PREDICTION OF CEMENT HYDRATION WITH SCM USING MACHINE LEARNING

A Thesis

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Under the supervision

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STUDENT DECLARATION

I hereby declare that the work presented in the M.Tech thesis entitled **“Prediction of Cement Hydration With SCM Using Machine Learning”** “submitted for partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering, with specialization in Structural Engineering at **Jaypee University of Information Technology, Waknaghat,** is an authentic record of my work carried out under the supervision of **Dr. Saurav, Assistant Professor.** This work has not been submitted elsewhere for the reward of any other degree/diploma. I am fully responsible for the contents of my M.Tech thesis.

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CERTIFICATE

This is to certify that the work which is being presented in the thesis titled “**Prediction of Cement Hydration With SCM Using Machine Learning**” in partial fulfillment of the requirements for the award of the degree of Master of Technology in Civil Engineering with specialization in “Structural Engineering” and submitted to the Department of Civil Engineering, **Jaypee University of Information Technology, Waknaghat** is an authentic record of work carried out by **Rohit kumar(225024006)** during a period from July 2023 to Dec 2024 under the supervision of **Dr. Saurav, Assistant Professor**, Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of our knowledge.

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ABSTRACT

This paper presents a comprehensive analysis of the application of machine learning techniques to predict the hydration behaviour of cementitious binders. It focuses on identifying the key factors influencing the complex hydration process of cement. The study is systematically divided into several critical phases. Initially, data collection is undertaken, capturing relevant parameters such as cement composition, water-to-cement ratios, and curing conditions. The dataset includes measurements of compressive strength, setting time, and heat evolution at various time intervals to accurately reflect the progression of hydration.

A key aspect of the study is the model's interpretability, with a significant focus on understanding the influence of different variables on the predictions. Feature significance scores are utilized to determine the impact of each input variable on the hydration process. The paper emphasizes the importance of iterative refinement, underscoring the continuous improvements made by retraining the model and integrating new data.

The findings of this detailed analysis highlight the crucial role of machine learning in understanding and forecasting the hydration behaviour of cementitious binders. This approach not only aids in optimizing concrete mix designs but also enhances the long-term performance of concrete structures, contributing to more durable and sustainable construction practices.

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CONCLUTION
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LIST OF ABBREVIATIONS

OPC	Ordinary Portland Cement
GGBFS	Ground Granulated Blast Furnace Slag
SCM	Supplementary Cementitious Materials
C-S-H	Calcium Silicate Hydrate
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
CTM	Compressive Testing Machine

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CHAPTER 1
INTRODUCTION

1.1 General

The study of cement hydration is a pivotal area of investigation and innovation at the dynamic intersection of concrete technology and advanced data analytics. Cement hydration is an intricate chemical process that transforms a plastic mixture into a durable and structurally robust material, which is essential to the performance and longevity of concrete structures. Historically, understanding this process has relied heavily on empirical models and experimental observations. However, the modern integration of machine learning techniques offers new opportunities for more accurate and predictive insights into cement hydration, especially when considering the diverse range of cementitious binders available today.

This report delves into the field of predictive modelling of cement hydration, focusing particularly on the incorporation of machine learning techniques. By leveraging extensive datasets that encompass critical parameters such as cement composition and key hydration indicators, we aim to develop robust models capable of predicting the nuanced changes in the hydration process. This is particularly important when (SCMs) like GGBFS are included in the mix.

In contemporary concrete technology, it is common practice to combine conventional cement with additional cementitious materials, such as fly ash. Fly ash is a byproduct of burning coal in power plants, and it's well known that it can improve the qualities of concrete and support environmentally friendly building techniques. The use of fly ash as an additive in cement mixtures stems from two goals: enhancing engineering qualities and resolving environmental issues. In addition to lowering the heat of hydration and increasing workability, fly ash also strengthens and prolongs the life of concrete structures.

On the other hand, because of its latent hydraulic properties, GGBFS, a byproduct of the iron and steel industry, is widely used as an SCM. GGBFS slowly hydrates when combined with water and calcium hydroxide, resulting in the production of more calcium-silicate-hydrate (C-S-H) gel. This makes concrete more resilient over time, which is especially helpful for applications that call for high-performance concrete. Furthermore, adding GGBFS can greatly lower concrete's permeability, strengthening it against different kinds of chemical attack.

The incorporation of GGBFS in cementitious systems offers several benefits:

- **Improved Durability**: GGBFS enhances concrete's defenses against sulfate attack, alkali-silica reaction (ASR), and penetration by chloride ions.
- **Environmental Benefits**: Utilizing GGBFS helps recycle industrial byproducts, reducing the environmental impact of cement production by lowering carbon dioxide emissions.
- **Enhanced Strength**: GGBFS contributes to the development of long-term strength due to its slow-reacting hydraulic nature.
- **Reduced Heat of Hydration:** GGBFS lowers the heat of hydration, making it beneficial for use in mass concrete applications where thermal cracking due to heat build-up is a concern.

Despite significant advancements in cement technology, accurately predicting the heat of hydration remains a challenge due to the complexity of hydration reactions. This study addresses this gap by integrating thermal analysis, mechanical testing, and artificial intelligence to develop a predictive model that utilizes extensive data from various analytical methods.

CHAPTER 2

LITERATURE REVIEW

Cement hydration is a critical chemical process that involves the interaction between cement particles and water, leading to the development of mechanical strength and durability in concrete. Understanding and predicting the heat of hydration—a key indicator of the exothermic nature of these reactions—is essential for optimizing cement formulations and ensuring the performance of construction materials. This literature review synthesizes previous research on cement hydration, mechanical testing of cement, isothermal calorimetry, and the application of AI in materials science to establish a foundation for advanced predictive modelling of cement hydration characteristics.

Numerous studies have explored the kinetics and mechanisms underlying cement hydration. Early research focused on the primary cementitious phases, including C_3S, C_2S, C_3A, and C_4AF. These phases undergo hydration reactions to produce C-S-H and calcium CH, which contribute significantly to the strength and stiffness of concrete **Diamond, 1984**. The heat released during hydration, termed the heat of hydration, is intrinsically linked to the progress of these reactions and is crucial for concrete curing and temperature regulation during construction **Taylor, 1997**.

- **Supplementary Cementitious Materials (SCMs) in Concrete**

The integration of fly ash and other mineral admixtures into concrete has been widely studied to enhance its properties. Diamond (1984) discusses the utilization of fly ash as a supplementary cementitious material, highlighting its potential benefits for improving the characteristics of concrete **(Diamond, 1984)**. In a subsequent study, **Joshi et al. (1987)** investigates the effects of high proportions of fly ash and other mineral admixtures on the strength and durability of concrete. Their findings underscore the importance of these materials in enhancing both the strength and longevity of concrete structures, although they also identify potential challenges associated with their use **Joshi et al., 1987**.

- **Advanced Predictive Modeling of Hydration**

Recent advancements in machine learning have opened new avenues for predicting cement hydration and assessing the performance of cementitious binders. A study by **Han et al. (2020)** explores the application of machine learning techniques to develop closed-form models for predicting the strength of alkali-activated systems. The authors demonstrate how machine learning can effectively model complex relationships in cementitious materials, providing accurate and efficient predictions of mechanical properties **Han et al., 2020**.

Another notable contribution by Johari et al. (2012) investigates the impact of supplementary cementitious materials on the engineering properties of high-strength concrete. The study highlights how these materials influence properties such as compressive strength, durability, and workability, offering valuable insights for optimizing high-strength concrete formulations **Johari et al., 2012**.

The integration of deep learning methods into the study of cement hydration has been explored by researchers aiming to advance the understanding and prediction of cementitious binder performance. The study by Brooks et al. (2020) discusses the potential of deep learning to model the intricate hydration process, emphasizing the importance of parameters such as temperature and time on hydration evolution **Brooks et al., 2020**. The application of deep learning is highlighted as a powerful tool for capturing complex relationships in cement hydration, thereby facilitating the sustainable use of fly ash in concrete.

- **Isothermal Calorimetry in Hydration Studies**

Isothermal calorimetry has emerged as a pivotal technique for investigating the kinetics of cement hydration. This method measures the heat flow associated with cement hydration at a constant temperature, providing continuous data on heat release that correlates with reaction kinetics and the degree of hydration **Taylor, 1997**. Research by **Oey et al. (2013)** delves into the "filler effect" in cementitious materials, examining how filler content and surface area influence hydration rates. The findings highlight the relevance of fillers in modifying the kinetics and overall performance of cement-based systems **Oey et al., 2013**. The water-to-cement ratio is a critical parameter influencing the hydration mechanisms of cement. Ley-**Hernandez et al. (2015)** investigate how variations in this ratio affect the hydration process, providing a detailed understanding of its impact on the chemical and physical transformations in cementitious materials. Their study elucidates the complex relationship between the water-to-cement ratio and hydration kinetics, offering insights for optimizing concrete mix designs **Ley-Hernandez et al., 2015**.

The optimization of concrete performance hinges on a thorough understanding of cement hydration processes and the effective use of supplementary materials. This literature review underscores the significant progress made in the field through the application of advanced analytical techniques and machine learning models. The integration of AI and deep learning offers promising avenues for enhancing the predictive accuracy of hydration models, ultimately contributing to more sustainable and durable concrete formulations. To maximize the performance and durability of concrete, it is essential to investigate the kinetics of cement hydration. The method of measuring the heat flow related to cement hydration, known as isothermal calorimetry, offers important insights into the kinetics and mechanisms of the reactions. This thesis investigates how to use isothermal calorimetry to better understand cement hydration, analyses different factors that impact hydration kinetics, and creates predictive models to improve the design of concrete mixes. The study combines cutting-edge analytical methods with experimental data from isothermal calorimetry to provide a solid framework for enhancing the performance of cementitious materials.

At a fixed temperature, the heat flow related to cement hydration is measured using isothermal calorimetry. This method offers a continuous log of the heat released, which is correlated with the reaction kinetics and degree of hydration. Research findings indicate that isothermal calorimetry is a useful technique for observing the initial phases of hydration and determining how admixtures and supplementary cementitious materials (SCMs) impact the kinetics of hydration.

2.2 Research Gaps:

- **Long-Term Sustainability Metrics**: There is insufficient long-term data on the sustainability metrics of concrete with fly ash and GGBFS, especially regarding carbon footprint and energy savings over the life cycle of concrete structures.
- **Regional Variability in Availability**: The impact of regional variability in the availability and quality of fly ash and GGBFS on sustainable construction practices needs more study.
- **Economic Viability of SCMs**: More research is required to assess the economic viability and benefits of using SCMs in different regions and types of construction projects.
- **Adaptation to Regulatory Changes**: Studies are needed to understand how future changes in regulations regarding industrial by-products and waste management will affect the use of fly ash and GGBFS in concrete

2.3 Objective

- To assess the mechanical properties of cement using a compressive testing machine (CTM).
- To use an isothermal calorimeter to calculate the heat of hydration.
- To develop a heat of hydration prediction model using artificial intelligence.

By employing data-driven models, this report aims to unravel the complexities surrounding cement hydration. We intend to further the development of concrete technology and provide insights that will influence the design of high-performance, environmentally friendly concrete structures in the future. The strategic integration of fly ash and GGBFS is pivotal in this endeavour, as their complementary properties significantly enhance the sustainability and resilience of concrete mixtures. Through this project, we aspire to contribute to the advancement of concrete technology and support the construction industry's shift towards more sustainable and resilient practices.

CHAPTER 3

METHODOLOGY

3. Materials and Method

3.1. Materials

In this section, we will provide a detailed description of all materials used in the research, including their sources, properties, and preparation methods. This detailed explanation will help to ensure the reproducibility of the experiments and allow for a comprehensive understanding of the factors influencing the results.

3.1.1 Cement

Type: Ordinary Portland Cement

Grade: OPC 43 as per ASTM C150 .

Properties:

Chemical Composition: Contains various oxide composition (e.g., CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO).

Physical Properties:

Fineness (Blaine Surface Area): The fineness of OPC is typically measured by the Blaine air permeability test, which gives the specific surface area of the cement particles. The Blaine surface area for OPC used in this study is approximately 320 m^2/kg. A higher Blaine number indicates finer cement, which can contribute to higher early strength.

Specific Gravity: The specific gravity of OPC is about 3.15, which is used in mix design calculations to determine the volume of cement in a given weight.

Setting Times: Setting times of cement are found using the Vicat apparatus. The initial setting time for the OPC used in this study is around 120 minutes, and the final setting time is approximately 240 minutes. These times ensure adequate workability and allow sufficient time for concrete placement and finishing.

3.1.2 Fly Ash

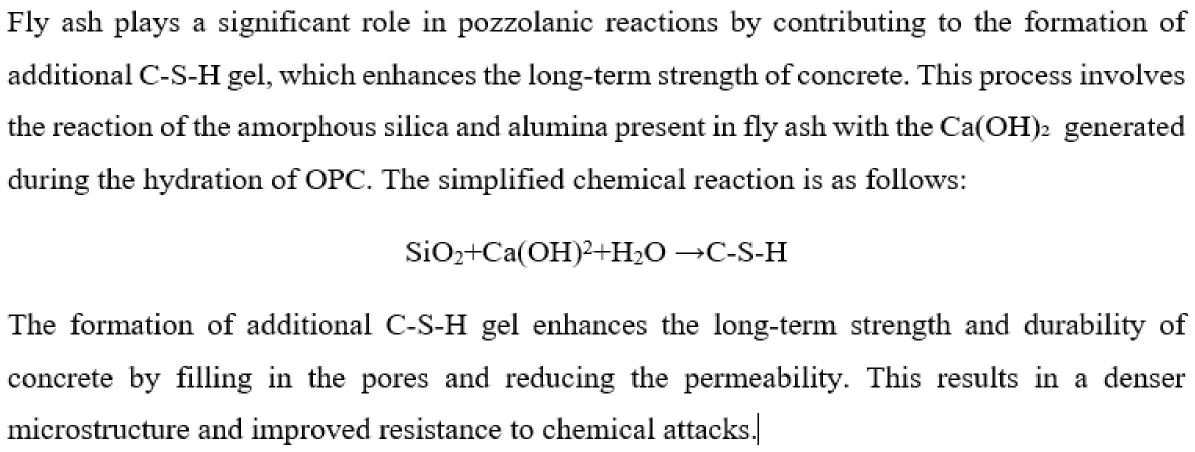
Type: Class F fly ash, conforming to ASTM C618.

Physical Properties:

I. Specific Surface Area: The Blaine surface area of fly ash typically ranges between 300 to 400 square meters per kilogram (m²/kg). This high specific surface area indicates a substantial reactivity because it provides a larger surface for chemical reactions to occur.

II. Specific Gravity: Fly ash has a specific gravity of approximately 2.74, which is lower compared to OPC. This reduced specific gravity is attributed to the presence of hollow spherical particles known as cenospheres within the fly ash.

Pozzolanic Activity: Explain how the fly ash contributes to the pozzolanic reaction, forming additional C-S-H gel and enhancing long-term strength.



Fly ash plays a significant role in pozzolanic reactions by contributing to the formation of additional C-S-H gel, which enhances the long-term strength of concrete. This process involves the reaction of the amorphous silica and alumina present in fly ash with the $Ca(OH)_2$ generated during the hydration of OPC. The simplified chemical reaction is as follows:

$$SiO_2+Ca(OH)^2+H_2O \rightarrow C\text{-}S\text{-}H$$

The formation of additional C-S-H gel enhances the long-term strength and durability of concrete by filling in the pores and reducing the permeability. This results in a denser microstructure and improved resistance to chemical attacks.

3.1.3 Ground Granulated Blast Furnace Slag (GGBFS)

Type: GGBFS conforming to ASTM C989, typically Grade 100 or 120.

Source: The GGBFS was sourced from MICROFINE PRODUCTS PVT. LTD.

Physical Properties: Fineness (Blaine Surface Area): The fineness of GGBFS is typically measured by the Blaine air permeability test. The Blaine surface area for the GGBFS used in this study is approximately 400-500 m²/kg, which indicates a high degree of fineness that contributes to its reactivity.

Specific Gravity: The specific gravity of GGBFS is around 2.9, which is lower than that of OPC but higher than fly ash. This intermediate specific gravity reflects the material's composition and particle structure.

Glass Content: GGBFS has a high glass content, usually above 90%, which is essential for its hydraulic reactivity. The glassy phase is responsible for the latent hydraulic properties of GGBFS.

Hydraulic Properties: Latent Hydraulic Nature: GGBFS exhibits latent hydraulic properties, meaning it has the potential to react with water, but requires an activator to do so effectively. The activator typically used is ($Ca(OH)_2$), which is a byproduct of the hydration of OPC. The reaction between GGBFS, water, and calcium hydroxide forms additional (C-S-H) gel, which is the primary binding phase in concrete.

Chemical Reaction: The latent hydraulic reaction can be simplified and represented by the following equations:

$$Ca(OH)^{2}+H_{2}O\rightarrow Ca^{2}++2OH-Ca(OH)^{2}+H_{2}O\rightarrow Ca^{2}++2OH-$$

$$Ca_{2}++SiO^{2}+H_{2}O\rightarrow C\text{-}S\text{-}HCa^{2}++SiO_{2}+H_{2}O\rightarrow C\text{-}S\text{-}H$$

Benefits: Concrete becomes stronger and more resilient as a result of the additional C-S-H formed by GGBFS reacting with water and calcium hydroxide. By reducing the porosity of the concrete, this gel's formation improves the material's resistance to harmful processes like the alkali-silica reaction and sulphate attack. This enhances the concrete structure's durability and functionality.

Activation: A number of variables, including the slag's fineness, the curing temperature, and the presence of extra chemical activators in the mixture, can affect the level of activation and the reactivity of GGBFS as a result. When used correctly, GGBFS can greatly enhance the concrete's durability and mechanical qualities.

When combined with fly ash and OPC, GGBFS has a synergistic effect that improves the overall qualities of concrete. Concrete that combines the latent hydraulic reaction from GGBFS with the pozzolanic reaction from fly ash produces a denser, more resilient material with better mechanical qualities and long-term performance.

3.1.4 Aggregates

Fine Aggregates:

Type: Natural river sand, conforming to ASTM C33.

Source: The fine aggregates were sourced from the sei construction mehre.

Particle Size Distribution: The particle size was determined using sieve analysis. The results showed that the majority of the sand particles ranged from 0.15 mm to 4.75 mm in diameter. This distribution is essential to ensure a well-graded sand that contributes to the workability and strength of the concrete.

Specific Gravity: Was measured to be of approximately 2.65. This value is crucial for the mix design calculations as it helps determine the volume of fine aggregates required for a given weight.

Fineness Modulus: The fineness modulus (FM) is a numerical value that indicates the average particle size of sand or fine aggregate. It is determined by summing the cumulative percentages of material retained on a series of standardized sieves and dividing by 100. In this study, the FM of the fine aggregates was found to be 2.75, suggesting a medium gradation that provides an optimal balance between workability and strength in the concrete mix.

Table 3.1: Properties of Fine Aggregates (River Sand)

Property	**Value**
Particle Size (mm)	0.15 - 4.75
Specific Gravity	2.65
Fineness Modulus	2.75

Fine aggregates play a critical role in the concrete mix by filling the voids between the coarse aggregates and contributing to the overall workability and finish of the concrete. The particle size distribution ensures that the sand provides a dense packing, while the specific gravity and fineness modulus are key parameters in the mix design, influencing the proportions of the other components to achieve the desired concrete properties.

Coarse Aggregates

Type: Stone Chips, conforming to ASTM C33.

Source: The coarse aggregates were sourced from sai construction mehre.

Properties:

Maximum Size: The maximum size is an important parameter that influences the workability and strength of concrete. In this study, the maximum size of the coarse aggregates was found to be 20 mm.

Specific Gravity: Was found to be approximately 2.70. This value is crucial for mix design calculations as it helps determine the volume of coarse aggregates required for a given weight.

Absorption Capacity: The absorption capacity of coarse aggregates indicates the amount of water that the aggregates can absorb. It is determined by immersing the aggregates in water for a specified period and then measuring the increase in weight. The absorption capacity of the coarse aggregates used in this study was found to be 0.8%.

Table 3.2: Properties of Coarse Aggregates

Property	Value
Maximum Size (mm)	20
Specific Gravity	2.70
Absorption Capacity (%)	0.8

Coarse aggregates, such as stone chips, provide the bulk and strength to concrete mixes. The maximum size, specific gravity, and absorption capacity of these aggregates are crucial parameters that influence the overall performance and durability of the concrete. Properly graded and well-controlled coarse aggregates ensure a dense and durable concrete mixture with minimal voids and improved resistance to environmental factors.

3.1.5 Water

Type: Potable water, free from impurities that could affect hydration or durability.

Source: Water supply from KANGNIDHAR MANDI HP sewerage water treatment plant.

Properties:

Quality Assurance Testing: To ensure the water quality is suitable for concrete mixing and curing, a series of tests were performed:

pH: The pH of the water was tested using a pH meter and found to be between 6.5 and 8.5. This range is suitable for concrete mixing as highly acidic or alkaline water can affect the setting time and strength of concrete.

Alkalinity: Alkalinity was measured using titration methods to determine the water's capacity to neutralize acids. The alkalinity of the water was found to be within the acceptable range of 50-200 mg/L as $CaCO_3$, which ensures that it does not negatively impact the concrete's properties.

Chloride Content: Chloride ions in water can lead to corrosion of steel reinforcement. The chloride content was determined using ion chromatography and found to be less than 500 mg/L, which is below the threshold that could cause corrosion-related issues in reinforced concrete.

Total Dissolved Solids (TDS): The TDS level was measured using a conductivity meter. The TDS of the water was found to be below 2000 mg/L, indicating that the water does not contain harmful concentrations of dissolved salts that could affect concrete properties.

Sulphate Content: Sulphate ions can lead to sulphate attack, which damages concrete. The sulphate content was measured using gravimetric methods and found to be less than 400 mg/L, ensuring it is within safe limits.

Table 3.3: Water Quality Test Results

Test	Method	Result	Acceptable Range
pH	pH Meter	7.2	6.5-8.5
Alkalinity (mg/L as $CaCO_3$)	Titration	150	50-200
Chloride Content (mg/L)	Ion Chromatography	200	<500
Total Dissolved Solids (mg/L)	Conductivity Meter	1200	<2000
Sulphate Content (mg/L)	Gravimetric	1300	<400

Ensuring the quality of water used in concrete mixing is critical to avoid adverse effects on the concrete's properties. The water quality tests conducted in this study confirm that the municipal water supply from Water Treatment Plant at KANGNIDHAR MANDI HP meets all the required standards for use in concrete production, ensuring the hydration process proceeds correctly and the durability of the concrete is not compromised.

3.1.6 Chemical Admixtures

Type: Chemical admixtures are used to enhance the properties of fresh and hardened concrete. The admixtures included in this study conform to ASTM C494 standards. The types used are superplasticizers and retarders.

Superplasticizer:

Product Name: Hyperplastic SP10

Retarder:

Product Name: SetRetard R20

Purpose:

Superplasticizer (Hyperplast SP101):

Role in Fresh Concrete: Superplasticizers are high-range water reducers that increase the workability of concrete without adding more water. They enable the production of highly workable or self-compacting concrete that can flow easily into forms and around reinforcement with minimal or no vibration. This is particularly beneficial for complex formwork or heavily reinforced sections.

Role in Hardened Concrete: By reducing the water-cement ratio while maintaining workability, superplasticizers enhance the strength and durability of the concrete. They contribute to higher early and ultimate compressive strengths and improve the concrete's impermeability, which increases its resistance to aggressive environments and reduces the likelihood of cracking.

Retarder (SetRetard R20):

Role in Fresh Concrete: Retarders delay the setting time of concrete, which is useful in hot weather conditions where rapid setting could be problematic. They allow for longer transportation times and extended workability periods, making them ideal for large pours or when placing concrete in difficult conditions.

Role in Hardened Concrete: By delaying the setting time, retarders help in reducing the risk of cold joints in successive layers of concrete. This ensures a more uniform and monolithic structure, enhancing the overall strength and integrity of the concrete. Additionally, they help in maintaining the workability of concrete for longer periods, which can result in a more consistent and homogenous mix.

Table 3.4: Chemical Composition and Physical Properties of Admixtures

Admixture Type	**Product Name**	**Specific Gravity**	**Dosage (%) by weight of cement**
Superplasticizer	Hyperplast SP101	1.08	0.5 - 1.5
Retarder	SetReta rd R20	1.02	0.1 - 0.5

admixtures play a vital role in modern concrete technology, enabling the production of concrete with tailored properties to meet specific performance requirements. The use of Hyperplast SP101 superplasticizer and SetRetard R20 retarder in this study ensures improved workability, enhanced strength, and extended durability of the concrete mix, which is essential for achieving the desired performance characteristics of the final product.

3.1.7 Supplementary Cementitious Materials (SCMs)

In order to partially replace regular OPC, fly ash and GGBFS are utilized as supplemental cementitious materials (SCMs) in this study. It is well known that both substances enhance concrete's durability and performance.

Fly Ash: Class F fly ash is used for its pozzolanic qualities. It is extracted from coal-fired power plants. It increases the long-term strength and durability of concrete by reacting with calcium hydroxide ($Ca(OH)_2$) created during the hydration of OPC to form additional C-S-H gel.

GGBFS: Sourced from microfine products pvt. Ltd. Corporation's blast furnace slag processing plant, GGBFS is a latent hydraulic material. It reacts with water and calcium hydroxide to form additional C-S-H gel, similar to fly ash, but with a higher early-age reactivity.

Proportions: Various replacement levels of fly ash and GGBFS were used in the experimental mixes to evaluate their combined effects on concrete properties. The proportions of SCMs are expressed as a percentage of the total cementitious material (OPC + SCMs):

Mix 1: 10% fly ash, 90% OPC

Mix 2: 20% fly ash, 80% OPC

Mix 3: 10% GGBFS, 90% OPC

Mix 4: 20% GGBFS, 80% OPC

These replacement levels were chosen to investigate the optimum blend of fly ash and GGBFS for enhancing the mechanical properties and durability of concrete while reducing the overall cement content, contributing to environmental sustainability.

3.2 Effects of Fly Ash and GGBFS in Concrete

3.2.1 Fly Ash

Fly ash enhances concrete strength through a pozzolanic reaction with calcium hydroxide, forming additional C-S-H gel, which improves compressive and tensile strengths over time. It also significantly increases durability by refining the concrete's pore structure, making it more resistant to chemical attacks from sulfates and chlorides. Additionally, fly ash reduces the heat of hydration, minimizing the risk of thermal cracking in mass concrete applications. Its spherical particles enhance workability, making concrete easier to place and finish without needing extra water or admixtures. Environmentally, incorporating fly ash in concrete lowers the carbon footprint by reducing the demand for Portland cement and managing industrial waste from coal-fired power plants.

3.2.2 GGBFS

GGBFS enhances strength through its latent hydraulic properties, forming C-S-H gel over time and making it suitable for high-performance concrete. It also improves durability by creating a dense microstructure resistant to sulfate attacks, alkali-silica reactions, and chloride ingress, leading to longer-lasting structures with reduced maintenance. Like fly ash, GGBFS reduces the heat of hydration, which is beneficial for large concrete pours to prevent thermal cracking. Its fine particles improve workability by reducing internal friction among aggregates, resulting in smoother and more workable concrete. Environmentally, GGBFS supports sustainability by recycling industrial waste from the steel industry and reducing CO_2 emissions associated with cement production.

Table 3.5: Proportions of SCMs in Experimental Mixes

Mix	**Fly Ash (%)**	**GGBFS (%)**	**OPC (%)**
Mix 1	10	00	90
Mix 2	20	00	80
Mix 3	00	10	90
Mix 4	00	20	80

The addition of fly ash and GGBFS as supplemental cementitious materials to concrete has several advantages. Concrete structures can have their performance, sustainability, and durability improved by knowing and utilizing their special qualities. When these materials are used strategically, concrete's engineering qualities are enhanced and more affordable and environmentally friendly construction solutions are produced.

3.3 Experimental Program

Mix Design

The experimental program aims to evaluate the effects of incorporating fly ash and ground granulated blast furnace slag (GGBFS) on the properties of concrete. Various mix designs with different proportions of these supplementary cementitious materials (SCMs) will be assessed for their impact on both fresh and hardened concrete.

Proportioning

To systematically investigate the influence of fly ash and GGBFS on concrete properties, a series of concrete mixes were designed with varying replacement levels of these SCMs while maintaining a constant ratio (w/b) of 0.4. This ratio ensures consistency in the mix and allows for a controlled comparison of the effects of the SCMs.

Mix Proportions:

- **Control Mix**: This mix contains 100% OPC with no SCMs, serving as the baseline for comparison.

- **Mix 1**: Incorporates 10% fly ash and no GGBFS, to isolate the effects of fly ash alone.
- **Mix 2**: Contains 20% fly ash and no GGBFS, providing a balanced mix to evaluate the combined effects of both SCMs.
- **Mix 3**: Includes 10% GGBFS and no fly ash, to isolate the effects of GGBFS alone.
- **Mix 4**: Uses 20% GGBFS, representing a significant replacement level for SCMs.

Each mix was designed to maintain a water-to-binder ratio (w/b) of 0.4, ensuring that the effects of the SCMs on workability, strength, and durability can be effectively compared without variations in water content.

Table 3.6: Mix Proportions for Experimental Concrete Mixes

Mix	**OPC (%)**	**Fly Ash (%)**	**GGBFS (%)**	**Water-to-Binder Ratio (w/b)**
Baseline	100	0	0	0.4
Mix 1	90	10	0	0.4
Mix 2	80	20	0	0.4
Mix 3	90	0	10	0.4
Mix 4	80	0	20	0.4

Mix Design Considerations:

Control Mix: Serves as the benchmark for evaluating the performance enhancements provided by fly ash and GGBFS.

Mix 1 (10% Fly Ash): Designed to assess the impact of fly ash on the workability, strength, and durability of concrete.

Mix 2 (20% Fly Ash): Examines the influence of higher fly ash content on the properties of concrete.

Mix 3 (10% GGBFS): Focuses on the contributions of GGBFS alone, particularly its early-age strength benefits.

Mix 4 (20% GGBFS): Looks at the impact of higher GGBFS content, particularly on the latent hydraulic reaction.

Rationale for Mix Proportions:

Consistency in Water Content: Maintaining a constant water-to-binder ratio of 0.4 ensures that any changes in concrete properties can be attributed to the SCMs rather than variations in water content.

Replacement Levels: The selected proportions allow for a comprehensive analysis of the individual and combined effects of fly ash and GGBFS on concrete properties. This approach helps identify the optimal blend of SCMs for enhancing performance and sustainability.

Evaluation Parameters: The designed mixes will be evaluated based on the following parameters:

Fresh Concrete Properties: Workability (slump test), setting time, and air content.

Hardened Concrete Properties: Compressive strength, tensile strength, flexural strength, and durability (chloride penetration, sulphate resistance, and freeze-thaw cycles).

By systematically varying the proportions of fly ash and GGBFS and maintaining a constant water-to-binder ratio, this experimental program aims to provide detailed insights into the optimal use of these SCMs in concrete production. The findings will contribute to the development of more sustainable and high-performance concrete mixtures.

3.4 Mixing Procedure

3.4.1 Batching

Batching involves accurately measuring and combining the materials required for each concrete mix based on the predetermined mix design proportions. This step is crucial for ensuring consistency and uniformity in the concrete mixes. Below are the detailed steps and a flowchart illustrating the batching process.

3.4.2 Detailed Batching Steps:

- **Preparation:**

Equipment Check: Ensure all batching equipment, including scales, mixers, and measuring devices, are calibrated and in proper working condition.

Materials Check: Confirm the availability and condition of all materials (cement, fly ash, GGBFS, aggregates, water, and admixtures).

- **Weighing of Materials:**

Cement: Measure the required amount of OPC based on the mix design.

Fly Ash: Weigh the specified quantity of fly ash as per the mix proportions.

GGBFS: Weigh the required amount of GGBFS according to the mix design.

Fine Aggregates: Measure the fine aggregates (sand) ensuring the correct weight.

Coarse Aggregates: Measure the coarse aggregates as specified.

Water: Measure the precise amount of water needed for the mix, taking into account any moisture content in the aggregates.

Chemical Admixtures: Measure the appropriate dosage of superplasticizers, retarders, or other admixtures as required.

- **Sequencing and Combining Materials:**

Dry Materials: Add the weighed cement, fly ash, GGBFS, fine aggregates, and coarse aggregates into the mixer.

Initial Mixing: Dry mix these materials for 1-2 minutes to ensure uniform distribution.

Water Addition: Gradually add the measured water into the mixer while it is running to avoid clumping and ensure even hydration.

Admixtures Addition: Add chemical admixtures as specified. Superplasticizers should be added after some water to avoid excessive clumping. Retarders or other admixtures can be added as per their recommended timing

- **Mixing:**

Initial Mixing: Continue mixing the combined materials for 3-5 minutes to achieve a homogenous mixture.

Rest Period: Allow the mix to rest for a few minutes to ensure proper absorption of water by the aggregates.

Final Mixing: Resume mixing for an additional 2-3 minutes to achieve the desired consistency and homogeneity.

- **Quality Check:**

Visual Inspection: Perform a visual check for uniformity and consistency of the mix.

Slump Test: Conduct a slump test to ensure the mix meets the required workability standards.

Adjustments: Make any necessary adjustments to water or admixture content based on the slump test results

- **Transfer:**

Transporting: Transfer the mixed concrete into wheelbarrows or other transport containers for delivery to the site or moulds.

Cleaning: Immediately clean all batching and mixing equipment to prevent material build-up and contamination for subsequent batches.

3.4.3 Mixing

The mixing process involves the careful combination of all concrete ingredients to ensure a uniform and consistent mixture. This is achieved through a specific sequence of adding dry materials, water, and chemical admixtures, followed by thorough mixing using a mechanical mixer. The following steps outline the detailed procedure for mixing:

3.4.4 Detailed Mixing Steps

Preparation:

Ensure the mechanical mixer is clean and free of any residual materials from previous mixes.

Check all materials (cement, fly ash, GGBFS, fine and coarse aggregates, water, and admixtures) are correctly measured and ready for use.

Loading the Mixer:

Add Dry Materials:

First, add the measured quantities of cement, fly ash, and GGBFS into the mixer.

Follow with the fine aggregates (sand) and then the coarse aggregates (gravel or crushed stone).

Initial Dry Mixing: Begin mixing the dry materials at a moderate speed for approximately 1-2 minutes to ensure an even distribution of all dry components.

Adding Water and Admixtures: Gradual Water Addition: Slowly add the measured water to the dry mix while the mixer is running to prevent clumping and ensure even hydration.

Incorporating Chemical Admixtures: Add the required dosage of super plasticizers and other chemical admixtures after some water has been mixed in. This helps distribute the admixtures more evenly and avoids potential clumping.

3.4.5 Main Mixing Phase:

Initial Wet Mixing:

Continue mixing all the ingredients at a moderate speed for about 3-5 minutes. This phase is crucial for achieving a homogeneous mixture.

Rest Period: Allow the mixture to rest for a few minutes to let the aggregates absorb the water and to reduce the formation of micro air bubbles.

Final Mixing: Resume mixing for an additional 2-3 minutes at a higher speed. This ensures that all materials are thoroughly combined and the mixture achieves the desired consistency.

Visual Inspection: Inspect the mixture visually to check for uniformity and consistency.

Slump Test: Perform a slump test to ensure that the concrete mix meets the required workability standards. Adjust the water or admixture content if necessary and re-mix to achieve the desired slump.

3.4.6 Discharging the Mix:

Transfer: Discharge the mixed concrete into wheelbarrows or other transport containers for delivery to the site or moulds.

Cleaning the Mixer: Immediately clean the mixer to prevent any remaining concrete from hardening and contaminating subsequent batches.

Mixing Times and Speeds

Initial Dry Mixing: 1-2 minutes at moderate speed.

Initial Wet Mixing: 3-5 minutes at moderate speed.

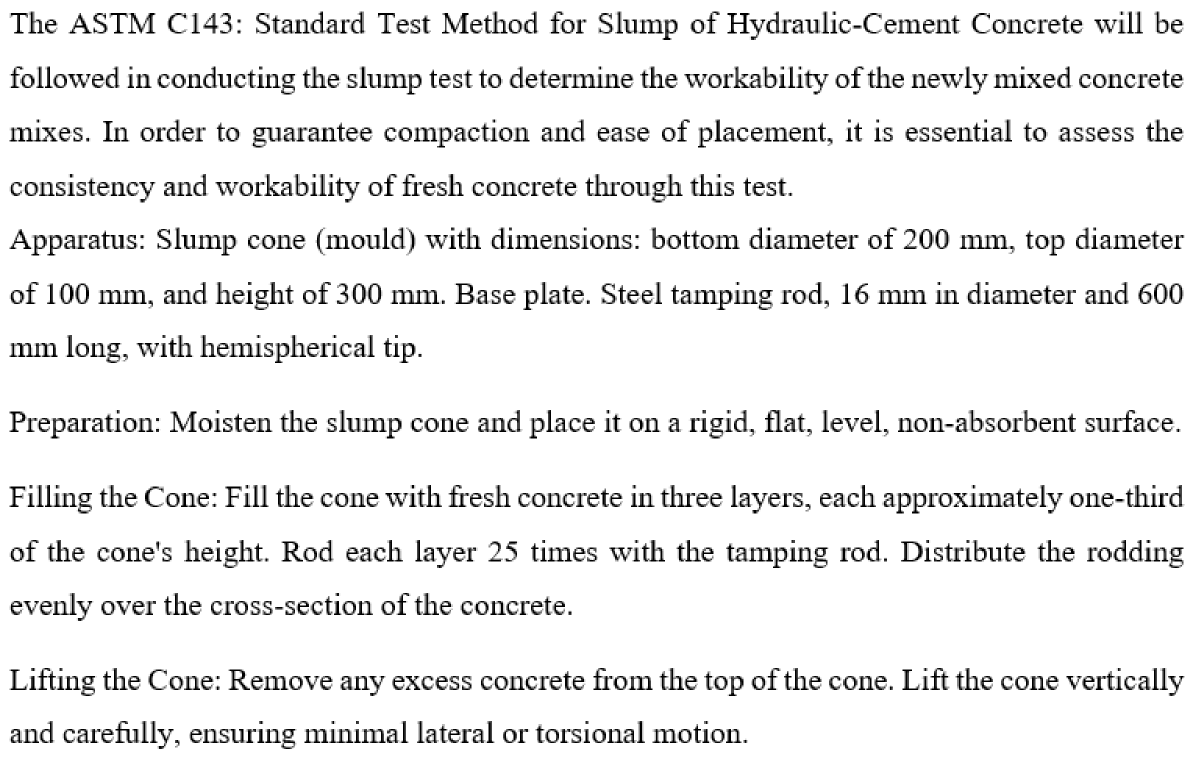
Rest Period: 2-3 minutes.

Final Mixing: 2-3 minutes at higher speed.

This detailed mixing procedure ensures the production of high-quality concrete with consistent properties. The sequence of mixing dry materials, gradual addition of water and admixtures, and thorough mixing at specified times and speeds are crucial for achieving a uniform and homogenous mix. Proper execution of these steps will result in concrete that meets the desired workability, strength, and durability requirements.

3.5 Physical Testing

3.5.1 Measuring the Slump of Fresh Concrete



The ASTM C143: Standard Test Method for Slump of Hydraulic-Cement Concrete will be followed in conducting the slump test to determine the workability of the newly mixed concrete mixes. In order to guarantee compaction and ease of placement, it is essential to assess the consistency and workability of fresh concrete through this test.

Apparatus: Slump cone (mould) with dimensions: bottom diameter of 200 mm, top diameter of 100 mm, and height of 300 mm. Base plate. Steel tamping rod, 16 mm in diameter and 600 mm long, with hemispherical tip.

Preparation: Moisten the slump cone and place it on a rigid, flat, level, non-absorbent surface.

Filling the Cone: Fill the cone with fresh concrete in three layers, each approximately one-third of the cone's height. Rod each layer 25 times with the tamping rod. Distribute the rodding evenly over the cross-section of the concrete.

Lifting the Cone: Remove any excess concrete from the top of the cone. Lift the cone vertically and carefully, ensuring minimal lateral or torsional motion.

Measuring the Slump:

Measure the vertical distance between the top of the cone and the displaced original centre of the concrete specimen. This distance is the slump value, indicating the concrete's workability.

Expected Impact of Fly Ash and GGBFS on Workability

Fly Ash: Typically improves the workability of concrete due to its spherical particle shape, which acts as a lubricant between the aggregate particles. Fly ash can reduce water demand and enhance the mix's flowability and cohesiveness, leading to improved workability and ease of placement.

GGBFS: Also improves workability, but to a lesser extent than fly ash. GGBFS particles are angular and less spherical compared to fly ash, contributing to better packing density. When used together with fly ash, GGBFS can help achieve a balance between workability and strength, making the mix easier to handle and place without compromising performance.

Table 7: Slump Values for Experimental Concrete Mixes

Mix	OPC (%)	Fly Ash (%)	GGBFS (%)	Slump (mm)
Control	100	0	0	75
Mix 1	80	10	0	82
Mix 2	90	20	0	85
Mix 3	80	0	10	77
Mix 4	90	0	20	78

By understanding the impact of different SCM proportions on workability, the mix designs can be optimized for specific construction needs, ensuring ease of placement and consolidation while maintaining desired mechanical properties.

3.5.2 Specimen Preparation and Curing

Moulding: Proper moulding of concrete specimens is crucial for ensuring accurate and reliable testing of concrete properties. This section describes the detailed process of pouring concrete into moulds, compacting each layer, and specifies the types and dimensions of moulds used.

Moulding Process:

Preparation: Clean the Molds: Ensure all moulds are clean, free from debris, and lightly oiled to facilitate easy demoulding.

Mix Preparation: After mixing, transport the fresh concrete to the moulding area promptly to prevent segregation and setting.

Type and Dimensions of Molds:

Cubes: Standard cube moulds with dimensions of 150 mm x 150 mm x 150 mm.

Pouring Concrete into Molds:

Layering: Pour the concrete mix into the mould in layers to ensure uniform compaction and minimize air voids. For cylindrical and cube moulds, fill in three equal layers.

Compaction: Compact each layer to remove entrapped air and ensure good contact between the concrete and the Mold surface.

Manual Compaction: Use a standard steel rod (16 mm diameter, 600 mm long) to rod each layer 25 times uniformly.

Vibration: If using a vibrating table, vibrate each layer for approximately 5-10 seconds or until air bubbles cease to rise to the surface.

Finishing: Surface Smoothing: After the final layer is placed and compacted, smooth the surface with a trowel to ensure it is level and free of voids.

Labelling:

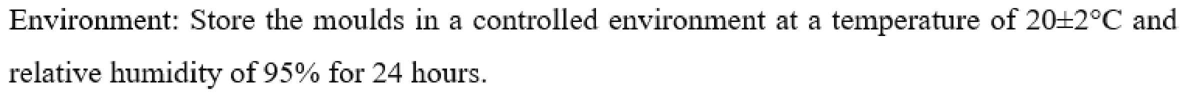
Identification: Label each mould with a unique identifier, including the mix type, date of casting, and any other relevant information for traceability.

Curing: For concrete to reach the appropriate strength and longevity, proper curing is necessary. This section describes the curing process, which entails preserving the proper levels of moisture, temperature, and time in order to promote the cementitious materials' ideal hydration.

Curing Process:

Initial Curing:

Protection in Molds: Keep the freshly moulded specimens in their moulds and cover them with plastic sheets or wet burlap to prevent moisture loss.



Environment: Store the moulds in a controlled environment at a temperature of 20±2°C and relative humidity of 95% for 24 hours.

Demoulding: After 24 hours, carefully remove the specimens from the moulds to avoid any damage.

Subsequent Curing:

Water Curing:

Submerge the demoulded specimens in a curing tank filled with water maintained at 20±2°C. Ensure the specimens are fully immersed and not touching each other or the sides of the tank.

Moist Curing: Alternatively, put the specimens in a moist curing room or chamber with a humidity level of 95% and a temperature maintained at 20±2°C. Wet burlap or other materials that retain moisture should be placed over the specimens.

Duration: Standard curing times are typically 7, 14, and 28 days, depending on the specific requirements of the testing protocol. Extended curing periods may be used for additional long-term strength and durability tests.

Quality Control:

Monitoring: Regularly check the water level and temperature in the curing tank or the humidity levels in the moist curing room to ensure consistent curing conditions.

Handling: Handle the specimens carefully during and after curing to avoid any mechanical damage that could affect test results. Proper moulding and curing are critical to achieving consistent and reliable concrete properties. By following these detailed procedures, we can ensure that the concrete specimens are prepared and cured under optimal conditions, leading to accurate assessments of their performance characteristics

3.5.3 Testing and Evaluation

Compressive Strength

The compressive strength test is a crucial step in determining the mechanical properties of concrete. The maximum compressive load that a concrete specimen can withstand before failing is determined by this test.

Testing Procedure

Objective: To find out the compressive strength of concrete specimens prepared with varying proportions of fly ash and GGBFS.

Apparatus:

Compression Testing Machine: Calibrated and capable of applying a continuous load at a controlled rate.

Bearing Plates: Hardened steel bearing blocks with spherical seating to ensure uniform load distribution.

Measuring Devices: Vernier callipers or other precision instruments to measure specimen dimensions.

Specimen Preparation:

Selection: Choose specimens that have been cured for the specified durations (e.g., 7, 14, and 28 days).

Conditioning: Remove the specimens from the curing environment and allow surface moisture to dry for a consistent testing condition.

Testing Steps:

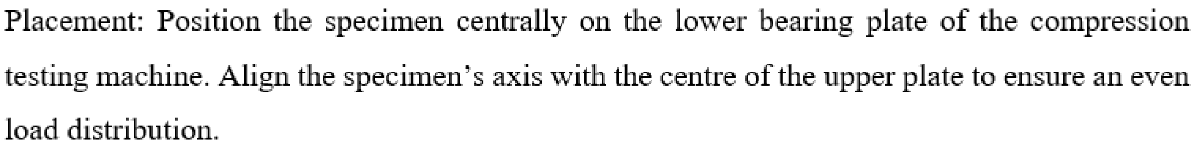
Preparation of Specimens:

Measure Dimensions: Use callipers to measure the diameter and height of each specimen to the nearest 0.1 mm. Record the measurements for calculating the cross-sectional area.

Clean Surfaces: Ensure the ends of the specimens are clean and free from any debris. If necessary, cap the ends with sulphur mortar or neoprene pads to provide a smooth bearing surface.

Setup of Compression Testing Machine:

Calibration: Verify that the compression testing machine is properly calibrated.



Placement: Position the specimen centrally on the lower bearing plate of the compression testing machine. Align the specimen’s axis with the centre of the upper plate to ensure an even load distribution.

Adjustment: Adjust the spherical seating to accommodate any irregularities in the specimen ends.

Loading Procedure:

Initial Contact: Apply a small preload to ensure full contact between the specimen and bearing plates.

Loading Rate: Apply the load continuously and without shock at a constant rate within the range of 0.15 to 0.35 MPa/s (megapascals per second), as per ASTM C39 specifications.

Monitoring: Observe the load applied and monitor the behaviour of the specimen. Continue loading until the specimen fails.

Recording Results:

Maximum Load: Record the maximum load carried by the specimen at the point of failure. This value is the peak load observed on the compression testing machine.

Failure Mode: Note the mode of failure (e.g., shear, splitting, or crushing) and any significant observations about the specimen's behaviour during testing.

Calculations:

Compressive Strength: Calculate the compressive strength of each specimen using the formula:

Compressive Strength (MPa)=Maximum Load (N)/-Sectional Area (mm)^2

Cross-Sectional Area: Determine the cross-sectional area based on the measured diameter of the specimen.

Documentation:

Data Recording: Document all relevant data including specimen identification, dimensions, maximum load, compressive strength, and any observations regarding the failure mode.

Average Values: Calculate the average compressive strength for specimens from each mix and curing age to assess the overall performance.

Safety Considerations:

Protective Gear: Ensure that all personnel wear appropriate personal protective equipment (PPE), such as safety goggles, gloves, and steel-toed boots.

Machine Operation: Only trained personnel should operate the compression testing machine. Follow all safety protocols to avoid accidents.

Interpretation of Results:

Strength Development: Compare the compressive strength values at different curing ages (7, 14, and 28 days) to understand the strength development pattern.

Impact of SCMs: Analyse the effect of fly ash and GGBFS proportions on the compressive strength. Identify any trends or significant differences attributable to the SCM combinations.

The compressive strength test provides vital information about the structural performance of concrete. By following this detailed procedure, accurate and reliable data can be obtained, which is essential for assessing the quality and suitability of concrete mixes incorporating fly ash and GGBFS. This information aids in optimizing mix designs and ensuring compliance with structural and durability requirements.

3.5.4 Hydration Kinetics

Analysing the hydration kinetics of concrete mixes provides insights into the rate and extent of cement hydration, which directly influences concrete properties such as strength development, setting time, and durability. Isothermal calorimetry is a valuable technique for studying the heat evolution during cement hydration reactions, offering real-time monitoring of the hydration process. In our study, we utilize isothermal calorimetry to investigate the hydration kinetics of concrete mixtures containing fly ash and ground granulated blast furnace slag (GGBFS).

Experimental Procedure

Sample Preparation: Prepare concrete mixtures with varying proportions of fly ash and GGBFS, along with control mixes containing only OPC. Ensure that the mix designs are consistent with those used for compressive strength and flexural strength testing. Cast small cylindrical specimens or prisms for calorimetry testing, ensuring uniformity in dimensions and curing conditions.

Calorimetry Setup: Use an isothermal calorimeter equipped with sensitive sensors to measure heat flow and temperature changes during cement hydration. Calibrate the calorimeter according to manufacturer specifications to ensure accurate data acquisition.

Test Conditions: Maintain a constant temperature throughout the test period, typically at 20°C or 25°C, to simulate ambient curing conditions. Place the concrete specimens in the calorimeter chamber and allow them to equilibrate to the desired test temperature before initiating hydration.

Data Collection: Start the calorimetry test and continuously monitor heat evolution and temperature changes over time. Record data points at regular intervals (e.g., every minute or every five minutes) to capture the entire hydration process.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Analysis

Statistical Analysis

Statistical analysis plays a crucial role in interpreting experimental data and drawing meaningful conclusions from research findings. In the context of our study on the effect of fly ash and ground granulated blast furnace slag (GGBFS) on concrete properties.

Inferential Statistics:

Hypothesis Testing: Use parametric or non-parametric tests to compare means or distributions between different mixtures or curing ages.

Regression Analysis: Fit regression models to predict concrete properties based on independent variables (e.g., SCM proportions, curing age). Assess the goodness of fit and significance of regression coefficients to understand the influence of predictors on concrete performance.

Graphical Analysis: Visualize the data using histograms, box plots, scatter plots, and line graphs to identify trends, outliers, or patterns. Create comparative graphs to illustrate differences in strength values between different experimental groups or curing ages.

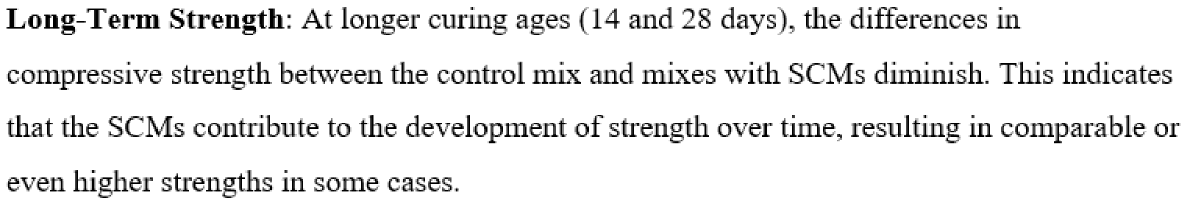
Software Tools: Statistical software packages such as R, Python, MATLAB, or dedicated statistical software like SPSS or SAS can be used for data analysis. Graphing tools like Excel, MATLAB, or Python's matplotlib and seaborn libraries can generate plots and visualizations.

Discussion of Trends

Overall Performance: The compressive strength of all concrete mixes generally increases with curing age, which is expected as hydration continues over time.

Effect of SCMs: Mixes incorporating fly ash and GGBFS (Mixes 1 to 4) demonstrate comparable or slightly lower compressive strength compared to the control mix at all curing ages.

Early Strength: Mixes containing SCMs (Mixes 1 to 4) exhibit slightly lower early-age strengths (7 days) compared to the control mix. This can be attributed to the pozzolanic and latent hydraulic properties of the SCMs, which may initially slow down the rate of strength gain.



Long-Term Strength: At longer curing ages (14 and 28 days), the differences in compressive strength between the control mix and mixes with SCMs diminish. This indicates that the SCMs contribute to the development of strength over time, resulting in comparable or even higher strengths in some cases.

Optimization: Further optimization of the mix designs incorporating SCMs may be necessary to fully exploit their potential benefits in terms of strength development and durability.

Consistency: The consistency in strength results across replicate specimens within each mix indicates the reliability of the testing procedures and the consistency of the concrete mixes.

By presenting the compressive strength results in both tabular and graphical formats, the trends and performance of the different mixtures can be easily visualized and compared. These insights are valuable for optimizing mix designs and informing decisions regarding the use of SCMs in concrete production.

Table 4: Compressive strength

Mix	**Curing Age (days)**	**Specimen 1 (MPa)**	**Specimen 2 (MPa)**	**Specimen 3 (MPa)**	**Average Strength (MPa)**
Control	7	30.2	31.5	29.8	30.5
	14	38.7	39.2	37.8	38.6
	28	45.6	46.2	44.8	45.5
Mix 1	7	28.5	29.1	27.8	28.5
	14	36.2	37.0	35.5	36.2
	28	42.8	43.5	41.9	42.7
Mix 2	7	29.8	30.5	28.9	29.7
	14	37.5	38.1	36.7	37.4
	28	44.1	44.8	43.2	44.0
Mix 3	7	27.3	28.0	26.7	27.3
	14	34.8	35.5	33.9	34.7
	28	41.2	41.8	40.3	41.1
Mix 4	7	29.0	29.7	28.3	29.0
	14	36.8	37.4	35.9	36.7
	28	43.2	43.8	42.1	43.0

4.2 Data Interpretation

Comparison of Heat Evolution Profiles:

Heat flow curves for each concrete mixture, depicting the rate of heat release over time.

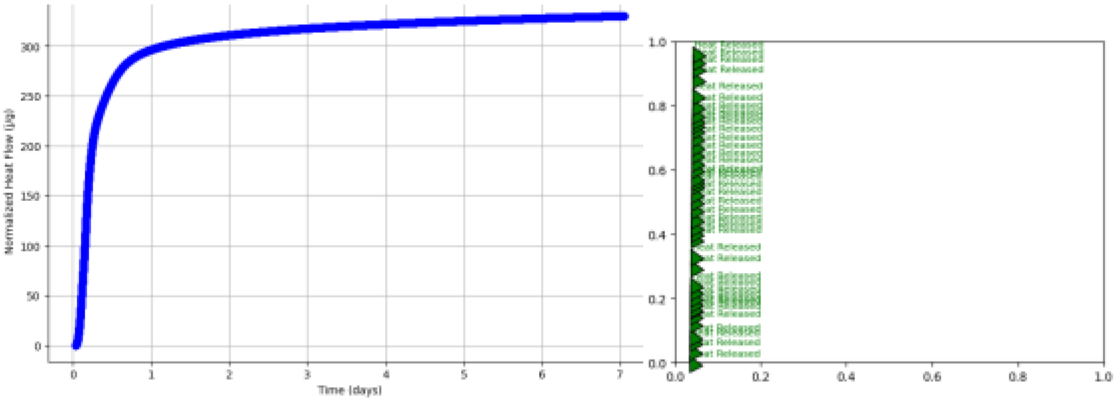


Figure 1: Baseline mix

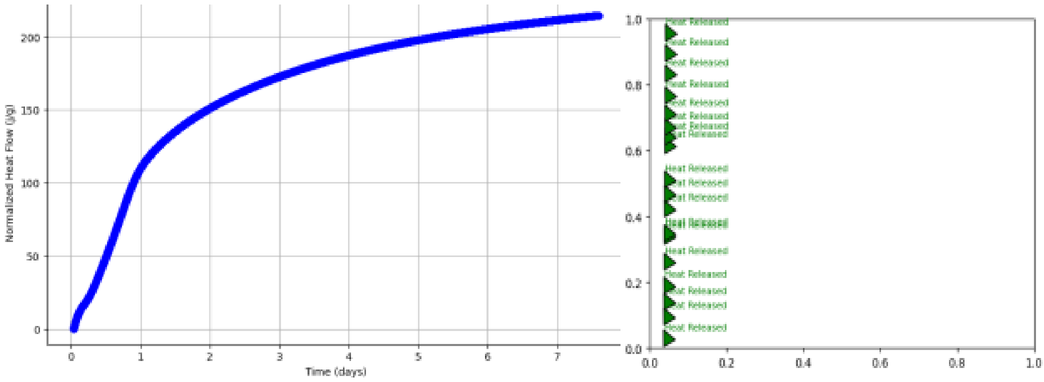


Figure 2:(opc+ggbfs20%)

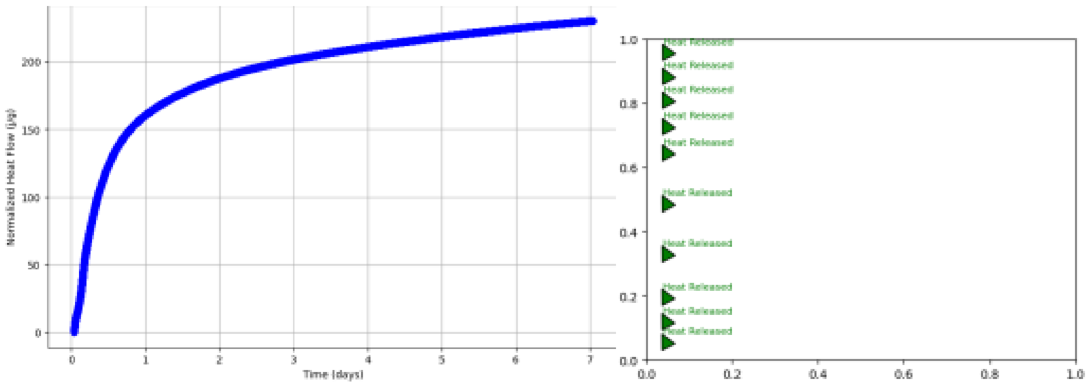


Figure 3:(opc+fly ash20%)

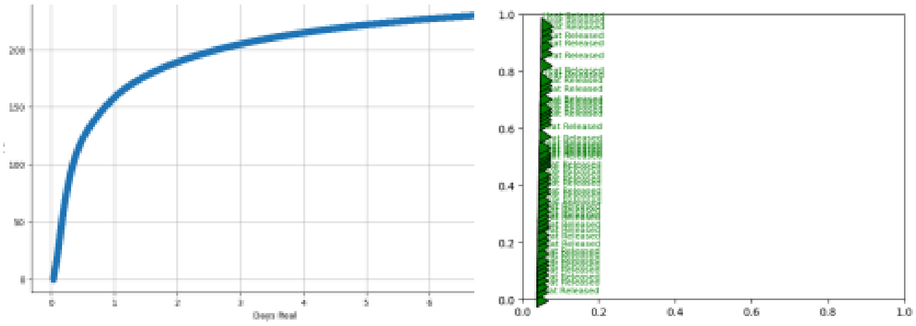


Figure 4:(opc+ggbfs10%)

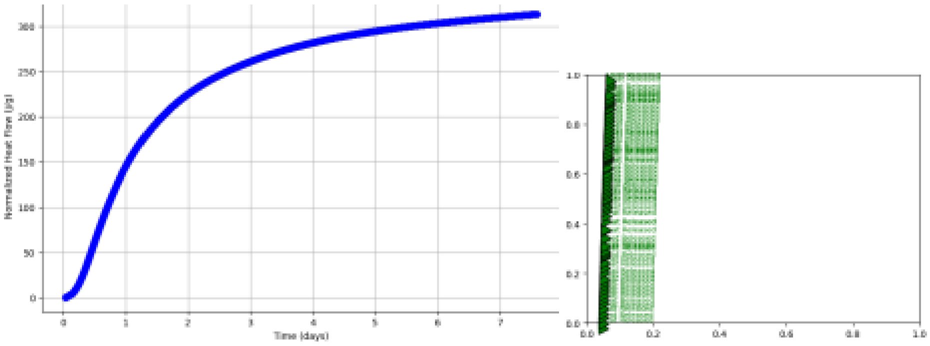


Figure 5:(opc+fly ash10%)

Impact of Supplementary Cementitious Materials (SCMs):

- **Early Heat Release:** GGBFS typically results in a higher early heat release compared to fly ash. This is due to its more reactive nature and the latent hydraulic reaction, which is more similar to the hydration of Portland cement.

- Overall **Heat Release:** Over the entire hydration period, mixtures with GGBFS will often release more heat in the early stages but may have similar or slightly higher cumulative heat release over time compared to mixtures with fly ash.

6.3.4 Predicted model Results:

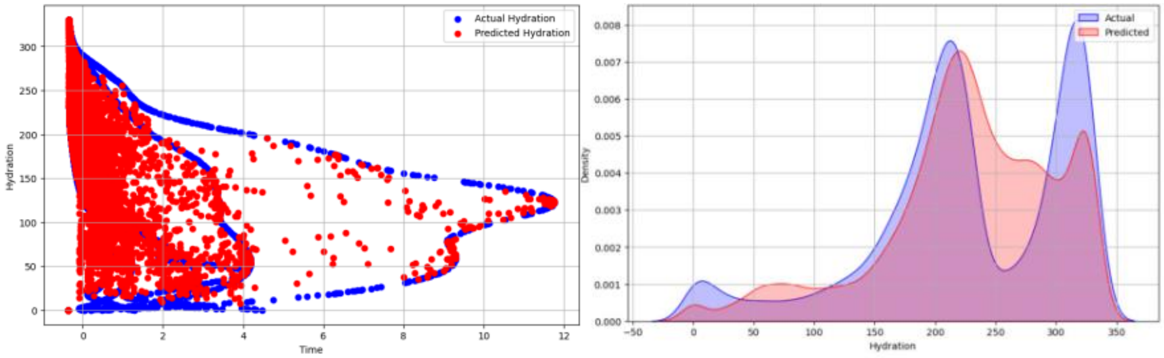


Figure 6:predicted hydration profile

The incorporation of SCMs like fly ash and GGBFS into concrete significantly influences both early-age and long-term hydration characteristics. These changes have far-reaching implications for concrete performance and sustainability. Isothermal calorimetry provides valuable insights into the hydration kinetics of concrete mixes, facilitating a deeper understanding of cementitious materials' behaviour and their impact on concrete performance. By analysing heat evolution profiles and comparing hydration kinetics among different mixtures, we can optimize mix designs, predict concrete behaviour, and advance the development of sustainable construction materials.

Accuracy of Hydration Prediction:

The graphs indicate a good overall agreement between the predicted hydration and the actual hydration over time, as shown by the proximity of the blue (actual) and red (predicted) data points. This suggests that the regression model effectively captures the general trend of the hydration process.

The dispersion of red points around the blue curve suggests some variability in the predictions, indicating that while the model captures the main trend, there are discrepancies at certain time intervals or hydration values. This may point to factors not fully accounted for by the model, such as specific interactions between different binders and cement.

4.3 Discussion

Comparison of Fly Ash and GGBFS

Performance of Mixtures Containing Fly Ash and GGBFS:

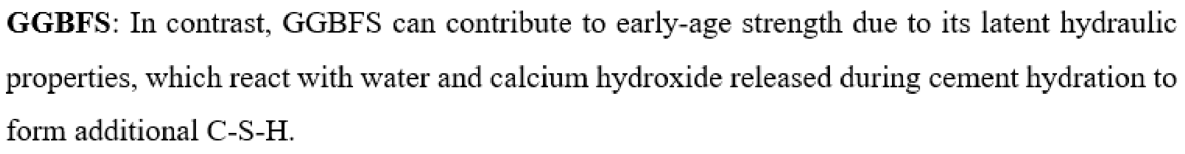
Workability:

Fly Ash: Because of its smooth texture and spherical particle shape, fly ash generally increases the workability of concrete mixtures. By functioning as tiny ball bearings, fly ash particles lower internal friction and facilitate the handling and placement of the concrete mix.

GGBFS: Ground granulated blast furnace slag (GGBFS) also enhances workability, though its effect is less pronounced compared to fly ash. The finer particles of GGBFS contribute to a more cohesive mix, reducing segregation and bleeding.

Strength:

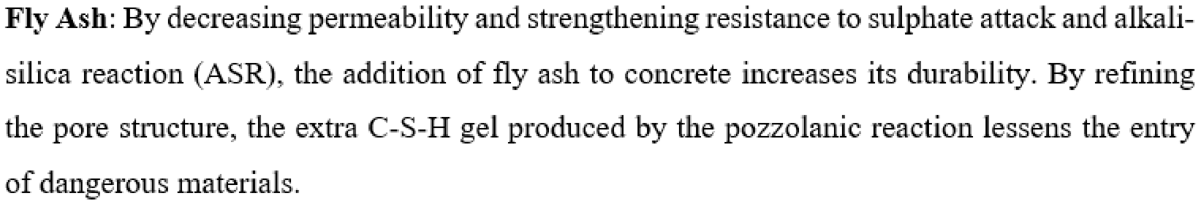
Early-Age Strength: Concrete mixes containing fly ash often show reduced early-age strength due to the slower pozzolanic reaction. The initial hydration products formed by fly ash are less dense and slower to develop compared to those from Portland cement hydration.



GGBFS: In contrast, GGBFS can contribute to early-age strength due to its latent hydraulic properties, which react with water and calcium hydroxide released during cement hydration to form additional C-S-H.

Long-Term Strength: GGBFS and fly ash both make substantial contributions to the long-term development of strength. By combining with calcium hydroxide, fly ash creates more C-S-H gel, which increases strength and decreases permeability. In comparison to fly ash, GGBFS offers comparable advantages through its hydraulic reaction, frequently producing higher long-term strengths.

Durability:



Fly Ash: By decreasing permeability and strengthening resistance to sulphate attack and alkali-silica reaction (ASR), the addition of fly ash to concrete increases its durability. By refining the pore structure, the extra C-S-H gel produced by the pozzolanic reaction lessens the entry of dangerous materials.

GGBFS: GGBFS also enhances durability through similar mechanisms. The formation of dense C-S-H gel from the hydraulic reaction reduces permeability and improves resistance to chemical attacks. GGBFS-containing concrete is particularly effective in environments exposed to chloride and sulphate ions.

Advantages and Limitations:

Fly Ash:

Advantages: Improved workability, reduced heat of hydration, enhanced long-term strength and durability, and cost savings. Fly ash is also an environmentally friendly material as it utilizes industrial by-products.

Limitations: Reduced early-age strength, variability in quality depending on the source, and potential delay in setting time.

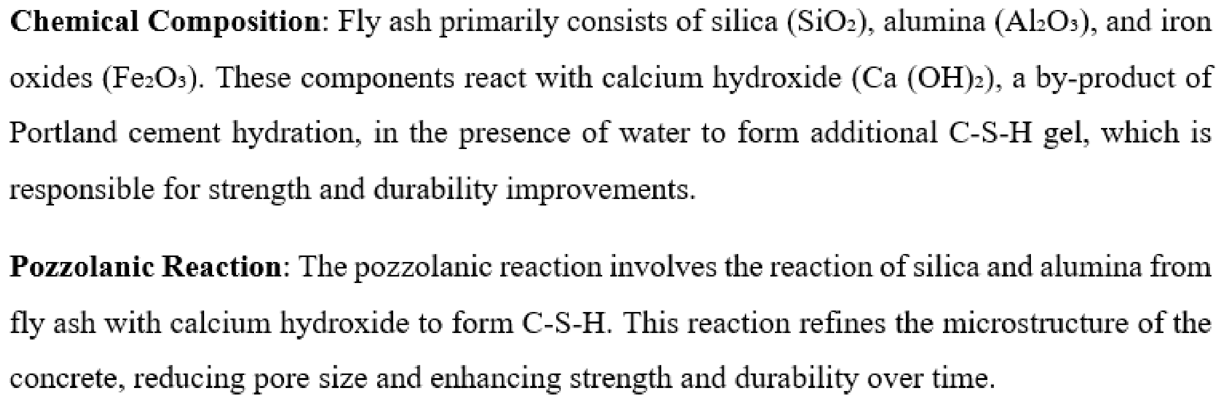
GGBFS:

Advantages: Enhanced early-age and long-term strength, improved durability, reduced permeability, and significant environmental benefits by utilizing industrial by-products.

Limitations: Higher cost compared to fly ash, potential variability in quality, and slower initial set times in some cases.

Mechanism of Action

Fly Ash:



Chemical Composition: Fly ash primarily consists of silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3). These components react with calcium hydroxide ($Ca(OH)_2$), a by-product of Portland cement hydration, in the presence of water to form additional C-S-H gel, which is responsible for strength and durability improvements.

Pozzolanic Reaction: The pozzolanic reaction involves the reaction of silica and alumina from fly ash with calcium hydroxide to form C-S-H. This reaction refines the microstructure of the concrete, reducing pore size and enhancing strength and durability over time.

GGBFS:

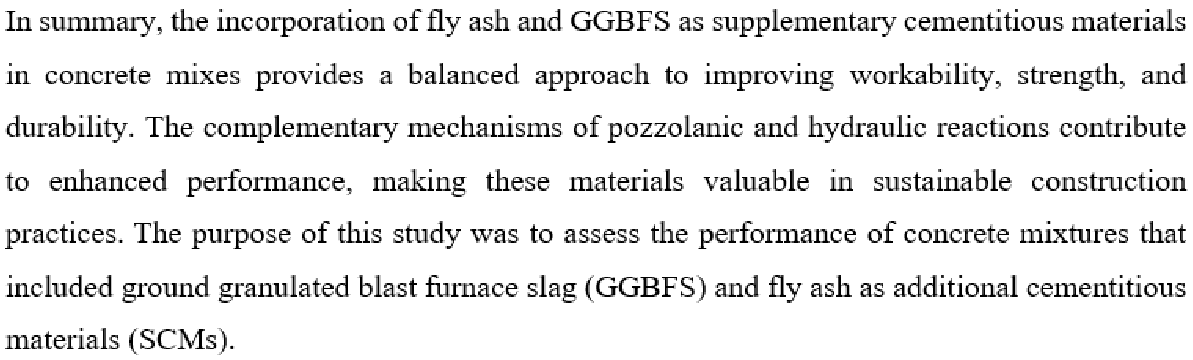
Chemical Composition: GGBFS is composed of calcium oxide (CaO), silica (SiO_2), alumina (Al_2O_3), and magnesia (MgO). These components react with water in a latent hydraulic reaction to form C-S-H, similar to the hydration products of Portland cement.

Hydraulic Reaction: The latent hydraulic nature of GGBFS means that it can react directly with water to form C-S-H and other hydration products. This reaction is accelerated in the presence of calcium hydroxide, leading to early strength gain and dense microstructure development.

Theoretical Explanations and Literature Support:

Studies have shown that the use of fly ash and GGBFS in concrete can significantly enhance performance. For example, Thomas (2007) demonstrated that fly ash improves long-term strength and durability by refining the pore structure and reducing permeability. Similarly, GGBFS has been shown to improve early-age strength and resistance to chemical attacks (Juenger et al., 2011).

Research by Escalante-García et al. (2003) indicates that blends of fly ash and GGBFS can optimize the hydration process, leading to a more homogeneous and resilient concrete matrix.



In summary, the incorporation of fly ash and GGBFS as supplementary cementitious materials in concrete mixes provides a balanced approach to improving workability, strength, and durability. The complementary mechanisms of pozzolanic and hydraulic reactions contribute to enhanced performance, making these materials valuable in sustainable construction practices. The purpose of this study was to assess the performance of concrete mixtures that included ground granulated blast furnace slag (GGBFS) and fly ash as additional cementitious materials (SCMs).

The following is a summary of the study's main conclusions:

Workability: Concrete mixtures containing fly ash demonstrated improved workability due to the spherical shape of the particles, which acted as a lubricant and reduced internal friction. GGBFS also contributed to improved workability, enhancing the cohesiveness of the mix and reducing segregation and bleeding.

Strength Development: Because of the delayed pozzolanic reaction, the early-age strength of concrete mixtures containing fly ash was marginally lower than that of the control mix.

GGBFS's incorporation, however, lessened this decrease by offering early strength via its latent hydraulic reaction.

Durability: Both fly ash and GGBFS improved the durability of concrete by reducing permeability and enhancing resistance to chemical attacks such as sulphate attack and alkali-silica reaction (ASR).

Hydration Kinetics: Isothermal calorimetry analysis revealed distinct heat evolution profiles for mixtures containing fly ash and GGBFS. Fly ash exhibited a slower heat release rate due to its pozzolanic nature, while GGBFS demonstrated a more rapid heat release associated with its hydraulic reaction.

Environmental and Economic Benefits: The use of fly ash and GGBFS as SCMs contributes to sustainability by reducing the reliance on Portland cement, lowering greenhouse gas emissions, and utilizing industrial by-products. Economic benefits include cost savings from reduced cement usage and potential long-term savings from improved durability and reduced maintenance requirements.

Practical Implications

The findings of this study have several practical implications for the use of GGBFS in concrete mixtures:

Cost Savings:The use of GGBFS can lead to significant cost savings in concrete production. By partially replacing Portland cement with GGBFS, the overall material costs can be reduced. This is particularly important in large-scale construction projects where material costs constitute a significant portion of the budget. Long-term cost savings can also be realized through enhanced durability and reduced maintenance requirements. Concrete mixtures containing GGBFS are more resistant to chemical attacks and have lower permeability, which translates to longer service life and fewer repairs.

Environmental Benefits: Reducing the carbon footprint associated with cement production is one way that incorporating GGBFS into concrete mixtures promotes sustainability. With its application in concrete, GGBFS—a byproduct of the steel industry—helps minimize waste and lower greenhouse gas emissions. GGBFS utilization is in line with green building principles and can help achieve LEED (Leadership in Energy and Environmental Design) certification for sustainability. By doing so, you can encourage sustainable development and improve the environmental profile of construction projects.

Performance Enhancement: The inclusion of GGBFS in concrete mixtures enhances both early-age and long-term performance. This makes it suitable for a wide range of applications, including structural concrete, precast elements, and high-performance concrete. The improved durability of GGBFS-containing concrete makes it particularly suitable for infrastructure projects exposed to harsh environmental conditions, such as marine structures, bridges, and wastewater treatment plants.

Workability and Handling: The improved workability of concrete mixtures containing GGBFS facilitates easier mixing, handling, and placement. This can lead to increased productivity on construction sites and better-quality control. The cohesive nature of GGBFS-containing mixtures reduces segregation and bleeding, resulting in more uniform and homogeneous concrete.

CONCLUSION

The integration of fly ash and GGBFS as SCMs in concrete not only enhances its performance but also offers significant environmental and economic benefits. The findings of this study underscore the importance of these materials in advancing concrete technology and promoting sustainable construction. By leveraging the advantages of SCMs, we can develop high-performance, durable, and sustainable concrete for a wide range of applications, contributing to a more resilient and sustainable built environment.

Future research on fly ash and GGBFS in concrete should focus on long-term performance studies to assess durability under varied environmental conditions, validating lab findings with real-world data. Exploring combinations with other supplementary cementitious materials (SCMs) like metakaolin and silica fume could lead to improved concrete mixes. Utilizing advanced techniques like X-ray diffraction and scanning electron microscopy will provide deeper insights into the microstructural changes and hydration mechanisms. Performance-based specifications for SCMs should be developed to ensure consistent quality and sustainability. Life cycle assessments are crucial for quantifying environmental impacts and promoting SCM use in sustainable construction. Overall, these research directions aim to optimize the performance, durability, and sustainability of concrete mixes incorporating fly ash and GGBFS.

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