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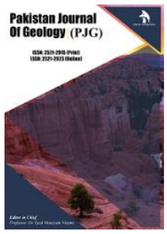

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RESEARCH ARTICLE

PARTIAL REPLACEMENT OF CEMENT WITH FLY ASH TO PRODUCE ENVIRONMENTAL FRIENDLY CONCRETE

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ABSTRACT

The rapid increase in industrial and agricultural waste poses ecological risks and threatens vital resources. To mitigate greenhouse gas emissions, global efforts promote alternative cementing materials. Fly ash, a byproduct of coal combustion, offers a viable substitute for cement in structural concrete. This study comprehensively analyzes fly ash's impact on concrete properties. Various fly ash replacement percentages were investigated through curing at 28 and 56 days. Testing revealed that 15% fly ash replacement yielded the highest compressive strength (3699 psi), signifying an optimal replacement level. Ultrasonic pulse velocity testing indicated a proportional decrease in concrete quality as the replacement percentage increased.

KEYWORDS

ecological risks, coal combustion, Ultrasonic pulse

1. INTRODUCTION

Concrete, a ubiquitous man-made construction material, boasts widespread use due to its availability, water resistance, and adaptability. It serves as the foundation for various construction projects, including dams, high-rise buildings, bridges, infrastructure, and residential developments. Concrete typically consists of four primary components: cement, natural sand, crushed stone, and mixing water. Testing the properties of hardened concrete plays a crucial role in construction oversight, offering vital insights into its structural integrity. Even when conducted later in the construction process, these tests help identify trends in concrete quality and inform future production adjustments.

Fly ash, recognized as a pozzolanic ingredient for concrete since 1914, underwent early comprehensive study in the works of (Davis, 1937; Abdun Nur, 1961), focusing on its properties. Initial research predominantly examined fly ashes derived from bituminous coal combustion, categorized as Class F pozzolans in ASTM specifications. Early findings suggested that substantial portions of Portland cement in concrete could be replaced with fly ash without compromising long-term strength (Timms and Grieb, 1956), particularly when dealing with sub-bituminous ashes. Since the 1970s, research has delved into the characteristics of sub-bituminous fly ashes.

Cement production, the second most consumed substance globally after water, has steadily increased by 2.5% annually. In 2020, production reached 3.5 gigatonnes (Gt), with expectations of reaching 3.7–4.4 Gt by 2050. Unfortunately, cement production is a major emitter of greenhouse gases, primarily carbon dioxide (CO2), contributing significantly to global warming. Approximately 3.4% of global CO2 emissions in 2000 and 5% in 2006 were attributed to the cement industry, with around 50% stemming from direct process-related activities, 40% from energy-related combustion, and 5–10% from indirect energy-related electricity use. This results in an annual generation of 1.35 billion tons of greenhouse gases. Carbon dioxide emissions occur during the fuel combustion process (about 325 kg per ton of cement), clinker production (approximately 525 kg per ton of clinker during limestone decarbonation), and electrical energy consumption (50 kg per ton of cement). One ton of cement production requires 80 units of electric power and consumes about 1.5 tons of raw materials.

To mitigate CO2 emissions, the concept of supplementary cementitious materials has gained traction. Industrial waste products such as sugarcane bagasse ash, rice husk ash, olive oil ash, palm oil fuel ash, and industrial byproducts like silica fume, ground granulated blast furnace slag, and fly ash are used as partial replacements for cement. The disposal of these agricultural and industrial byproducts in open land poses environmental risks by contaminating air and water bodies.

During the initial period from 1940 to 1960, research mainly focused on Class F fly ash, as it was the most readily available ash type at the time. These ashes primarily consisted of sub-bituminous materials. Since the 1970s, numerous studies have explored the characteristics of sub-bituminous fly ashes.

Fly Ash in Concrete Fly ash, a supplementary cementitious material (SCM), enhances various properties of Portland cement concrete. It improves workability, pumpability, cohesion, finish, ultimate strength, and durability while resolving common concrete issues, all at a lower cost. Often known as flue ash, it has been a favored SCM since the mid-1900s. Depending on factors like application, fly ash type, specifications, location, and climate, it can be used at levels ranging from 15% to 25% (common) to 40% to 60% (when rapid setting isn't needed), reducing emissions accordingly and maintaining concrete affordability.

Fly ash, a pozzolanic material, is a finely divided, amorphous alumina-silicate with variable calcium content. When mixed with Portland cement and water, it reacts with the calcium hydroxide released during cement hydration, yielding calcium-silicate hydrates (C-S-H) and calcium-aluminate hydrates. Some fly ashes with higher calcium content can also exhibit cementitious behavior by reacting with water without a calcium hydroxide source. These pozzolanic reactions increase the cementitious binder phase (C-S-H) and, to a lesser extent, calcium-aluminate hydrates,

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enhancing long-term strength and reducing permeability, thus improving concrete durability. Fly ash's performance in concrete is greatly influenced by its physical, mineralogical, and chemical properties, which depend largely on coal composition, spanning a wide range of domestic and imported coals. Fly ash, a typically discarded waste, harms the environment and aquatic life when dumped in open areas or water. Additionally, cement, a costly and less eco-friendly alternative to fly ash, generates more heat during production and emits carbon dioxide.

Figure 1: Suplimentary Cementitous Material

Utilizing fly ash in concrete can reduce costs, mitigate environmental damage caused by dumping and heat generation, and potentially yield improved strength and other benefits.

1.1 Goal of Research

The basic aim is to evaluate the strength potential of fly ash with addition of additives like

gypsum, lime, surfactant & water. The aim has to be achieved through addressing the following Specific objectives.

2. Literature Review

2.1 Fly Ash Utilization in Concrete for Sustainable Construction

Coal is a primary energy source, constituting approximately 67% of the nation's total energy consumption. With a daily coal extraction rate of around 0.8 million tons, India's coal reserves are expected to last over a century. In India, coal-derived energy surpasses that from oil, unlike the global trend where coal lags oil by around 30%. Notably, 90% of the country's thermal power generation capacity relies on coal. Consequently, the management of fly ash, a by-product of coal combustion, poses significant environmental concerns.

Around 110 million tons of fly ash accumulate annually at thermal power stations in India, a material considered internationally as a versatile by-product with various applications. This literature review explores the geotechnical properties of fly ash and aims to identify suitable utilization methods, thereby reducing the need for vast disposal areas and mitigating environmental damage.

Concrete and Modification: Concrete stands as the most widely employed construction material worldwide. Recent decades have witnessed extensive research into supplementary cementitious materials, including fly ash, slag, and silica fume, aimed at enhancing concrete's durability and sustainability. Fly ash, a pozzolanic material resulting from coal pulverization, exhibits the capacity to form a denser, less permeable microstructure when mixed with Portland cement and water. High-strength concrete typically recommends a fly ash replacement level of 15-25%, while normal-strength concrete can incorporate over 50% fly ash in the binder composition.

Minimizing the environmental impact and energy consumption associated with concrete construction has gained prominence as resources diminish and greenhouse gas emissions pose a growing concern. Utilizing life cycle and sustainable engineering approaches in concrete mix design involves maximizing durability, resource conservation, waste utilization, and recycling. Waste and supplementary cementing materials, including fly ash, blast furnace slag, silica fume, rice husk ash, and metakaolin, serve as partial replacements for Portland cement. These materials enhance concrete durability, reduce the risk of thermal cracking, and exhibit lower energy and CO2 intensity compared to traditional cement.

Characterization of Fly Ash: Fly ash, a by-product of coal combustion in power plants, displays inherent variability due to several factors. These factors encompass coal type, mineral composition, coal pulverization degree, furnace type, oxidation conditions, and handling and storage practices before utilization. Additionally, within the same plant, fly ash properties may fluctuate due to load variations over a 24-hour cycle. This non-uniformity poses a significant challenge in the extensive and effective utilization of fly ash as a pozzolanic or cementitious component in cement and concrete applications.

Table 1: Chemical Composition of Fly Ash

References	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	LOI	Others
Hwang and Yeon (2022)	5.0	30.8	9.9	39.6	11.4	0.4	1.0	0.9	7.6	0.6
Saboo et al. (2019)	11.3	47.5	21.7	8.2	1.7	2.5	–	–	2.5	–
Shafabakhsh and Ahmadi (2016)	1.6	50.9	27.9	4.7	–	2.3	–	–	3.7	–
Liu et al. (2019)	10.7	51.3	22.8	6.9	1.9	2.8	–	–	–	–
Muthaiyan and Thirumalai (2017)	10.8	51.6	23.2	7.2	1.9	2.9	–	–	2.5	–
Swe et al. (2016)	11.1	41.7	24.2	13.2	2.8	2.2	2.6	0.7	0.4	0.7
Subramaniam and Sathiparan (2022)	6.3	50.8	28.0	7.0	0.4	1.2	1.9	1.5	–	1.0
Ni et al. (2022)	11.7	42.1	29.1	6.8	1.9	1.9	0.9	2.2	–	1.2
Lin et al. (2022)	35.5	29.5	19.3	3.5	7.4	1.8	–	–	–	3.1
Singh et al. (2021)	0.3	57.4	40.0	1.1	0.0	0.3	0.9	0.1	–	–
Opiso et al. (2019)	23.3	23.9	9.1	28.5	3.0	9.7	0.6	–	16.0	0.9
Wang et al. (2019)	3.8	56.2	26.7	4.4	–	0.1	–	1.3	–	0.1
Mohammed et al. (2018)	17.5	36.4	14.1	22.4	1.0	2.6	2.1	0.2	1.5	–
Ong et al. (2016)	8.40	46.0	17.8	18.2	2.59	0.95	2.16	0.59	1.49	–
Peng et al. (2018)	12.5	50.2	30.5	2.1	0.4	0.1	–	1.3	1.1	1.8
Muthaiyan and Thirumalai (2017)	10.8	51.6	23.2	7.2	–	2.9	–	–	2.5	–
Soto-Pérez and Hwang (2016)	39.6	30.8	9.9	5.0	11.4	0.4	1.0	0.9	–	0.6
Jo et al. (2015)	39.6	30.8	9.9	5.0	11.4	0.4	1.0	0.9	7.6	0.6

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2.2 Classification

ASTM C-618 classifies fly ash into two main categories based on the type of coal burned: Class F and Class C. Class F fly ash is typically produced from burning bituminous coal, while Class C fly ash comes from sub-bituminous or lignite coal combustion. Class F fly ash, derived from bituminous coal, is further categorized into low calcium ashes (CaO < 6%) that exhibit pozzolanic properties and contain over 2% unburned carbon. Quartz, mullite, and hematite are the primary crystalline phases in Class F fly ash. Concrete research mainly focuses on Class F fly ash, as it can replace 15-30% of cement in concrete mixes, reducing water demand, heat of hydration, and enhancing resistance to sulfate attack and chloride ion ingress. Class C fly ashes, known as high calcium ashes (CaO > 15%), have become available for concrete use in the last few decades. These ashes are both pozzolanic and self-cementitious. The specific gravity of fly ash, influenced by particle shape, color, and chemical composition, serves as an indirect quality parameter. ASTM C618 monitors the uniformity of fly ash by limiting the variability in specific gravity and fineness. Specific gravity ranges from 1.3 to 4.8, with Canadian fly ashes having a range of 1.91 to 2.94 and American ashes between 2.14 and 2.69. Factors like minerallic impurities and the presence of magnetite and hematite affect specific gravity. Pulverization of fly ash releases gases trapped within the particles, increasing bulk specific gravity. The particle density of fly ash ranges from 1.5 to 2.5 mg/m3, with lower density linked to a high LOI. Smaller particles have higher densities due to air voids, and some particles even float on water. Particle density variations require alternative methods for particle size distribution determination, like laser scattering. Adding fly ash to concrete has numerous advantages. It enhances fresh concrete properties, affecting workability, pumpability, compactability, water demand, bleeding, segregation, and finishability. Fly ash influences the rate of hydration reactions and the effectiveness of chemical admixtures like air entraining agents and water reducers.

Early age strength in fly ash-based concrete may be lower due to reduced dicalcium silicate content, but later age strength approaches that of control concrete due to higher tricalcium silicate content. Water penetration decreases with increased fly ash replacement in concrete, as fly ash's fine and cohesive nature reduces water permeability. Additionally, workability improves with higher fly ash replacement levels, as it reduces water requirements and fills fewer pores due to fly ash's small size and cohesive properties.

3. Materials and Methodology

3.1 Research Methodology

The research process involves a literature review, analysis of manuals and specifications, material collection, sample preparation, experimental testing, and numerical analysis. The goal is to draw conclusions and make recommendations. Extensive review of manuals, material test specs, and design provisions is conducted, followed by an analysis of research journals and articles to identify best practices and gaps.

3.1.1 Materials Used

- Cement: DG cement is used.

- Fine Aggregate: Sakhi Server sand passing through 4.75 mm sieve is utilized.

- Coarse Aggregate: Locally sourced crushed stone aggregate of 10mm and 20mm sizes is used.

- Fly Ash: Obtained from D.G Cement & Company Ltd.

3.1.2 Experimental Methods

- Sample Preparation: Cement, fly ash, fine aggregate, coarse aggregate, and water are mixed in various proportions for sample preparation.

- Mix Proportion: Cylindrical molds (150 mm by 300 mm) are used for casting concrete samples. Samples are demolded after 24 hours and cured for 28 and 56 days.

- Workability: Concrete slump test is performed as per ASTM C143, yielding a slump value of 65mm.

- Density: Density determination is conducted following ASTM C138.

- Compression Testing: ASTM C39 is used for compressive strength testing of concrete cylinders at 28 and 56 days.

- Ultrasonic Pulse Velocity: ASTM C597 is employed to measure pulse velocity through concrete for categorization.

- Rebound Hammer Test: ASTM C805 is used to determine rebound number, indicating concrete quality.

- Water Permeability Test: Water permeability test follows ASTM C642, assessing concrete's resistance to water penetration.

3.1.3 Fly Ash Replacement Percentage

A fly ash replacement percentage typically ranges from 10% to 30%. This study adopts a 50% replacement ratio to investigate comparative differences in fly ash percentages rather than focusing on absolute compressive strength values, aligning with the goal of maximizing the effects of fly ash composition variations.

4. Results and Discussion

The results and discussion section present the findings and analysis of various tests conducted to evaluate the performance and properties of the fly ash concrete. The tests included compressive strength, split tensile strength, rebound hammer, ultrasonic pulse velocity (UPV), water penetration, and workability tests. These tests provide comprehensive insights into the mechanical, durability, and workability aspects of the fly ash concrete, enabling a comprehensive understanding of its performance and potential applications.

4.1 Workability

The results of the slump cone test revealed a clear correlation between the fly ash content and the slump values of the fly ash concrete samples. As the percentage of fly ash content increased from 0 percent to 30 percent, the slump values of the fly ash concrete samples exhibited a decreasing trend. The incorporation of fly ash in the concrete mix influenced the workability of the material.

Table 2: Slump Cone Test values of Fly Ash from 0% to 30% Replacement

Code	% age of Fly Ash	W/C	Slump value (mm)	Slump type	Remarks
PCC-1	0%	0.6	50	True slump	Slump is within the limit
FAC-S1	5%	0.6	55	True slump	Slump is within the limit
FAC-S2	10%	0.6	59	True slump	Slump is within the limit
FAC-S3	15%	0.6	65	True slump	Slump is within the limit
FAC-S4	20%	0.6	69	True slump	Slump is within the limit
FAC-S5	25%	0.6	74	Shear slump	Slump is within the limit
FAC-S6	30%	0.6	81	Shear slump	Slump is out of the limit

The increase in slump values indicates an increase in the ability of the concrete mix to flow. This can be attributed to the finer particle size and spherical shape of fly ash, which contribute to a thinner packing of particles and allow the movement of cement paste. As a result, the workability of the concrete increases with an increasing percentage of fly ash replacement. This emphasizes the need for careful consideration of mix design and appropriate adjustments to ensure the desired level of workability while harnessing the benefits associated with fly ash concrete. These findings contribute to a comprehensive understanding of the influence of fly ash content on the fresh properties of concrete, aiding in the optimization of mix designs and facilitating the successful application of fly ash concrete in various construction projects.

4.2 Compressive Strength

The compressive strength developments of the concrete mixtures are shown below. The results indicate that incorporation of fly ash in concrete decreased strength at the earlier age as compared to the control concrete. However, they either gained more strength or reached very close to control at a later age.

Table 3: Compressive Strength at 0% to 30% Replacement			
Sample	% age Replaced	28 Days Compressive Strength (psi)	56 Days Compressive Strength (psi)
PCC-1	0	3478	3545
FAC-S1	5	3482	3550
FAC-S2	10	3490	3571
FAC-S3	15	3699	3781
FAC-S4	20	3215	3255
FAC-S5	25	3110	3140
FAC-S6	30	2908	2915

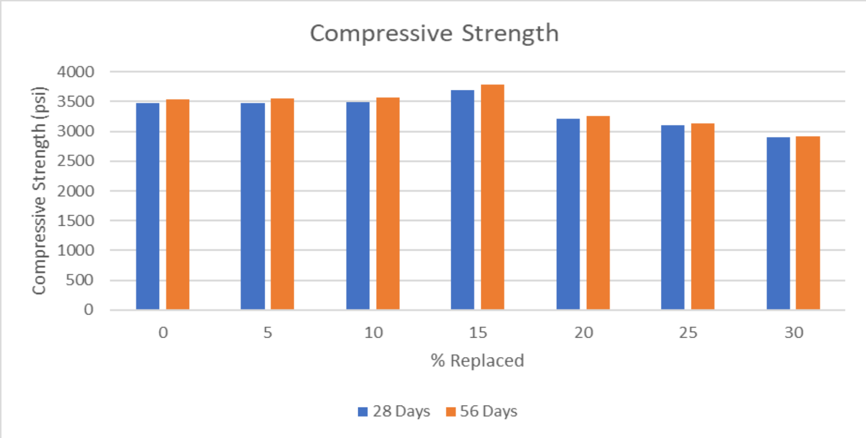

Figure 2: Behavior of Compressive Strength of Partially Replaced Concrete

Concretes with 20% fly ash have shown higher strength gain than those with 30% fly ash. The strength of fly ash concretes in both series developed at a higher rate than that of control concrete until 56 days. The strength increase after 56 days of age is very small in all the mixtures. These results are very much accordance with Khankhaje, E., Kim, T., Jang, H., Kim, C., & Kim, J. (2023)[1]. In Series, the fly ash concrete gained similar strength of control concrete at 28 days. At 56 days, both the fly ash concretes gained more strength of control concrete. It implies the notable strength development capability of fly ash concrete due to pozzolanic reaction after 28 days. Strengths of the fly ash concretes in Series were less than that of the control concrete because the w/b ratio and total binder content were same in all the mixtures. However, fly ash concretes achieved over 80% of control concrete's strength at 28 days. They reached 92% and 96% of control concrete's strength at 56 days, for 40% and 30% fly ash content respectively. The trends of the strength development of the fly ash concretes are similar to those reported in literature.

4.3 Split Tensile Strength

As the percentage of fly ash content increased from 0 percent to 30 percent, the split tensile strength of the fly ash concrete specimens exhibited varying trends. Initially, a gradual decrease in split tensile strength was observed with increasing fly ash content. However, at a fly ash replacement level of 15 percent, the maximum split tensile strength was achieved.

The concrete specimens with 15 percent fly ash replacement demonstrated the highest split tensile strength among all the tested mixtures. This finding indicates that an optimum amount of fly ash in the concrete mix positively influenced the tensile strength of the material. The improved strength can be attributed to the pozzolanic reaction of fly ash, which contributes to the formation of additional cementitious compounds, resulting in denser and stronger concrete matrix which is also in accordance with (Khankhaje et al., 2023).

Beyond the optimal fly ash replacement level of 15 percent, a gradual decline in split tensile strength was observed. This reduction can be attributed to the excessive replacement of cement with fly ash, leading to a decrease in the overall binding capacity of the concrete matrix. As a result, the cohesion between the aggregate particles and the surrounding matrix weakened, resulting in reduced tensile strength.

Table 4: Split Tensile Strength at 0% to 30% Replacement			
Sample	% age Replaced	28 Days Split Tensile Strength (psi)	56 Days Split Tensile Strength (psi)
PCC-1	0	322	330
FAC-S1	5	325	333
FAC-S2	10	328	342
FAC-S3	15	330	343
FAC-S4	20	319	324
FAC-S5	25	311	318
FAC-S6	30	301	307

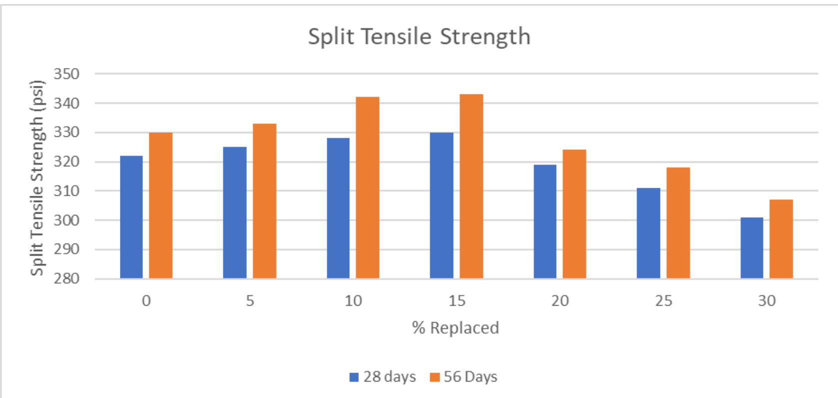

Figure 3: Behavior of Split Tensile Strength of Partially Replaced Concrete

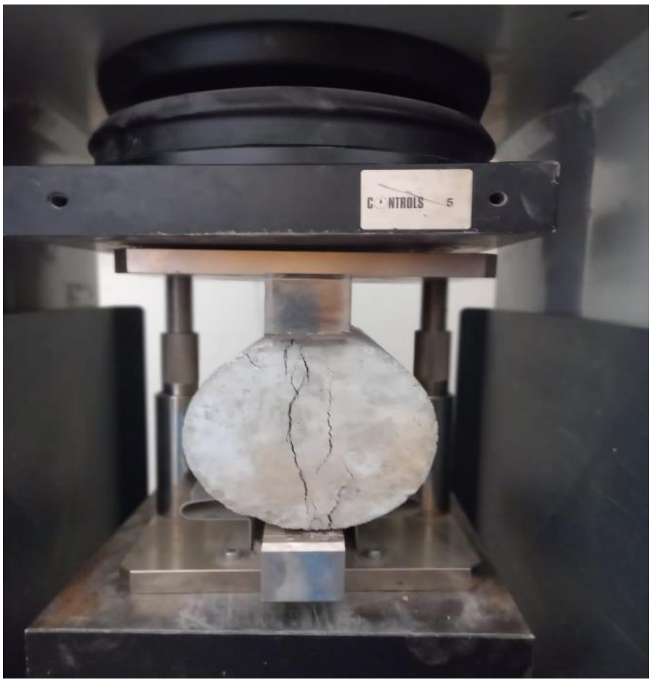

Figure 4: Split Tensile test on Partially Replaced Concrete.

4.4 Water Permeability

In the procedure of water permeability test, the samples were placed in the apparatus for 3 days and the pressure was maintained to be 5 bars. From the below shown results we can demonstrate that, as the fly ash replacement percentage in the concrete increases the water permeability of the concrete decreases thus it is evident that density must increase.

For every 5 percent increase in fly ash replacement, a decrease in water penetration of approximately 1 or 2mm was observed. This trend is according to (Nath and Sarker, 2011), which suggests that increasing the percentage of fly ash in the concrete mix led to a more compact and less permeable material, limiting the movement of water through the concrete.

The reduced water permeability in fly ash concrete indicates improved durability and quality of the material. The pozzolanic reaction of fly ash contributes to the formation of additional cementitious compounds, resulting in a denser and less porous concrete matrix. This densification hinders the movement of water, thereby enhancing the resistance of the concrete to water penetration and potential deterioration caused by water-related factors such as freeze-thaw cycles and chemical ingress. These findings highlight the potential of fly ash concrete to enhance the durability and quality of concrete structures, supporting sustainable construction practices and mitigating water-related issues.

Table 5: Water Permeability Test at 0% to 30% Replacement

Sample	% age Replaced	Water Penetration (mm)
PCC-1	0	31
FAC-S1	5	30
FAC-S2	10	29
FAC-S3	15	27
FAC-S4	20	26
FAC-S5	25	24
FAC-S6	30	23

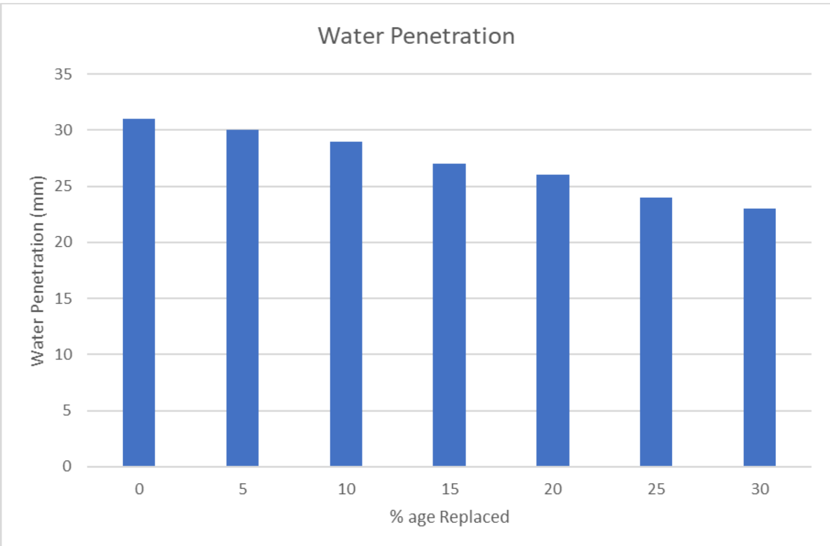

Figure 5: Behavior of Water Permeability of Partially Replaced Concrete

Figure 6: Cubical Moulds in Water Permeability Apparatus

4.5 Ultrasonic Pulse Velocity

In this study, the pulse velocity test was conducted on fly ash concrete specimens with different percentages of fly ash replacement, ranging from 0 percent to 30 percent. The objective was to investigate the effect of fly ash content on the pulse velocity characteristics of the concrete. The results of the pulse velocity test revealed a clear correlation between the fly ash content and the pulse velocity characteristics of the fly ash concrete specimens. The following observations were made.

For every increase in fly ash replacement, there was a corresponding decrease in the pulse velocity of the concrete specimens. Alike the trend by Nath, P., & Sarker, P. (2011), This trend also suggests that as the fly ash content increased, the propagation of stress waves through the material slowed down. Consequently, the time taken for the stress waves to travel a given distance, known as the pulse velocity, increased. This can be attributed to the pozzolanic reaction of fly ash, which contributes to the formation of additional cementitious compounds. These compounds can result in a denser and more heterogeneous concrete matrix, affecting the transmission of stress waves and leading to an increased time period for wave propagation.

The decrease in pulse velocity suggests an alteration in the elastic and dynamic properties of the material. While the decrease in pulse velocity may indicate a decrease in stiffness, it is important to consider that the densification resulting from fly ash replacement can improve other durability-related properties, such as resistance to cracking and permeability.

These findings highlight the importance of considering the effects of fly ash replacement on the performance and integrity of concrete structures, particularly in applications where dynamic properties are crucial, such as seismic-resistant structures and structures subjected to dynamic loading.

Table 6: Ultrasonic Pulse velocity test at 0% to 30% Replacement

Sample	Age (days)	Weight (kg)	Density (kg/m3)	Length (mm)	Time (s)	Pulse Velocity (km/s)	Quality of Concrete
PCC-1	28	2.39	2390	100	27.6	3.61	Good
FAC-S1	28	2.33	2330	100	28.9	3.45	Medium
FAC-S2	28	2.23	2230	100	30.5	3.24	Medium
FAC-S3	28	2.2	2220	100	33.7	3	Medium
FAC-S4	28	2.15	2150	100	35	2.85	Doubtful
FAC-S5	28	2.08	2080	100	36.6	2.71	Doubtful
FAC-S6	28	2.03	2030	100	37.6	2.61	Doubtful

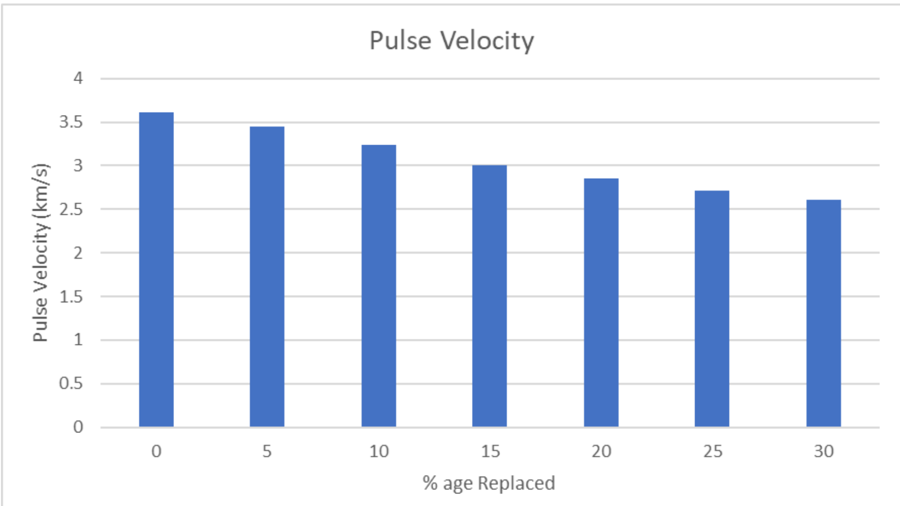

Figure 7: Behavior of Pulse Velocity of Partially Replaced Concrete

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4.7 Rebound Hammer

In this study, the rebound hammer test was conducted on fly ash concrete cube samples with different percentages of fly ash replacement, ranging from 0 percent to 30 percent. The objective was to investigate the effect of fly ash content on the rebound values and thereby assess the compressive strength of the concrete. The results of the rebound hammer test demonstrated a clear relationship between the fly ash content and the rebound values of the fly ash concrete cube samples. The following observations were made.

Table 7: Rebound Hammer Test at 0% to 30% Replacement

Sample	% age Replaced	28 Days Rebound Value	Strength (psi)	56 Days Rebound Value	Strength (psi)
PCC-1	0	28	3045	28	3045
FAC-S1	5	28	3045	29	3146
FAC-S2	10	28	3045	29	3146
FAC-S3	15	30	3256	32	3654
FAC-S4	20	26	2697	27	2930
FAC-S5	25	24	2415	26	2697
FAC-S6	30	21	2022	22	2130

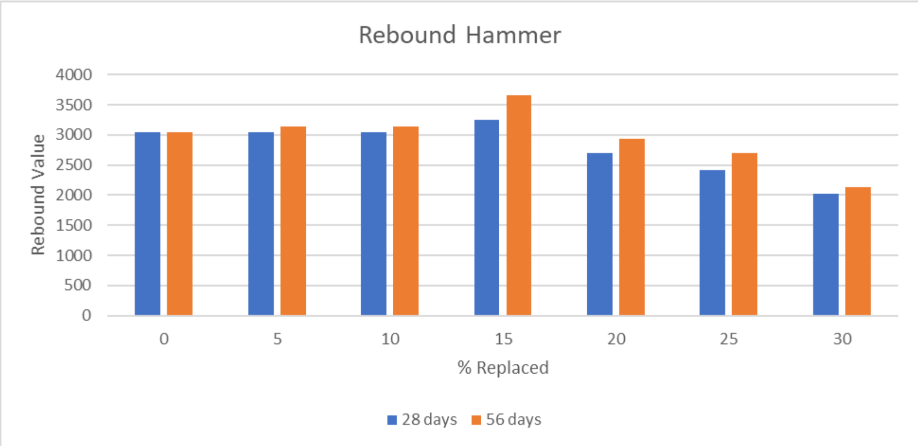

Figure 8: Behavior of Rebound Hammer Value for Partially Replaced Concrete

As the percentage of fly ash content increased from 0 percent to 30 percent, the rebound values of the fly ash concrete cube samples exhibited a noticeable trend according to Nath, P., & Sarker, P. (2011). The incorporation of fly ash in the concrete mix influenced the rebound values. The fly ash concrete cube samples with 15 percent fly ash replacement demonstrated the maximum rebound value among all the tested mixtures. This finding suggests an optimum fly ash content for maximizing the rebound value and, consequently, the compressive strength of the concrete. The increased rebound value can be attributed to the pozzolanic reaction of fly ash, which contributes to the formation of additional cementitious compounds, resulting in a denser and stronger concrete matrix. The proper trend observed in the rebound values underscores the importance of considering the effects of fly ash replacement on the performance and quality of concrete structures. These findings provide valuable insights for the design and implementation of fly ash concrete in various construction applications.

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