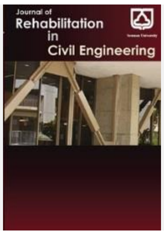

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Impact of GGBFS and Pond Ash on the Strength and Durability of Concrete Mixes

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ABSTRACT

This study investigates the sustainability and performance of M20 and M30 grade concrete incorporating Ground Granulated Blast Furnace Slag (GGBFS) and Pond Ash as partial replacements for Ordinary Portland Cement (OPC) and fine aggregates, respectively. Replacement levels were varied between 10% and 50%, and their effects on workability, strength, and durability were analyzed using Multiple Linear Regression (MLR) and Principal Component Analysis (PCA). Concrete mixes with up to 40% replacement demonstrated enhanced workability (R^2 = 99.96%, MAPE = 0.85%), attributed to improved particle packing and reduced internal friction. However, beyond this threshold, workability declined due to increased porosity and water absorption. Compressive strength (CS), flexural strength (FS), and split tensile strength (SPT) showed a diminishing trend with higher replacement levels. Model for compressive strength achieved an R^2 of 97.21% and MAPE of 3.21%, while flexural strength model had an R^2 of 99.68% and MAPE of 1.13%, indicating high predictive accuracy. Durability assessments revealed a decline in water absorption (R^2 = 88.05%, MAPE = 5.45%) and acid attack resistance (R^2 = 99.83%, MAPE = 0.58%) with increasing GGBFS and Pond Ash content, primarily due to increased porosity and altered microstructural characteristics. Microstructural analysis confirmed reduced hydration density and weaker bond formation at higher replacement levels. Economically and environmentally, the use of GGBFS and Pond Ash reduces carbon emissions and reliance on natural resources, providing cost-effective and sustainable alternatives for concrete production. The findings highlight that optimal replacement levels (up to 40%) achieve a balance between sustainability and mechanical performance, contributing to sustainable development in construction.

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1. Introduction

The construction industry faces a critical challenge in reducing its environmental impact due to the substantial carbon footprint associated with the production and use of conventional concrete. Traditional concrete relies heavily on Ordinary Portland Cement (OPC), which contributes significantly to CO_2 emissions and depletes natural resources. To mitigate these environmental concerns, the focus has shifted towards incorporating alternative materials that enhance sustainability while maintaining or improving concrete performance. Ground Granulated Blast Furnace Slag (GGBFS) and Pond Ash are emerging as viable solutions to address these challenges. GGBFS, a by-product of steel production, has been widely recognized for its environmental benefits [1,2]. It not only reduces the carbon footprint of concrete but also improves its durability and resistance to aggressive environments. Recent research highlights the effectiveness of GGBFS in enhancing the longevity and sustainability of concrete structures. For instance, A. Agnihotri et.al [3,4] demonstrated that GGBFS can significantly reduce CO_2 emissions and improve long-term durability compared to conventional OPC-based concrete.

Pond Ash, a by-product of coal combustion, offers another sustainable alternative by partially replacing fine aggregates in concrete mixes. Studies have shown that Pond Ash[5,6] can effectively reduce the consumption of natural sand and contribute to waste reduction. Fasil et al.[7,8] found that using Pond Ash in concrete not only decreases the environmental impact but also improves certain properties such as workability. However, the optimal percentage of Pond Ash replacement remains a topic of ongoing research, as excessive use can adversely affect concrete strength [9]. The impact of Ground Granulated Blast Furnace Slag (GGBFS) and Pond Ash on concrete strength and durability has been extensively studied. Research shows that incorporating additives such as ZnO [10–13] nanoparticles can enhance cement mortar strength, with optimal improvements observed at specific concentrations. Similarly, substituting cement with wash sand waste powder demonstrates technological and environmental benefits, particularly at a 7.5% replacement level. Studies on self-compacting concrete (SCC) reveal that Nano-sized Blasting Grit (nBG) and Zinc Ash (nZA) improve rheological properties and overall performance. Additionally, the use of self-curing agent’s like Superabsorbent polymers (SAP), Polyethylene glycol (PEG) etc [14–16] addresses water waste issues and enhances concrete quality. These findings highlight the crucial role of innovative materials and techniques in optimizing concrete mixes for enhanced strength, durability, and sustainability. Mandal et al. [17]studied the use of pond ash (PA) and ground granulated blast furnace slag (GGBFS) as cementless binders in construction materials, activated by a sodium hydroxide and sodium metasilicate solution. Their research focused on evaluating the setting times, hydration behavior, and compressive strength of alkali-activated paste (AAP) and mortar (AAM) samples. The study found that the AAP samples exhibited initial and final setting times within the standard range, and the AAM samples demonstrated a compressive strength of approximately 12 MPa after 28 days of curing. The pozzolanic reaction between PA, GGBFS, and the alkali activators was verified through FTIR, XRD, and SEM analysis. Furthermore, a comparative study was conducted to assess the reduction in CO2 emissions when using the PA-GGBFS binary mixture as a replacement for cement in the construction sector.

This study aims to explore the potential of GGBFS and Pond Ash in improving the sustainability of M20 and M30 grade concrete. The effects of various replacement levels on concrete's workability, compressive strength, and durability will be assessed.. By leveraging recent advancements and employing robust statistical analyses, this research seeks to provide actionable insights into optimizing concrete mixes for sustainable development, balancing performance with environmental benefits. This investigation aligns with the growing emphasis on eco-friendly construction practices and contributes to developing sustainable concrete solutions. A detailed outline of the research is presented in the Figure 1.

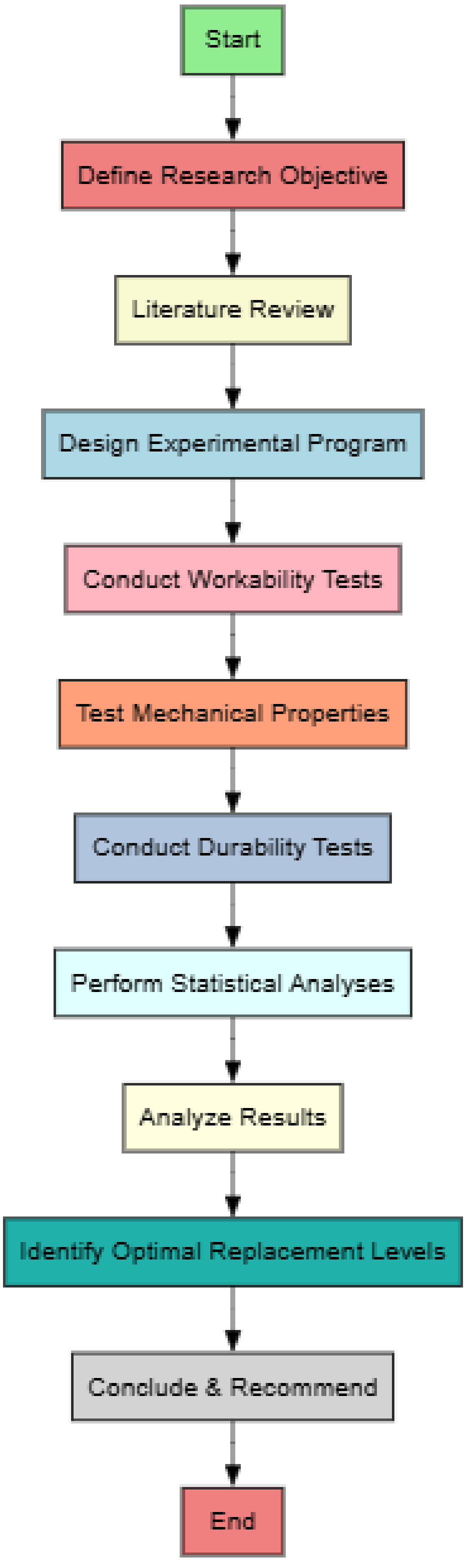


Fig. 1. Outline of research work.

2. Literature review

Ground Granulated Blast Furnace Slag (GGBFS) and pond ash have emerged as significant supplementary cementitious materials (SCMs) in concrete production. Their incorporation not only enhances the durability and sustainability of concrete but also mitigates the environmental impacts associated with traditional Portland cement production. This review examines the historical context of GGBFS and pond ash in concrete, alongside recent advancements and findings from literature up to 2024.

2.1. Historical background

GGBFS: The use of GGBFS dates back to the mid-20th century, primarily in Europe and Japan. It is produced by rapid cooling of molten iron slag from a blast furnace, which is then ground into a fine powder. Initially, its use was limited to a few applications, but as awareness of its benefits grew—such as reducing carbon emissions and enhancing the strength and durability of concrete—its adoption in concrete mixtures expanded globally. The significant performance characteristics of GGBFS, including its pozzolanic properties, have been recognized and standardized in various codes and specifications over time [18].

Pond Ash: Pond ash, a byproduct of coal combustion in thermal power plants, has a longer history of utilization, particularly in the United States since the 1930s. It has been employed in civil engineering projects, initially as lightweight fill material. Its potential as a pozzolanic material was recognized later, especially in the 1970s. Over the decades, research has increasingly focused on the benefits of incorporating pond ash in concrete, ranging from improved workability to enhanced long-term strength [19].

2.2. Recent advancements and findings

Recent studies have highlighted the synergistic effects of using GGBFS and pond ash in concrete mixtures:

Durability and Strength: A study by Lee et al. [20] reported that concrete incorporating both GGBFS and pond ash displayed significantly higher compressive and flexural strength compared to traditional concrete. The combined use of these materials improved resistance to sulfate attack and chloride ion penetration, indicating enhanced durability for infrastructure in harsh environments.

Environmental Benefits: Research by Michel et al. [21]assessed the life cycle of concrete mixtures including GGBFS and pond ash. The study concluded that the carbon footprint could be reduced by up to 30% when substituting these materials for Portland cement, showcasing the potential for decreasing greenhouse gas emissions in the construction industry.

Optimized Mixtures: Advancements in mixture design have been facilitated by digital modeling and simulation techniques. Ana et al. [22] presented a novel approach to optimizing concrete mixtures containing GGBFS and pond ash using machine learning algorithms, resulting in improved mechanical properties while minimizing material costs.

Field Applications: Innovations have also extended to practical applications. A noteworthy project reported by Mehata et al.[23] demonstrated the successful use of GGBFS and pond ash in the construction of high-performance concrete pavements, with promising results in terms of sustainability and longevity.

The integration of GGBFS and pond ash in concrete continues to evolve, backed by decades of research and application. Their combined use not only enhances the mechanical properties and durability of concrete but also promotes sustainability within the construction sector. Recent advancements have underscored the importance of these materials in addressing environmental concerns, paving the way for more resilient infrastructure. Continued research and development, guided by insightful studies, will be crucial in harnessing their full potential in future concrete applications.

2.3. Previous studies on ggbfs and pond ash in concrete

Ground Granulated Blast Furnace Slag (GGBFS) and Pond Ash are prominent industrial by-products that have gained attention for their potential to enhance the sustainability of concrete production. GGBFS, a by-product of iron and steel manufacturing, has been extensively researched for its role in improving concrete's environmental and performance attributes. Studies such as those by Cook et.al [24] and

Barkaulo et.al [25] have demonstrated that GGBFS can significantly reduce CO_2 emissions associated with concrete production, while also enhancing the durability and strength of the resulting concrete. The work of Aydin and Aydin highlighted that GGBFS-modified concrete exhibits superior resistance to sulphate attack and chloride penetration, crucial factors for the longevity of concrete structures. Pond Ash, a by-product of coal combustion in power plants, is another material investigated for its potential in concrete production. Research by Rakesh et al. [26] indicates that incorporating Pond Ash as a partial replacement for fine aggregates can improve concrete's workability and reduce its environmental footprint. However, Vidyadhara et al.[27] have shown that excessive Pond Ash content might adversely affect the compressive strength of concrete, suggesting that optimal replacement levels are critical for maintaining performance.

2.4. Comparison with other industrial by-products

Compared to other industrial by-products like Fly Ash and Rice Husk Ash, GGBFS and Pond Ash offer distinct advantages and limitations. Fly Ash, a well-established supplementary cementitious material, has been praised for its ability to enhance concrete's workability and long-term durability. Research by Alexandra et al. [28] indicates that Fly Ash concrete often shows improved resistance to thermal cracking and better long-term strength development.

Rice Husk Ash, another supplementary material, is noted for its high silica content, which can enhance the pozzolanic reaction in concrete, as highlighted by Adesina et al. [29]. In contrast, GGBFS is particularly effective in improving concrete's resistance to aggressive environments and reducing permeability, as noted by Andal et al. [30]. Pond Ash, while beneficial in terms of waste utilization and reduced demand for natural sand, presents challenges related to achieving desired strength properties, necessitating careful optimization of its proportion in concrete mixes [7,31,32].

2.5. Discussion on sustainability aspects

The sustainability of using GGBFS and Pond Ash in concrete is underscored by their ability to mitigate environmental impacts. GGBFS helps in reducing the carbon footprint of concrete production by substituting a portion of OPC, which is a major source of CO_2 emissions. Its utilization also promotes resource efficiency by recycling industrial by-products. Similarly, Pond Ash contributes to waste management by repurposing coal combustion by-products, thus reducing landfill usage and associated environmental concerns. However, the sustainability benefits of these materials must be balanced against their potential drawbacks. For instance, while GGBFS offers substantial environmental advantages, its availability is limited to regions with significant steel production. Pond Ash's variability in quality and potential impact on concrete strength require careful management and optimization.

2.6. Identification of research gaps

Despite the promising findings, several research gaps persist. There is a need for more comprehensive studies to understand the long-term performance of GGBFS and Pond Ash in various environmental conditions and loading scenarios. Additionally, the optimal blend of GGBFS and Pond Ash with other supplementary materials and their impact on concrete properties warrants further investigation. Research focusing on the economic aspects and lifecycle analysis of incorporating these by-products into concrete mixes would provide valuable insights for broader adoption. Furthermore, standardized guidelines for the use of Pond Ash, considering its variability, could enhance its reliability and effectiveness as a concrete ingredient. Addressing these gaps will be crucial for advancing sustainable concrete technologies and ensuring their practical applicability in diverse construction scenarios.

3. Materials and methods

3.1. Description of materials

The materials used in this study include Ground Granulated Blast Furnace Slag (GGBFS), Pond Ash, Ordinary Portland Cement (OPC), fine aggregates (sand), coarse aggregates, and water.

Table 3. represents the physical and chemical properties of various materials used in concrete construction, including their specific values, IS code references, and limits. The materials used in this study include:

- **Ground Granulated Blast Furnace Slag (GGBFS)** [33] with a specific surface area of 565 m²/kg, as per IS 12089 [34], though no explicit limit is set, typical values range from 400 to 600 m²/kg. Figure 2.a) illustrates the GGBS sample employed in this study.
- **Pond Ash** [1], sourced from Deepnagar, Busawal (Maharashtra), India, has a specific gravity of 2.0 and a fineness of 35% passing through a 45 µm sieve, according to IS 3812 [35]. While there are no specific limits, typical values are 1.9-2.2 for specific gravity and 30-40% passing the sieve for fineness. Figure 2.b) illustrates the pond ash sample employed in this study.
- **Ordinary Portland Cement (OPC)**, specifically 53 Grade from UltraTech, has a specific surface area of 350 m²/kg, aligning with the IS 12269 [20] range of 300-400 m²/kg. Its fineness is 5% retained on a 90 µm sieve, meeting the IS 12269 [36] requirements of less than 10%. Other properties include a soundness of 8 mm, consistency of 33%, initial setting time of 45 minutes, final setting time of 500 minutes, and a compressive strength of 53 MPa at 28 days.
- **Fine Aggregates (Sand)**, which is locally sourced, has a specific gravity of 2.7 and a fineness modulus of 2.8, both of which fall within the typical ranges specified by IS 383 [37] (2.6-2.8 for specific gravity and 2.3-3.1 for fineness modulus). The moisture content is 1%, which should be considered in the mix design as per IS 383 [37].
- **Coarse Aggregates** have a specific gravity of 2.7 and a maximum size of 20 mm, adhering to the limits specified by IS 383.
- **Water** used in the concrete mix is required to be free from harmful impurities such as oil, acid, alkali, and organic matter, in accordance with IS 456 [38].

3.2. Experimental setup

The study utilized M20 and M30 grade concrete mixes as the baseline (probe) mixes, with mix designs performed in accordance with the guidelines specified in IS 10262 [39]. The primary variables in this investigation were the replacement of fine aggregates (sand) with Pond Ash and the replacement of Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBFS). Both replacements were systematically varied in increments of 10%, ranging from 10% to 50%. The mix proportions utilized in this experimental study are presented in Preparation of Specimens: Concrete cubes with dimensions of 150 mm × 150 mm × 150 mm were cast for evaluating compressive strength, while cylindrical specimens with a diameter of 150 mm and a height of 300 mm were prepared for split tensile strength testing. The preparation of these specimens adhered to the guidelines specified in IS 516 [41]. After casting, the specimens were subjected to a curing period of 28 days under standard conditions to ensure proper hydration and strength development. The curing was conducted in a controlled environment to maintain consistent moisture levels and temperature, essential for achieving accurate and reliable test results.

Table 3. These proportions were meticulously designed to assess the effects of substituting Ground Granulated Blast Furnace Slag (GGBFS) for cement and Pond Ash (PA) for fine aggregate across various

concrete mixes. By systematically varying the content of GGBFS and PA while keeping other parameters constant, the study aimed to determine how these replacements influence the mechanical and durability properties of the resulting concrete. Each mix was carefully prepared and tested to ensure accurate and reliable results, allowing for a comprehensive evaluation of the potential benefits and challenges associated with incorporating these supplementary materials into concrete production.

- This study aims to develop and assess sustainable concrete mixes by partially replacing Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBFS) and substituting fine aggregates with Pond Ash (PA). The evaluation was conducted on two concrete grades, M20 and M30, to determine the impact of these substitutions on different strength levels, as detailed in Preparation of **Specimens:** Concrete cubes with dimensions of 150 mm × 150 mm × 150 mm were cast for evaluating compressive strength, while cylindrical specimens with a diameter of 150 mm and a height of 300 mm were prepared for split tensile strength testing. The preparation of these specimens adhered to the guidelines specified in IS 516 [41]. After casting, the specimens were subjected to a curing period of 28 days under standard conditions to ensure proper hydration and strength development. The curing was conducted in a controlled environment to maintain consistent moisture levels and temperature, essential for achieving accurate and reliable test results.
- Table 2. For the M20 grade concrete, the reference mix (NM20) was prepared with a mix ratio of 1:1.75:3.67 (cement: fine aggregate: coarse aggregate) and a water-cement (W/C) ratio of 0.5. Similarly, the M30 grade concrete (NM30) was formulated with a mix ratio of 1:1.5:3 and a W/C ratio of 0.45. Both control mixes utilized 100% OPC and 100% natural fine aggregates, following standard practice.
- To explore the impact of GGBFS and PA on concrete properties, a series of modified mixes were prepared for each grade. In these modified mixes, GGBFS replaced OPC in increments of 10%, 20%, 30%, 40%, and 50%, while PA replaced natural sand in the same increments.
- The resulting mix designs were labelled as 10M20, 20M20, 30M20, 40M20, and 50M20 for the M20 grade, and 10M30, 20M30, 30M30, 40M30, and 50M30 for the M30 grade, respectively. In each modified mix, the total amount of cementitious material (cement plus GGBFS) and the total amount of fine aggregate (sand plus PA) were kept constant. The coarse aggregate content and water content were also maintained at the same level across all mixes, ensuring that the variations in concrete properties could be directly attributed to the replacement levels of GGBFS and PA. This methodical approach enabled a thorough investigation into the effects of GGBFS and PA on various concrete properties, including workability, compressive strength, split tensile strength, and durability. The control mixes (NM20 and NM30) provided baseline data against which the modified mixes were compared, allowing for a detailed analysis of how increasing levels of GGBFS and PA influence the mechanical and durability performance of concrete.

The study also considered the practical implications of using GGBFS and PA in concrete production, such as the potential for reducing the carbon footprint and conserving natural resources. By systematically varying the replacement levels, the research aimed to identify the optimal blend of GGBFS and PA that balances performance with sustainability, thereby contributing valuable insights for the construction industry. The results from this study are intended to inform future practices in concrete mix design, particularly in regions where these supplementary materials are readily available and can be used to enhance the environmental sustainability of concrete structures. To explore the impact of GGBFS and PA on concrete properties, a series of modified mixes were prepared for each grade. In these modified mixes, GGBFS replaced OPC in increments of 10%, 20%, 30%, 40%, and 50%, while PA replaced natural sand in the same increments. The resulting mix designs were labelled as 10M20, 20M20, 30M20, 40M20, and 50M20 for the M20 grade, and 10M30, 20M30, 30M30, 40M30, and 50M30 for the M30 grade, respectively. In each modified mix, the total amount of cementitious material (cement plus GGBFS) and the total amount of fine aggregate (sand plus PA) were kept constant. The coarse aggregate content and water content were also maintained at the same level across all mixes, ensuring that the variations in concrete properties could be directly attributed to the replacement levels of GGBFS and PA. This methodical approach enabled a thorough investigation into the effects of GGBFS and PA on various concrete properties, including workability, compressive strength, split tensile strength, and durability. The control mixes (NM20 and NM30) provided baseline data against which the modified mixes were compared, allowing for a detailed analysis of how increasing levels of GGBFS and PA influence the mechanical and durability performance of concrete. The study also considered the practical implications of using GGBFS and PA in concrete production, such as the potential for reducing the carbon footprint and conserving natural resources. By systematically varying the replacement levels, the research aimed to identify the optimal blend of GGBFS and PA that balances performance with sustainability, thereby contributing valuable insights for the construction industry. The results from this study are intended to inform future practices in concrete mix design, particularly in regions where these supplementary materials are readily available and can be used to enhance the environmental sustainability of concrete structures. Fig. 2.c) illustrates the casted samples employed in this study.

Table 1. Material Properties.

	Description	Pond Ash	GGBFS	OPC 53 Grade	Fine Aggregate	Coarse Aggregate	Water	IS Code	Limits
Physical	Specific Gravity	2	2.9	3.15	2.7	2.67	1	IS 1727	2.5 - 3.0
	Particle Shape	Irregular	Angular	Angular	Round	Angular	Liquid	IS 383	Round or Angular
	Water Absorption (%)	20	0.1	NA	0.15	0.3	N/A	IS 2386 (Part 3)	≤ 2% for coarse aggregates
	Specific Surface Area(m^2/kg)	600	350	450	200	700	NA	IS 1727	250 - 400
	Fineness %	55	95	10	95	90	NA	IS 4031	≥ 75% passing 45 µm sieve
	Soundness in mm	NA	2	2	1	2	NA	IS 2386 (Part 5)	≤10 mm
	Consistency in %	NA	30	30	30	NA	NA	IS 1200	NA
	Initial Setting Time (IST) in min	NA	NA	45	NA	NA	NA	IS 4031	≥ 30 minutes
	Final Setting Time (FST) in min	NA	NA	240	NA	NA	NA	IS 4031	≤ 600 minutes
	Compressive Strength in Mpa	NA	NA	55.6	NA	NA	NA	IS 4031	≥ 53 MPa
	Fineness Modulus	NA	NA	NA	2.8	6	NA	IS 2386 (Part 1)	2.3 - 3.1 for fine aggregates
	Bulk Density (kg/m^3)	1200	1265	1440	1653	1600	NA	IS 2386 (Part 3)	1500 - 1700
Chemical	SiO_2 (%)	50	32	22	65	55	NA	IS 1727	≥ 25%
	Al_2O_3 (%)	15	12	6	7	17	NA	IS 1727	≥ 5%
	Fe_2O_3 (%)	8	1	2	2	2	NA	IS 1727	≤ 10%
	CaO (%)	3	35	63	2	30	NA	IS 1727	≤ 50%
	MgO (%)	2	8	5	3	2	NA	IS 1727	≤ 5%
	SO_3 (%)	2.5	1.5	2	0.5	1	NA	IS 4032	≤ 3%
	Loss on Ignition (LOI) (%)	3	2.5	3	1.5	1	NA	IS 1727	≤ 10%
	Chloride Content (%)	0.02	0.02	0.08	0.03	0.02	0.02	IS 383	≤ 0.03%

Preparation of Specimens: Concrete cubes with dimensions of 150 mm × 150 mm × 150 mm were cast for evaluating compressive strength, while cylindrical specimens with a diameter of 150 mm and a height of 300 mm were prepared for split tensile strength testing. The preparation of these specimens adhered to the guidelines specified in IS 516 [40]. After casting, the specimens were subjected to a curing period of

28 days under standard conditions to ensure proper hydration and strength development. The curing was conducted in a controlled environment to maintain consistent moisture levels and temperature, essential for achieving accurate and reliable test results.

Table 2. Mix Proportions.

Grade of concrete	Materials in (%) ↓	Mixes					
		NM20	10M20	20M20	30M20	40M20	50M20
M20 1:1.75:3.67 W/C: 0.5	C	100	90	80	70	0	50
	GGBS	0	10	20	30	40	50
	FA	100	90	80	70	0	50
	PA	0	10	20	30	40	50
	CA	100	100	100	100	100	100
	W	50	50	50	50	50	50
M30 1:1.5:3 W/C: 0.45	Materials in (%) ↓	NM30	10M30	20M30	30M30	40M30	50M30
	C	100	90	80	70	0	50
	GGBS	0	10	20	30	40	50
	FA	100	90	80	70	0	50
	PA	0	10	20	30	40	50
	CA	100	100	100	100	100	100
	W	50	50	50	50	50	50

3.3. Testing procedures for mechanical and durability properties

The workability of the concrete mixes containing Ground Granulated Blast Furnace Slag (GGBFS) and Pond Ash was assessed using the slump test, as outlined in IS 1199[41]. This test evaluates the ease of handling and placing the fresh concrete. A slump cone was filled with the concrete mix, and after the cone was removed, the vertical subsidence of the concrete was measured. This measurement provided valuable information on the flow ability and consistency of the concrete, which influences its suitability for various construction applications.

a) Mechanical properties evaluation

1. Compressive Strength: The compressive strength of the concrete mixes was determined by casting and curing specimens according to IS 516 [40]. After the specified curing period, the specimens were tested using a Compression Testing Machine (CTM) to measure the maximum load they could sustain before failure. The compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen. Testing multiple specimens for each mix proportion allowed for an average compressive strength to be determined, providing a reliable measure of the concrete's load-bearing capacity.

2. Split Tensile Strength: The split tensile strength was evaluated using the Brazilian test method, as described in IS 5816 [42]. Cylindrical specimens were subjected to a diametric compressive force to induce uniform tensile stress along the vertical diameter. The maximum tensile force was recorded, and the split tensile strength was calculated using the appropriate formula. This test assessed the concrete's tensile capacity, which is crucial for understanding its performance under tensile stresses.

3. Flexural Strength: Flexural strength was determined through a beam bending test, in accordance with IS 516 [40]. Concrete beams of specified dimensions were subjected to central loading until failure occurred. The flexural strength was calculated based on the maximum load applied and the dimensions of the beam. This test provided insights into the concrete's resistance to bending stresses, which is important for structural applications where flexural forces are significant.

b) Durability testing

1. Water Absorption: Water absorption was measured by determining the increase in weight of dried specimens after immersion in water, following the procedure outlined in IS 1199 [41] . This test provided insights into the porosity and permeability of the concrete, which are critical factors in assessing its resistance to water ingress and overall durability.

2. Resistance to Acid Attack: The resistance of the concrete to acid attack was evaluated by immersing specimens in an acid solution for a specified duration, as per IS 456 [38]. The mass loss and retained compressive strength of the specimens were assessed to determine the concrete's durability in acidic environments. This test highlighted the effectiveness of different mix proportions in enhancing the concrete's resistance to chemical degradation.

GGBS

Pond ash

Casted Specimen samples

Fig. 2. a) GGBS b) Pond Ash c) Casted Specimen samples.

4. Results and discussion

4.1. Experimentation

Figure 3. provides a comprehensive analysis of workability, strength, and durability for M20 and M30 grade concrete mixes incorporating partial replacements of fine aggregates with Pond Ash and cement with Ground Granulated Blast Furnace Slag (GGBFS). The data reveal notable effects on concrete performance with these replacements, particularly concerning workability, strength, and durability.

1) Workability: In the investigation of M20 grade concrete, workability showed significant improvement with the addition of Pond Ash and GGBFS, which increased to a 40% replacement level. This enhancement is evident from the increased slump values and the corresponding decrease in Vee-Bee time. The improved workability can be attributed to several factors. Firstly, the fineness and particle shape of Pond Ash and GGBFS play a crucial role. These materials, having finer particles compared to traditional cement and aggregates, improve particle packing and reduce the water demand for a given level of workability. This results in higher slump values and reduced Vee-Bee time, indicating enhanced flow ability and ease of compaction. Additionally, the improved lubrication properties of the mix contribute to better workability. The finer particles in Pond Ash and the latent hydraulic properties of GGBFS promote smoother mixing and better particle lubrication. This reduction in internal friction further enhances the workability of the mix, facilitating easier placement and compaction. However, at a 50% replacement level (50M20), the trend reverses. Slump values decrease, and Vee-Bee time increases, indicating a reduction in workability. This adverse effect is likely due to the increased surface area of the fine particles, which leads to higher water absorption and a stiffer mix. The excessive presence of fine particles can make the mix sticky and less workable, thereby complicating the placement and compaction processes. A similar trend is observed in the M30 grade concrete. Workability improves from NM30 to 40M30 due to better particle packing, improved lubrication, and reduced internal friction, consistent with the observations in M20 grade concrete. However, at the 50% replacement level (50M30), the mix again exhibits reduced workability. This reduction is attributed to the same factors affecting the M20 grade, where the mix becomes overly fine, leading to increased water absorption and decreased free water content, making the mix less workable and more difficult to handle. These findings align with recent research by Nayak et.al [43], Wenjie Ge et al. [44] and Senthil Kumar Velumani et.al [45], which indicates that while partial replacement of cement with mineral admixtures like fly ash enhances workability due to improved lubrication and reduced internal friction, higher replacement levels can result in decreased workability. This supports the observation that excessive fine particles at high replacement levels negatively impact the workability of concrete.

2) Strength: The strength characteristics of concrete, including compressive strength (CS MPa), flexural strength (FS MPa), and split tensile strength (SPT MPa), tend to decrease when the replacement levels of Pond Ash and GGBFS exceed 40% for both M20 and M30 grades. This decline in strength can be attributed to several key factors.

3) Dilution Effect: The partial replacement of cement with GGBFS, while offering benefits such as reduced heat of hydration and enhanced sustainability, lowers the overall cementitious content of the mix. GGBFS contributes to strength development through its pozzolanic reactions, but these reactions are slower compared to those of ordinary Portland cement. Consequently, the rate of strength gain is reduced, particularly in the early stages of curing, leading to lower overall strength.

4) Reduced Bonding: Replacing fine aggregates with Pond Ash introduces particles that differ in texture and reactivity compared to natural sand. These differences can weaken the bond between the cement paste and the aggregate. The lower reactivity and altered surface properties of Pond Ash particles can diminish the bond strength, resulting in reduced compressive, flexural, and tensile strengths.

5) Increased Porosity: The incorporation of Pond Ash and GGBFS increases the overall porosity of the concrete mix. This is due to the finer particle size of Pond Ash and the incomplete hydration of GGBFS, which leads to more voids within the hardened concrete. Increased porosity typically results in lower strength because the presence of voids compromises the integrity of the concrete matrix.

These observations are consistent with recent findings by Iffat Sultana et.al [46], Noor Yaseen [47], and Arvind Vishavkarma [48] who demonstrated that increased replacement levels of cement with supplementary cementitious materials, such as fly ash and GGBFS, can lead to decreased compressive strength due to dilution effects and slower reaction rates. Their study highlights the trade-offs between incorporating these materials for sustainability and the potential impacts on concrete strength.

6) Durability: The durability of concrete, evaluated through water absorption (WA %) and acid attack resistance (AA %), shows a decline with increasing replacement levels of Pond Ash and GGBFS for both M20 and M30 grades. This decrease in durability can be attributed to several factors discuss as follows.

Increased Porosity: The incorporation of finer particles from Pond Ash and GGBFS results in higher porosity within the concrete mix. Increased porosity leads to more capillary pores that can absorb water and other harmful agents, which adversely affects the durability of the concrete. The higher water absorption is indicative of a more permeable matrix that is less resistant to environmental factors.

Lowered Resistance to Aggressive Environments: The elevated porosity and reduced density of concrete with higher replacement levels make it more vulnerable to acid attack and other aggressive environmental conditions. Unreacted or partially reacted GGBFS and Pond Ash particles contribute to the concrete's susceptibility to such attacks, leading to increased acid attack percentages and reduced durability.

Reduced Densification: Although GGBFS can enhance long-term durability through its pozzolanic reaction, high replacement levels may exceed the optimal threshold, resulting in reduced densification of the concrete matrix. This can lead to weaker and more permeable concrete, diminishing its durability over time.

The results highlight that while partial replacement of fine aggregates with Pond Ash and cement with GGBFS can initially improve workability, particularly at moderate replacement levels (up to 40%), the benefits diminish beyond this threshold. At higher replacement levels, the negative impacts on strength and durability become more pronounced. The increase in porosity, reduced bonding, and dilution of cementitious content are key factors contributing to decreased durability. These findings underscore the need for optimizing replacement levels to balance the sustainability benefits of using industrial by-products with maintaining adequate concrete performance. These observations align with recent research by Fode et.al [49] , which found that increased levels of supplementary cementitious materials, such as GGBFS and fly ash, result in higher porosity and decreased resistance to aggressive environments. Their study also noted that while these materials can offer benefits in terms of sustainability, excessive replacement can lead to durability issues, which is consistent with the findings of this study.

4.2. Optimization techniques used

Figure 4. (a) shows strong positive correlations among variables such as AA, WA, SPT (MPa), FS (MPa), and CS (MPa), with coefficients approaching 1.0, indicating that these variables tend to increase together. For instance, SPT (MPa) and FS (MPa) may represent related strength measures, where an increase in one

corresponds with an increase in the other. Conversely, Figure also reveals strong negative correlations between variables like AA and C (Kg), with coefficients near -1.0, suggesting that as one variable increases, the other decreases—potentially indicating that a higher cement content (C Kg) results in a reduction in the aggregate measurement (AA). In contrast, a correlation coefficient close to 0 between VB (sec) and Curing Days implies a minimal relationship, meaning changes in one variable do not predict changes in the other. Intermediate correlations are observed between variables such as FA (Kg) and GGBS (Kg), reflecting a moderate relationship where these variables influence each other but not as strongly as those with coefficients closer to ±1. Additionally, clusters of variables with similar correlation patterns suggest a common underlying factor or process. For example, SPT (MPa), FS (MPa), and CS (MPa) are positively correlated with each other and negatively correlated with VB (sec), indicating that these variables may represent different aspects of material strength or behavior under stress.

4.3. Principal component analysis (PCA)

Scree Plot: The scree plot in Figure 4. (b) is used to determine the number of significant factors in a factor analysis. The plot displays the eigenvalues on the y-axis against the corresponding factors on the x-axis. Typically, factors with eigenvalues greater than 1 are considered significant. In this plot, the first two factors have eigenvalues above 1, indicating that they explain a substantial amount of variance in the dataset. The subsequent factors have eigenvalues close to or below 1, suggesting that they contribute minimal additional explanatory power. Therefore, it is appropriate to retain only the first two factors for further analysis, as they capture the most important variations in the data.

Factor Loading Plot: The Figure 4. (c) also illustrates the factor loading plot, which maps the variables according to their loadings on the two retained factors (Factor 1 and Factor 2). The factor loadings represent the correlation between the variables and the extracted factors.

Factor 1 appears to be strongly associated with parameters related to the concrete mix proportions and supplementary materials (e.g., GGBS, PA, WA, AA, FA, and cement). These materials load heavily on

Factor 1, suggesting that this factor primarily represents variations in the concrete mix composition.

Factor 2 seems to capture variations related to the mechanical properties and curing conditions of the concrete, such as compressive strength (CS), split tensile strength (SPT), flexural strength (FS), and curing time. These properties show significant loadings on Factor 2, indicating that this factor reflects the performance characteristics of the concrete. The plot illustrates how various variables group around two main factors, offering insights into the data's underlying structure. For example, the significant loading of curing time on Factor 2 indicates that curing time has a critical impact on the strength characteristics of concrete. Similar findings were reported by Patil et al.[10] in their research.orkability.

The model revealed how each predictor impacted the results, emphasizing key correlations. Key statistical metrics such as R^2, p-values, and coefficients were analyzed to assess the model's accuracy and predictive capabilities. This analysis provided a comprehensive understanding of how various variables collectively influenced the performance outcomes. The discussion is presented below.

Multiple Linear Regression Analysis: The multiple linear regression models were developed to explore the relationships between key dependent variables (S, CS, VB, FS, SPT, AA, WA) and their respective independent variables.

Model 1 for S (mm): The first model defines the relationship between S (mm) and the independent variables, represented by Equation 1. The ANOVA results demonstrated a statistically significant correlation between the variables at a 95.0% confidence level ($p < 0.05$). The model accounts for 99.9612% of the variation in S (mm), with an adjusted R-squared of 99.9589%. The standard error of the estimate is 0.182958, while the mean absolute error (MAE) stands at 0.148822. However, the Durbin-Watson statistic suggests a potential serial correlation, indicating that residual patterns warrant further examination.

$$S(mm) = 134.824 - 0.185972 \times C(Kg) - 0.0189203 \times PA(Kg) \quad (1)$$

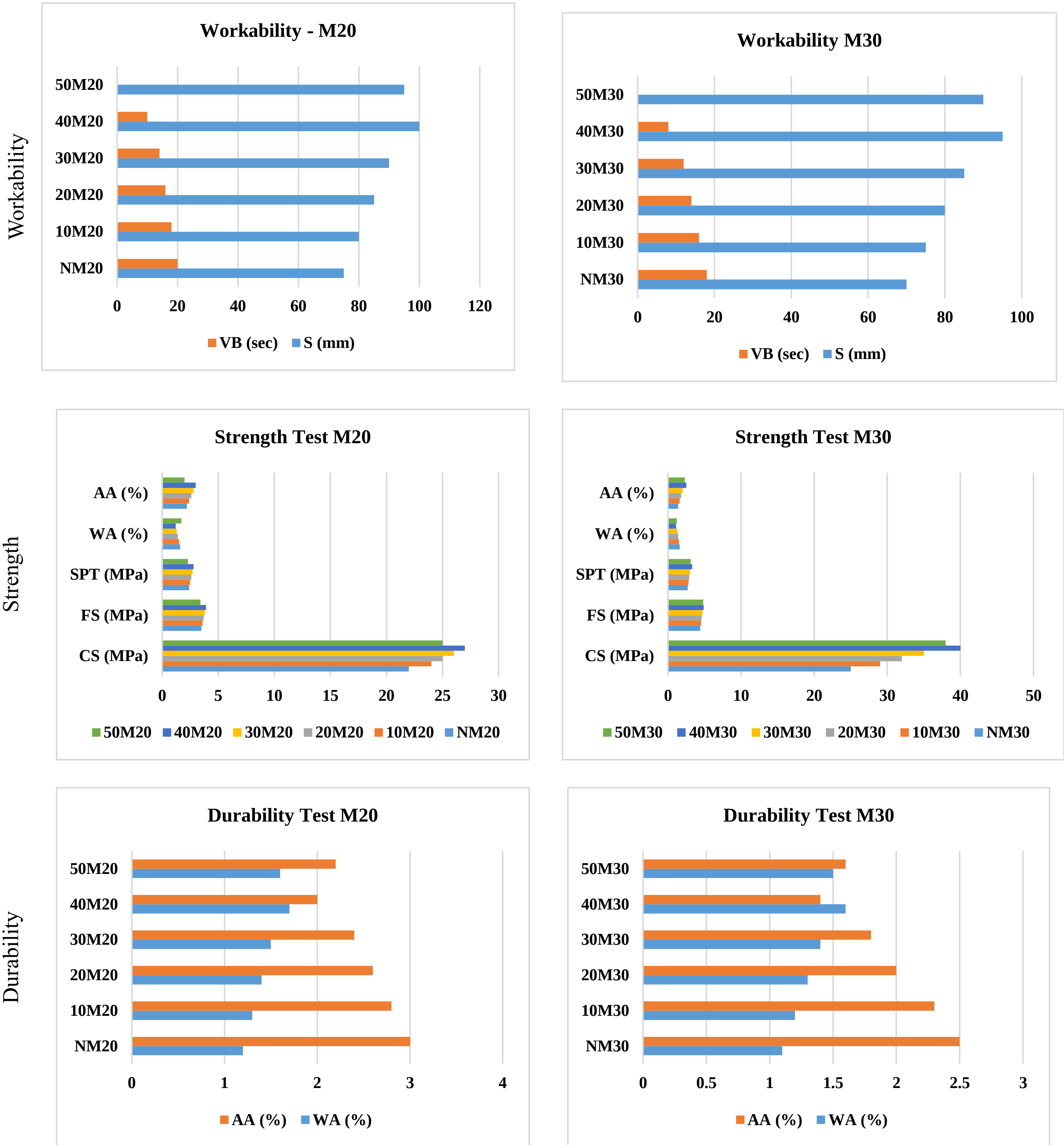
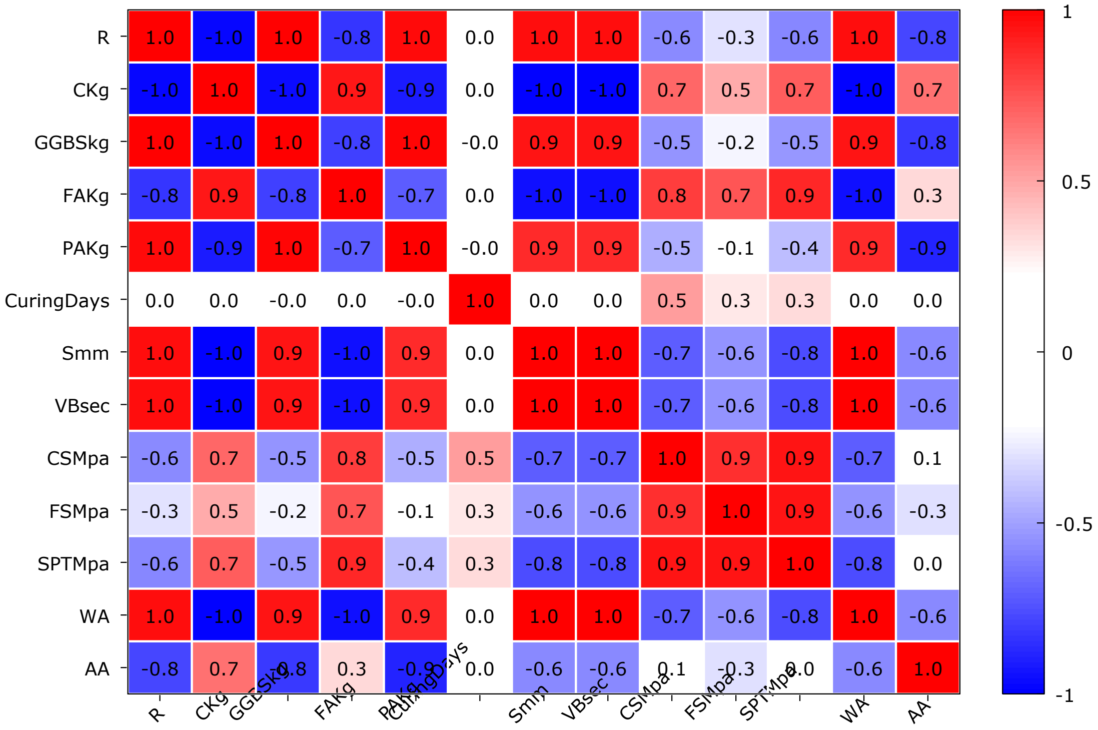
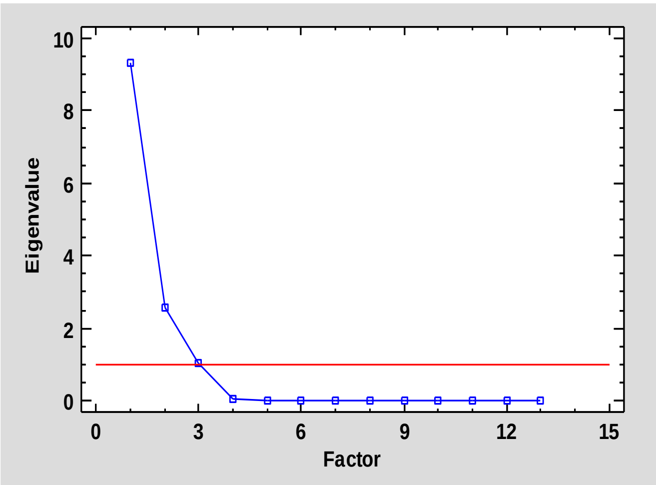


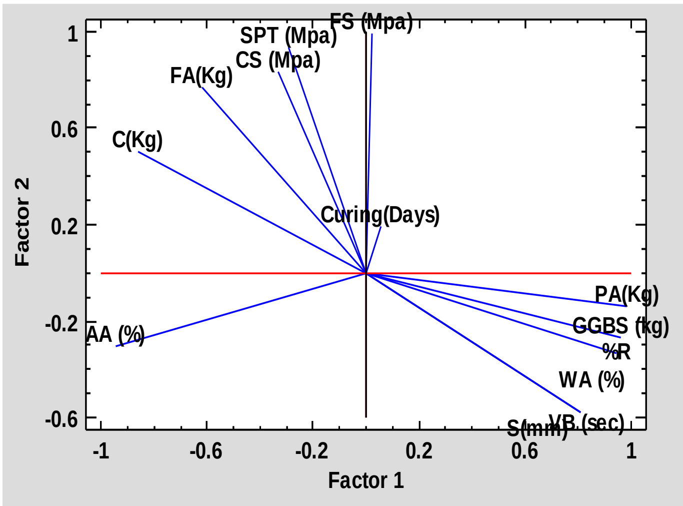
Fig. 3. Experimental testing comparision for M20 and M30 grade of concrete for a) Workability b) Strength c) Durability.



a) Correlation Matrix



a) Scree Plot



b) Factor loadings Plot

Fig. 4. (a) Correlation Matrix (b) Scree Plot (C) Factor Lading Plot.

MLR: Multiple Linear Regression (MLR) [37,38] analysis was performed to explore the relationships between the dependent variables and multiple independent factors.

Model 1 for S (mm): The first model defines the relationship between S (mm) and the independent variables, represented by Equation 1. The ANOVA results demonstrated a statistically significant correlation between the variables at a 95.0% confidence level ($p < 0.05$). The model accounts for 99.9612% of the variation in S (mm), with an adjusted R-squared of 99.9589%. The standard error of the estimate is 0.182958, while the mean absolute error (MAE) stands at 0.148822. However, the Durbin-

Watson statistic suggests a potential serial correlation, indicating that residual patterns warrant further examination.

$$S(mm) = 134.824 - 0.185972 \times C(Kg) - 0.0189203 \times PA(Kg) \quad (1)$$

Model 2 for CS (MPa): The second model investigates the relationship between CS (MPa) and its independent variables, as presented in Equation 2. With a p-value below 0.05, the model is statistically significant at the 95.0% confidence level. The R-squared value of 97.2116% and the adjusted R-squared of 96.8518% indicate a strong fit to the data. The standard error of the estimate is 1.18923, and the mean absolute error (MAE) is 0.955115. Additionally, the Durbin-Watson test ($p > 0.05$) indicates no signs of serial correlation, suggesting that the residuals are independent.

$$CS(Mpa) = -15.9115 + 0.605458 \times \%R - 0.12963 \times GGBS(Kg) + 0.0602339 \times FA(Kg) + 0.392007 \times Curing\ Days \quad (2)$$

Model 3 for VB (sec): The third model describes the relationship for VB (sec), as shown in Equation 3. The model is statistically significant ($p < 0.05$), with an R-squared of 99.9612% and an adjusted R^2 of 99.9589%, indicating an excellent fit. The standard error is 0.0731832, and the mean absolute error (MAE) is 0.0595287. Similar to the S (mm) model, the Durbin-Watson statistic indicates possible serial correlation, suggesting that further analysis of the residuals is necessary.

$$VB(sec) = 33.9295 - 0.0743887 \times C(Kg) - 0.00756814 \times PA(Kg) \quad (3)$$

Model 4 for FS (MPa): The fourth model examines FS (MPa) as a function of its independent variables, as presented in Equation 4. This model is statistically significant ($p < 0.05$), accounting for 99.6886% of the variability in FS (MPa), with an adjusted R-squared of 99.6594%. The standard error of the estimate is 0.0327327, and the mean absolute error (MAE) is 0.0285714. The Durbin-Watson statistic suggests no serial autocorrelation in the residuals, indicating their independence.

$$FS(Mpa) = 1.4 + 0.1 \times Grade - 0.01 \times \%R + 0.0183673 \times Curing\ Days \quad (4)$$

Model 5 for SPT (MPa): For SPT (MPa), the relationship is expressed in Equation 5. This model is statistically significant ($p < 0.05$), explaining 98.038% of the variability in SPT (MPa), with an adjusted R-squared of 97.8541%. The standard error of the estimate is 0.0454259, and the mean absolute error (MAE) is 0.0344722. The Durbin-Watson test indicates no significant serial correlation ($p > 0.05$), confirming the independence of the residuals.

$$SPT(Mpa) = 1.54216 + 0.0467899 \times Grade - 0.00312732 \times GGBS(Kg) + 0.0115646 \times Curing\ Days \quad (5)$$

Model 6 for AA (%): The sixth model outlines the relationship for AA (%), as shown in Equation 6. This model is statistically significant ($p < 0.05$), accounting for 99.8348% of the variability in AA (%), with an adjusted R-squared of 99.8193%. The standard error of the estimate is 0.0198206, and the mean absolute error (MAE) is 0.0111111. However, the Durbin-Watson statistic suggests potential serial correlation, which requires further investigation of the residuals.

$$AA\ (\%) = 4.01905 - 0.0509524 x Grade - 0.0132632 x \%R - 0.00120301 x PA\ (Kg) \quad (6)$$

Model 7 for WA (%): The final model for WA (%) is represented by Equation 7. This model is statistically significant ($p < 0.05$) and explains 88.0494% of the variability in WA (%), with a correlation coefficient of 0.938346, indicating a relatively strong relationship. The standard error is 0.0633006, and the mean absolute error (MAE) is 0.0609105. The Durbin-Watson test suggests serial correlation, which necessitates a closer review of residual patterns.

$$WA\ (\%) = 1.15633 + 0.00290946 \times GGBS\ (kg) \quad (7)$$

The regression models provided robust statistical evidence of relationships between the dependent and independent variables. Although most models demonstrated excellent goodness-of-fit, potential serial correlations in certain cases warrant further examination of residual patterns to ensure model reliability and accuracy. These models offer critical insights into the behaviour of the studied variables, with practical applications in the field. The observed versus predicted plots in Figure 5. provide a visual assessment of the accuracy of the multiple linear regression (MLR) models for various dependent variables, including S (mm), VB (sec), CS (MPa), FS (MPa), SPT (MPa), WA (%), and AA (%). Each plot compares the predicted values (X-axis) generated by the models to the actual observed values (Y-axis). The diagonal blue line represents the ideal 1:1 relationship, where the predicted values perfectly match the observed ones. For most variables, such as S (mm), VB (sec), FS (MPa), and AA (%), the data points are tightly clustered around the diagonal, indicating a high degree of accuracy in the predictions. This suggests that the MLR models are highly effective for these variables, with minimal error between predicted and observed values. The plots for CS (MPa) and WA (%) show some minor deviations from the diagonal line, suggesting that while the models perform well, there may be slight unexplained variances, particularly at higher values for CS and WA. Figure 5. demonstrates that the MLR models offer robust predictive accuracy for most concrete properties, with only minor deviations in certain cases, indicating that the models are reliable tools for understanding the relationships between the studied variables and their independent factors.

The inclusion of performance criteria such as MAPE, MSE, and Durbin-Watson in Table 3. provides a comprehensive evaluation of the models, enhancing the robustness of the study. While most models exhibit excellent predictive accuracy, addressing residual patterns for potential serial correlation will further improve model reliability.

Table 3. Comparison of Models.

Model	Dependent Variable	R-squared	Adjusted R-squared	MAPE (%)	MSE	Durbin-Watson
Model 1	S (mm)	99.96%	99.96%	0.85%	0.0334	Potential Serial Correlation
Model 2	CS (MPa)	97.21%	96.85%	3.21%	1.414	No Serial Correlation
Model 3	VB (sec)	99.96%	99.96%	0.72%	0.00535	Potential Serial Correlation
Model 4	FS (MPa)	99.68%	99.65%	1.13%	0.001071	No Serial Correlation
Model 5	SPT (MPa)	98.04%	97.85%	2.15%	0.002064	No Serial Correlation
Model 6	AA (%)	99.83%	99.81%	0.58%	0.000393	Potential Serial Correlation
Model 7	WA (%)	88.05%	87.72%	5.45%	0.00401	Potential Serial Correlation

Figure 6. presents a graphical user interface (GUI) developed to predict various concrete properties, including slump, compressive strength, flexural strength, split tensile strength, acid attack resistance, and water absorption, based on user-defined input parameters. The model incorporates key factors such as the percentage replacement of cement and fine aggregate (%R) with ground granulated blast furnace slag (GGBS) and pond ash, as well as variables like curing duration and concrete grade. This interactive tool enables researchers and practitioners to evaluate the impact of sustainable materials on concrete performance, supporting data-driven optimization of mix designs. A similar GUI was developed by Mina Naseri Nasab et al. [50] to estimate the punching shear capacities of concrete slabs reinforced with steel and FRP rebars.

4.4. Microstructural analysis

The SEM and EDX analysis in Figure 7. reveal important characteristics regarding porosity, pore structure, microstructural bonding, and hydration products in concrete materials, consistent with the findings of Maheswaran et al. [1] in their research on GGBS and pond ash.

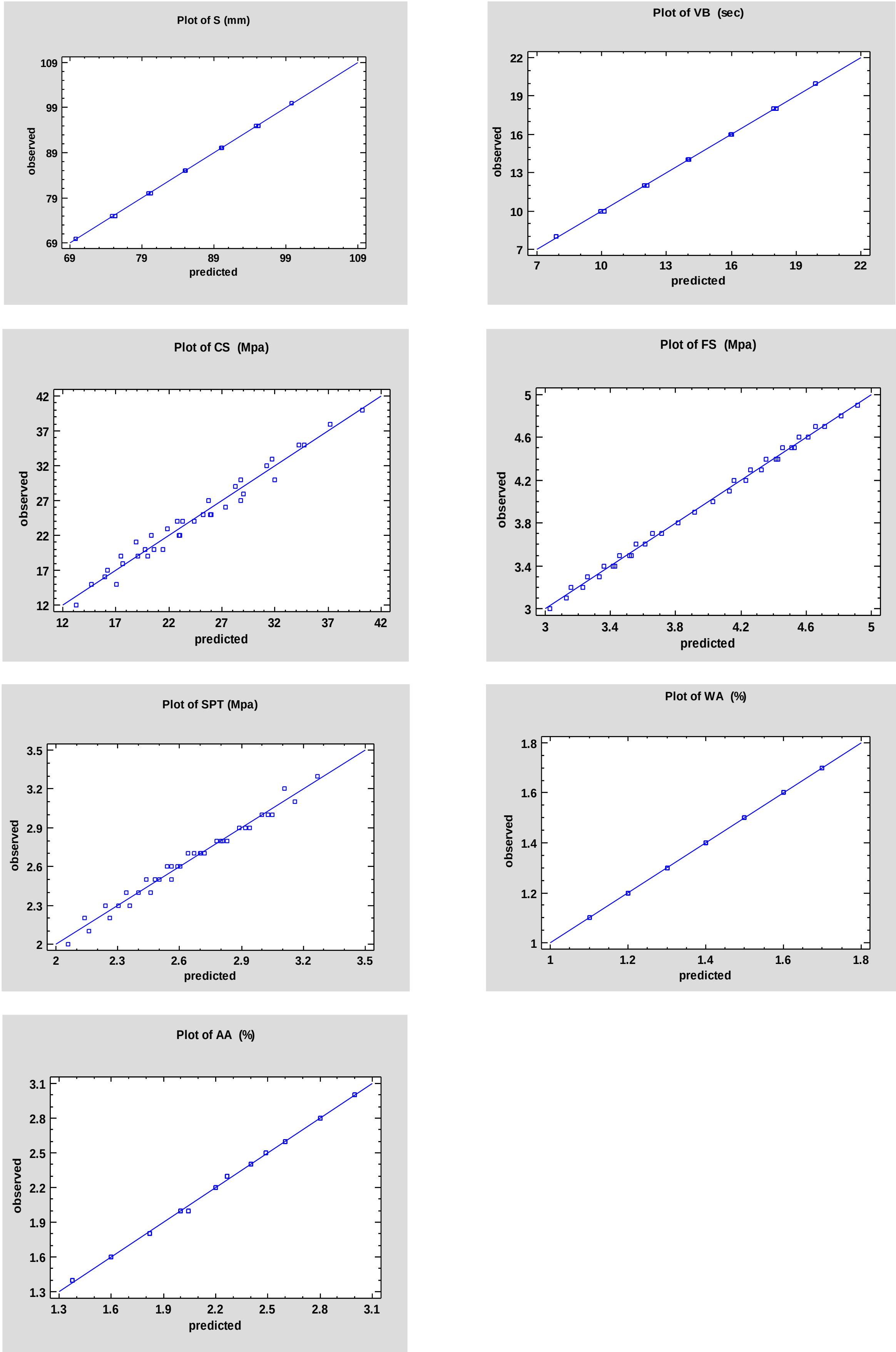


Fig. 5. MLR model outputs of S (mm), VB (sec), CS (MPa), FS (MPa), SPT (MPa), WA (%), and AA (%)

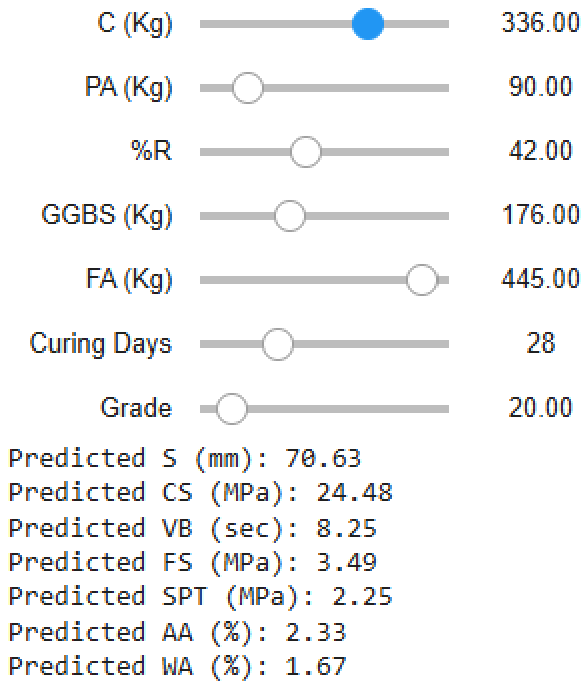


Fig. 6. The provided gui toolbox for prediction of different parameters of concrete.

a) Porosity and Pore Structure: The SEM image demonstrates sharp edges and angular broken ends, which are characteristic of materials with high porosity. The irregular surfaces and fractured structures indicate the presence of interconnected pores. These sharp and angular features suggest that the material might have undergone mechanical or chemical deterioration, leading to micro cracking. The calcium settlements in some areas, as noted in the SEM, may indicate the presence of pore-filling hydration products, which can alter the pore structure over time. As reported by Maheswaran et al. [1], materials with higher porosity tend to show increased water absorption and lower compressive strength due to the presence of voids. These voids act as weak points within the matrix, allowing for the ingress of harmful agents such as chloride ions or sulphates, thereby accelerating the degradation process. The study by Maheswaran et al. [1]. emphasized the need to control porosity through careful selection of supplementary cementitious materials and optimized mix designs to enhance durability.

b) Microstructure and Bonding: The microstructure in the provided image exhibits a fragmented and poorly bonded network. The presence of sharp angular edges indicates incomplete bonding or a brittle fracture, which can compromise the structural integrity of the concreteThe calcium settlements observed in the SEM suggest that hydration products are attempting to fill the micro-cracks, potentially leading to delayed strength development. However, without sufficient hydration or adequate curing, these microstructures can remain as weak points in the overall matrix. According to the findings of Maheswaran et al. [1]., a well-bonded microstructure is critical for enhancing the mechanical properties of concrete. They demonstrated that the addition of pozzolanic materials such as fly ash and slag improves bonding by producing additional calcium silicate hydrates (C-S-H) that fill micro cracks and reduce the formation of brittle phases. The current image, which shows only partial bonding, may suggest an early stage of hydration or insufficient curing, leading to reduced compressive and tensile strength.

c) Hydration Products: The EDX spectrum reveals key peaks of **calcium (Ca)**, **silicon (Si)**, **aluminum (Al)**, and **iron (Fe)**, which are indicative of common hydration products like calcium silicate hydrate (C-S-H), calcium hydroxide ($Ca(OH)_2$), and possibly ettringite. The formation of these products plays a vital role in the hardening and strength gain of the material. The presence of high calcium concentrations, as observed in the image, suggests ongoing hydration reactions, particularly the formation of C-S-H, which is responsible for the binding and hardening of the concrete matrix. Maheswaran et al. [1]**.** reported similar findings in their study, where hydration products were shown to significantly enhance the mechanical properties of concrete over time. Their study emphasized that the proper formation of C-S-H and ettringite is crucial for improving the durability and long-term strength of concrete. They also observed that insufficient hydration, particularly in high porosity systems, results in lower mechanical performance due to the incomplete development of these key phases.

d) Comparative Analysis with Literature: In comparison to the work of Maheswaran et al. [1], the SEM image in this study reveals similarities in terms of porosity and the presence of hydration products. Their study highlighted that materials with high porosity or poorly developed microstructures tend to exhibit inferior durability. The EDX analysis further corroborates this by showing the dominance of elements like calcium and silicon, which are essential for forming C-S-H phases. However, the lack of well-developed microstructure in the current specimen, with visible micro cracks, points toward the potential for future degradation unless the hydration process continues to fill these cracks. In conclusion, the current SEM and EDX results align with the observations made by Maheswaran et al. [1]., suggesting that concrete with high porosity, poor bonding, and incomplete hydration products is prone to lower mechanical performance and increased vulnerability to environmental attacks. To enhance durability and strength, improvements in the pore structure, complete hydration, and enhanced microstructural bonding are necessary, as recommended by previous studies.

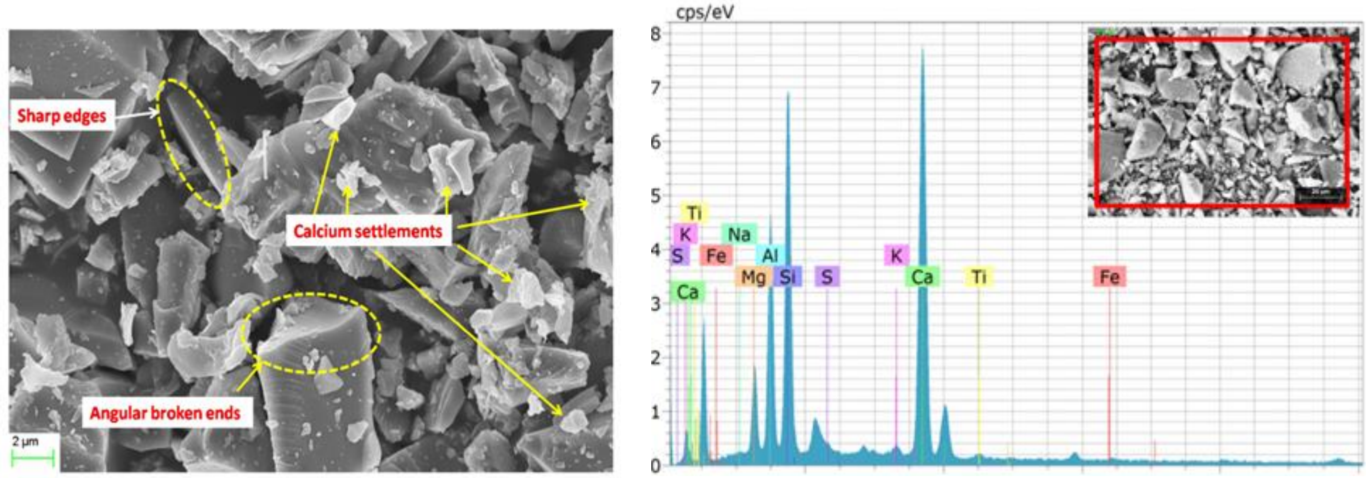


Fig. 7. SEM and XRD of concrete with GGBS [1].

4.5. Sustainability assessment

The sustainability assessment of concrete incorporating Pond Ash and GGBFS as partial replacements for traditional materials involves evaluating several key factors: environmental impact, resource efficiency, and overall contribution to sustainable construction practices. This assessment provides insight into the ecological and economic benefits of using these industrial by-products in concrete production.

a) Environmental Impact: The use of Pond Ash and GGBFS in concrete contributes to reduced environmental impact in several ways. Pond Ash, a by-product of coal combustion, is often disposed of in landfills, leading to environmental concerns. By utilizing Pond Ash as a partial replacement for fine aggregates, the volume of waste sent to landfills is decreased. Similarly, GGBFS, a by-product of steel production, helps in recycling industrial waste, thus reducing the need for virgin materials. According to recent studies, the incorporation of GGBFS and Pond Ash can significantly lower the carbon footprint of concrete production. For instance, Althoey et al. [51] demonstrated that replacing Portland cement with

GGBFS reduces CO_2 emissions due to the lower energy requirements and the sequestration of carbon in the GGBFS.

b) Resource Efficiency: Using Pond Ash and GGBFS in concrete enhances resource efficiency by partially substituting conventional materials with industrial by-products. This not only conserves natural resources, such as sand and cement, but also promotes the utilization of waste materials that would otherwise contribute to environmental pollution. The research by Alzaza et al. [52] highlights that high replacement levels of GGBFS can reduce the consumption of Portland cement, which is a resource-intensive material. This substitution leads to a more sustainable use of resources while still maintaining adequate performance characteristics of the concrete.

c) Economic Benefits: The economic benefits of incorporating Pond Ash and GGBFS are significant. The cost of these supplementary materials is generally lower than that of traditional cement and fine aggregates. By using Pond Ash and GGBFS, concrete producers can achieve cost savings while simultaneously reducing the environmental impact of their products. According to Mohammadi et.al [53] , the lower cost of supplementary cementitious materials can offset the potential increase in production costs associated with their use, making it an economically viable option for sustainable concrete production.

d) Life Cycle Assessment (LCA): A comprehensive life cycle assessment (LCA) of concrete containing Pond Ash and GGBFS evaluates the environmental impact from raw material extraction to end-of-life disposal. Recent research by Nilimaa [54] indicates that the use of these materials in concrete generally results in a lower overall environmental impact compared to traditional concrete mixes. The LCA considers factors such as energy consumption, emissions, and resource depletion throughout the concrete's lifespan. The study found that incorporating Pond Ash and GGBFS can lead to a significant reduction in the life cycle environmental impact, further supporting the sustainability credentials of these materials. The sustainability assessment of concrete containing Pond Ash and GGBFS reveals multiple advantages, including reduced environmental impact, enhanced resource efficiency, and economic benefits. These findings underscore the potential of using industrial by-products in concrete production to promote sustainable construction practices and reduce the ecological footprint of the built environment.

4.6. Results validation

The results of this study are well-supported by both statistical analyses and microstructural observations. The improvement in workability up to 40% replacement of Pond Ash and GGBFS is validated by increased slump and reduced Vee-Bee time, attributed to better particle packing, reduced water demand, and improved lubrication. However, beyond 40%, workability declines due to higher water absorption and increased mix stiffness, which aligns with findings in sustainable concrete studies. Strength properties, including compressive, flexural, and split tensile strengths, show a consistent decline beyond 40% replacement, primarily due to the dilution effect from reduced cement content, weakened aggregate-cement bonding, and increased porosity. Durability also decreases with higher replacement levels, making the concrete more susceptible to aggressive environments, a result supported by microstructural analysis showing incomplete hydration and reduced densification. The statistical models, including Multiple Linear Regression (MLR), exhibit high accuracy, with R^2 values exceeding 97% for compressive strength, flexural strength, and Vee-Bee time, indicating reliable predictions. Principal Component Analysis (PCA) further highlights the significant influence of mix composition on mechanical properties, with the first two components explaining most of the variance. Observed vs. predicted plots show tight clustering along the 1:1 line, confirming the accuracy of the models, with minor deviations for compressive strength and water absorption. Overall, the results validate that optimal replacement levels of up to 40% maximize both performance and sustainability, while higher replacements compromise workability, strength, and durability, highlighting the need for careful optimization in sustainable concrete production.

4.7. Limitations and recommendation

This study provides valuable insights into the sustainability benefits of incorporating Ground Granulated Blast Furnace Slag (GGBFS) and Pond Ash into M20 and M30 grade concrete mixes. However, the research is limited by the fact that only a specific range of replacement levels (10% to 50%) was considered, and other potential variations or combinations of GGBFS and Pond Ash could offer different results. Additionally, the long-term durability and performance of concrete containing higher replacement levels need further exploration to assess its behavior under real-world conditions. Future research should focus on optimizing the mix proportions beyond the 40% replacement threshold to explore potential enhancements in strength and durability, as well as evaluating the impact of different curing conditions. Moreover, more comprehensive environmental impact assessments, including life cycle analysis, could offer a more holistic view of the sustainability benefits.

5. Conclusions

The conclusion of the study presents several key quantitative findings regarding the incorporation of Pond Ash and GGBFS in concrete mixes, particularly for M20 and M30 grades.

a) Impact on Workability and Strength:

- **Workability**: Concrete mixes with up to 40% replacement of cement with Pond Ash and GGBFS showed improved workability due to better particle packing and reduced internal friction. However, beyond this level, workability decreased due to increased porosity and higher water absorption.
- **Strength**: Both compressive, flexural, and split tensile strengths of M20 and M30 grades decreased with higher replacement levels, primarily due to the dilution effect and increased porosity, which weakened the bond strength within the concrete. The strength reduction was quantifiable and reflected a diminishing trend as the replacement percentage increased.

b) Durability:

- The durability of the concrete, evaluated through water absorption and resistance to acid attack, declined with increasing Pond Ash and GGBFS content. The primary reasons for this decline were increased porosity and reduced resilience to harsh environmental conditions.

c) Microstructural Analysis:

- The microstructure of concrete with higher levels of Pond Ash and GGBFS exhibited increased porosity, altered bonding characteristics, and less dense hydration products, all contributing to a reduction in mechanical strength and durability.

d) Environmental and Economic Benefits:

- The use of these materials promotes environmental sustainability by reducing the need for natural resources, lowering carbon emissions, and decreasing waste in landfills.
- Cost savings were observed as Pond Ash and GGBFS are generally less expensive than traditional materials, supporting the economic feasibility of using these industrial by-products.

e) Future Research Directions:

- Further optimization of replacement levels is needed to balance workability, strength, and durability. The study suggests that focusing on the cement matrix interactions and conducting long-term performance evaluations will offer valuable insights for improving concrete performance.
- The application of Life Cycle Assessments (LCA) is recommended to better understand the environmental impact of these materials in concrete.

These findings emphasize the importance of optimizing the use of Pond Ash and GGBFS to enhance concrete performance while supporting sustainability in construction practices.

Conflict of Interest Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Authors' Contributions Statement

Sangeeta Agrawal: Conceptualization, Investigation, Formal analysis (including Multiple Linear Regression and Principal Component Analysis), Data curation, Visualization, Writing – original draft.

Pravin Shirule: Experimental design, Supervision, Resources, Data curation, Writing – original draft.

Husain Mujahid and Sudhakar Pawar: Methodology, Literature review, Validation, Writing – review & editing, Critical feedback, Final revisions.

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Declaration of AI Assistance

The authors acknowledge the use of AI tools in assisting with literature review and data analysis. The AI tools were used for initial data processing and generating draft sections of the manuscript. The final manuscript was reviewed and approved by all authors.

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