading to pronounced deceleration. Lower temperatures slow down both acceleration and deceleration. GGBFS can delay initial hydration and accelerate C2S hydration at elevated temperatures. OPC, primarily C3S and C2S, experiences rapid initial hydration followed by deceleration. Elevated temperatures can cause sudden deceleration due to increased product solubility. (42)

In the next phase, gypsum started to deplete and forms monosulphate. The Ettringite (Aft) is the one which converts to monosulphate (43) . This phase is called sulphate depletion phase.

c. The prediction graph is constructed using the compressive strength test data mentioned earlier in order to estimate the 28-day compressive strength of Mix A, B, and C. This estimation is based on the compressive strength results obtained from accelerated oven cured samples that were subjected to two different curing temperatures. The developed prediction model is established as the main goal of this study, and it is noticed that an average strength difference between accelerated oven cured specimens cured at 70 degrees and cubes tested at 28 days is around 21% for Mix B whereas for Mix C it is 19.53%. This number is quite higher in Mix A which is 35%.

The prediction graph is established and displayed below can be used for predicting the 28 days compressive strength of concrete from accelerated oven cured compressive strength results. In the prediction graph, the target strength is calculated as 59.8 MPa (44). The average Strength gain in 28 days is analysed from accelerated oven cured specimens compressive strength is tabulated in Table 6. The trend of this strength is clearly visible in Fig.9.

Table 6. Strength Gain Analysis

Mixes	% of Average Strength gain in 28 days from 50°C Cured Specimen	% of Average Strength gain in 28 days from 70°C Cured Specimen
C50-OPC	33.96	29.47
C50-OPC+50%GGBFS	32.75	21.01
C50-OPC+70% GGBFS	27.56	19.53

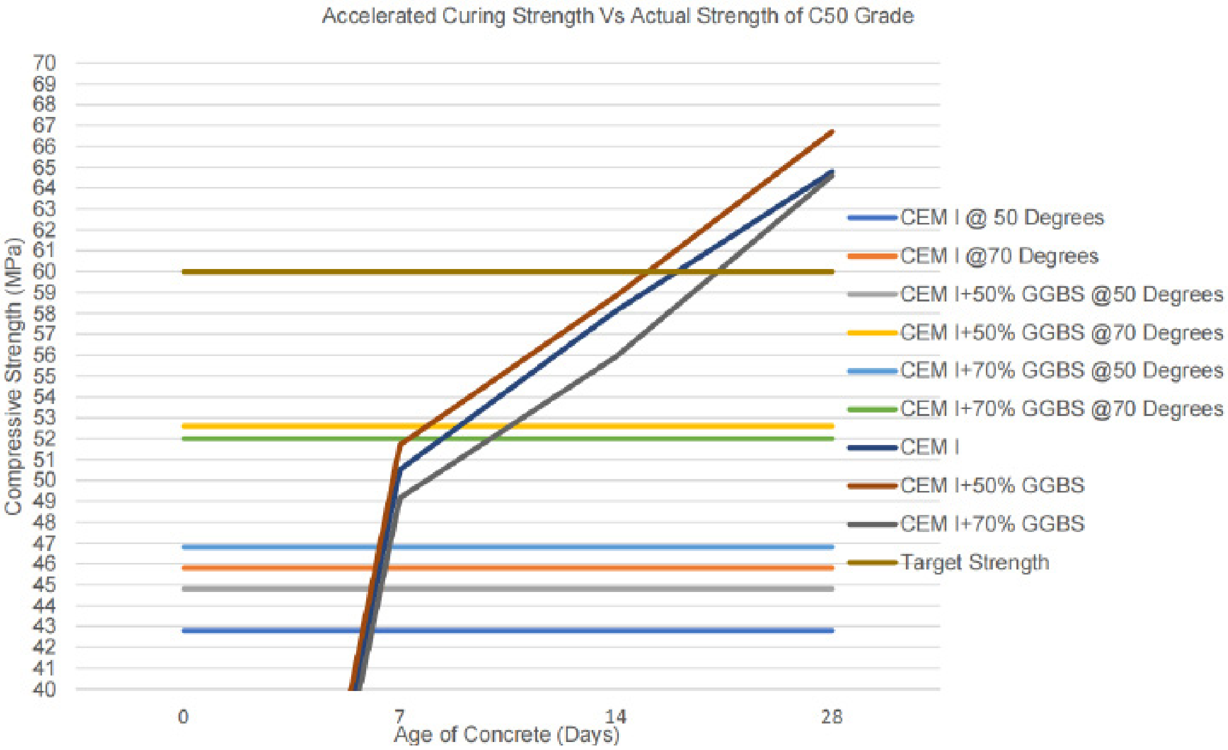

Fig.9. Compressive Strength Prediction Graph

5. Limitation of the analysis

The scope of this study was limited to a single grade with two different composition of GGBFS under 2 distinct temperatures only. In order to validate the developed model, future research should investigate the accelerated oven curing at 70°C for all grades of concrete with GGBFS compositions ranging from 35% to 70%.

6. Conclusion

This study is set out to predict the 28 days compressive strength of high slag concrete by establishing the accelerated curing regimes. The findings of this investigation are delineated in the subsequent sections.

- For analysed temperatures and levels of OPC replacement with GGBFS, prediction graph shows the evident correlation between the accelerated oven cured compressive strength and the 28 days compressive strength. By examining the accelerated strength achieved at two distinct temperatures, it is possible to anticipate the compressive strength of concrete at 28 days.
- This study has identified that curing temperature of 70 °C is closer to the 28 days compressive strength.

In other words, the percentage of average strength gained in 28 days from 70 °C cured specimens across all mix types amounts to merely 23.33%. Whereas average strength gained in 28 days from 50ºC cured specimens are 31.42%.

- The mix of OPC+70%GGBFS tends to achieve greater strength gain in 70 °C curing temperature and average strength gained in 28 days from 70ºC is comparatively lower that is 19.53%. Hence Oven curing temperature of 70 °C can be considered as regarded as the closest accelerated curing temperature for high slag concrete.
- This study observes that induction period for Mix C is higher than that of other mixes. However, in acceleratory period higher heat releasing is observed on Mix A which is 9.8mW/g for specimens cured at 50 degrees and 23.2mW/g for specimens cured at 70°C.

Future research should investigate the accelerated oven curing at 70 °C for all grades of concrete with GGBFS compositions ranging from 35% to 70%. A thorough examination of the microstructure of concrete samples cured in an oven at elevated temperatures is required to ensure that curing at high temperatures has no negative effects on the microstructure of cementitious paste.

Acknowledgements

The authors wish to acknowledge with gratitude to Mr. Imran Khan Bhati from Qatar Beton Readymix for providing with an ample quantity of concrete for the research.

Data Availability: The data collected and analysed in this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest: The authors have no competing interests to declare that are relevant to the content of this article.

References

Matthes W, Vollpracht A, Villagrán Y, Kamali-Bernard S, Hooton D, Gruyaert E, et al. Ground Granulated Blast-Furnace Slag. In 2018. p. 1–53.

Embodied CO 2 e of UK cement, additions and cementitious material [Internet]. 2019. Available from: https://www.hanson.co.uk/en/system/files_force/assets/document/53/9b/environmental- product-declaration-hanson-

BRE. Concrete in aggressive ground. Special Digest 1. 2005.

Cement_Type_Early_Age_Properties_23_Jun_11.

Korde C, Cruickshank M, West RP. Activation of slag: a comparative study of cement, lime, calcium sulfate, GGBS fineness and temperature. Magazine of Concrete Research. 2021 Jan;73(1):15–31.

Winter N. Understanding Cement. Suffolk: WHD Microanalysis Consultants Ltd.; 2009.

Zulu BA, Miyazawa S, Nito N. Properties of blast-furnace slag cement concrete subjected to accelerated curing. Journal of Infrastructures. 2019. 69 p.

Jha AK, Adhikari S, Thapa S, Kumar A, Kumar A, Mishra S. Evaluation of Factors Affecting Compressive Strength of Concrete using Machine Learning. In: 2020 Advanced Computing and Communication Technologies for High Performance Applications (ACCTHPA). IEEE; 2020. p. 70–4.

British Standards Institute. BS 8500-1:2023: Concrete. Complementary British Standard to BS EN 206: Method of specifying and guidance for the specifier. 2023.

British Standards. BS EN 12390-2-2019.

Shetty MS, Jain AK. Concrete Technology (Theory and Practice). S. Chand Publishing.; 2019.

Rhodes JA, Carreira++ DJ, Beaudoin JJ, Brauson DE, Gamble BR, Geymayer HG, et al. Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures. 2008.

Austin SA, Robins PJ, Issaad A. Influence of curing methods on the strength and permeability of

GGBFS concrete in a simulated arid climate. cement and concrete composites. 1992. 157–167 p.

Domone P, IIston J. Construction Materials: Their Nature and Behavior. Oxon: Spon Press; 2010.

Moranville-Regourd M. Cements Made from Blastfurnace Slag In: Lea's Chemistry of Cement and Concrete. Butterworth-Heinemann; 637–678 p.

Black L. Low clinker cement as a sustainable construction material. In: Sustainability of Construction Materials. Elsevier; 2016. p. 415–57.

Whittaker M, Zajac M, Ben Haha M, Bullerjahn F, Black L. The role of the alumina content of slag, plus the presence of additional sulfate on the hydration and microstructure of Portland cement- slag blends. Cem Concr Res. 2014 Dec;66:91–101.

Stephant S, Chomat L, Nonat A, Charpentier T. Influence of the slag content on the hydration of blended cement [Internet]. 2015. Available from: https://cea.hal.science/cea-02509185

Fierens P. The hydration and properties of slags. CANMET Special Publication; 1989. 35–45 p.

International A. Standard Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens [Internet]. Available from: www.astm.org,

Wedatalla AMO, Jia Y, Ahmed AAM. Curing Effects on High-Strength Concrete Properties. Advances in Civil Engineering. 2019 Jan 6;2019(1).

STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES - 2007 'Materials and Construction'. 2010.

AKROYD TNW. THE ACCELERATED CURING OF CONCRETE TEST CUBES. Proceedings of the Institution of Civil Engineers. 1961 May;19(1):1–22.

Dorn T, Blask O, Stephan D. Acceleration of cement hydration – A review of the working mechanisms, effects on setting time, and compressive strength development of accelerating admixtures. Constr Build Mater. 2022 Mar;323:126554.

Kurdowski W. Cement and Concrete Chemistry. Dordrecht: Springer Netherlands; 2014.

Wang J, Long G, Xiang Y, Dong R, Tang Z, Xiao Q, et al. Influence of rapid curing methods on concrete microstructure and properties: A review. Case Studies in Construction Materials. 2022 Dec;17.

Delayed Ettringite Formation: In situ Concrete. Vol. BRE IP11/01. British Research Establishment; 2001.

Lawrence CD. Mortar expansions due to delayed ettringite formation. Effects of curing period and temperature. Cem Concr Res. 1995 May;25(4):903–14.

Perrie B. Strength of Hardened Concrete. In: Fulton's Concrete Technology. 9th Edition. Midrand: Cement and Concrete Institute; 2009. p. 97–110.

Neville AM, Brooks JJ. Concrete Technology. Harlow Longman Publications; 1994.

Chang PK. An approach to optimizing mix design for properties of high-performance concrete. Cem Concr Res. 2004 Apr;34(4):623–9.

Hutchison RG, Chang JT, Jennings HM, Brodwin ME. Thermal acceleration of Portland cement mortars with microwave energy. Cem Concr Res. 1991 Sep;21(5):795–9.

King JWH. An accelerated test for the seven- and twenty-eight-day compressive strengths of concrete. Journal of Applied Chemistry. 1960 Jun 4;10(6):256–62.

British Standards. BS EN 206-2013+A2-2021.

British Standards. BSEN 197-1:2011.

Newman John, Choo BS. Advanced concrete technology : constituent materials. Butterworth-Heinemann; 2003.

Dixon DE, Prestrera JR, George U Burg SR, Abdun-Nur EA, Barton Leonard W Bell SG, Blas SJ, et al. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) Chairman, Subcommittee A. 1991.

British Standards. BS EN 12390-3-2019.

Scrivener K, Snellings R, Lothenbach B, editors. A Practical Guide to Microstructural Analysis of Cementitious Materials. CRC Press; 2018.

American Concrete Institute. ACI 305.1 Specification for Hot Weather Concreting [Internet]. 2014. Available from: http://concrete.org/Publications/

CIRIA C660- Early-age Thermal Crack Control in Concrete. CIA.

Qi T, Zhou W, Liu X, Wang Q, Zhang S. Predictive hydration model of Portland cement and its main minerals based on dissolution theory and water diffusion theory. Materials. 2021 Feb 1;14(3):1– 34.

Linderoth O, Wadsö L, Jansen D. Long-term cement hydration studies with isothermal calorimetry. Cem Concr Res. 2021 Mar;141:106344.

Guide to evaluation of strength test results of concrete. American Concrete Institute; 2011. 16 p.