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Research Paper

A Comprehensive Analysis of the Influence of Fly Ash on the Bond Properties between Reinforcing Steel and Concrete

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ABSTRACT

This paper examines the possible use of fly ash to make concrete greener. Because cement manufacturing adds to CO₂ levels, using fly ash instead is becoming more popular. This study seeks to find out how bond strength changes for 0–30% fly ash replacement, study the effects of microstructure, and establish the best ratios for use in structures. For this experiment, we used Grade 53 OPC concrete, which was made to meet a target strength of 20 MPa with a water-binder ratio of 0.5. On-center compressive strength (ASTM C39), tensile strength (ASTM C496), and bond strength (ASTM C900) were tested. The study showed that using a 10% fly ash replacement resulted in the best outcome, raising the concrete's compressive strength by 7.3% (from 22.3 to 23.6 MPa), tensile strength by 5% (4.2 MPa), and bond strength by 3% (13.9 MPa) by pozzolanic reactions at the interface between aggregates and cement. When the quantity of added fly ash was increased to 20–30%, the concrete became weaker and difficult to work with (slump: 0–0.9 in.), again due to fly ash diluting the binder. We found out that 10% is the most sustainable amount of fly ash for construction. We had used superplasticizers with silica fume when we were going to replace the amount of cement. In the future, experiments with added salt, carbonation, and earthquake loads could extend how widely this approach is used.

1 Introduction

Concrete is the construction material most often used across the world, and it is key to modern infrastructure because it is inexpensive, flexible, and reliable [1, 2]. The primary component that binds concrete, called ordinary Portland cement (OPC), produces extraordinary environmental consequences. The CO₂ emissions from cement manufacturing represent between 8 and 10 percent of total worldwide emissions [3-5]. The incorporation of supplemental cementitious materials (SCMs) like fly ash from coal combustion serves as a way to increase cement reduction, decreasing carbon emissions while recovering industrial residue [6-9]. Although fly ash reduces environmental impact, it alters concrete mechanical properties and microscopic features, including compressive strength and porosity, and interfacial transition zone (ITZ) characteristics [10-12]. The steel-concrete connection acts as a key structural component because it regulates stress transmission and failure

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behavior and ductile performance in reinforced concrete (RC) systems [13-15]. Previous researchers have studied the compressive strength and durability effects of fly ash extensively, but its influence on steel-concrete bond mechanics remains unknown, which raises questions about sustainable RC structure reliability [16-21]. Each physicochemical property of fly ash, including particle size, CaO content, and loss on ignition (LOI), leads to different behaviors in ITZ properties as well as hydration rate and interface bond strength development [22-24]. The delayed chemical reactions of high volume fly ash (HVFA) concrete containing at least 30% fly ash result in bond strength reductions up to 25% relative to OPC concrete during its early development stage, according to the research [25, 26]. Bond strength performance experiences positive changes in the long term when fly ash replacement levels stay between 15 and 25% because pozzolanic reactions and improved pore structure take place [27, 28]. The prediction of bond behavior becomes complicated by three external factors, including curing period combined with environmental exposure elements (such as chlorides and carbonation) and different bar surface types (deformed versus plain) [29-31]. The current design standards, including [ACI 318 along with Eurocode 2], do not specify recommendations to modify bond strength in structures with fly ash modifications; thus, researchers need to rely on empirical relationships based on OPC-based research [32-34]. Fly ash effects on bond performance necessitate an extensive investigation because this confirms the urgent need for bond characteristic evaluation. Research on steel-concrete bonding processes conducted previously employed pull-out tests, beam-end specimens, and splice tests as experimental approaches, while finite element analysis (FEA) became the main numerical modeling method [35-37]. Analysis by primary researchers shows that bond strength directly relates to concrete compressive strength and divides concrete cover thickness by bar diameter units [38]. Current scientific examinations of supplemental cementitious materials (SCMs), which incorporate silica fume and slag, demonstrate enhanced bond properties from ITZ refinements coupled with decreased material permeability [39-41]. The effects of using fly ash on bond strength are different between studies, with two groups showing either a 12-18% decline at a 40% substitution or no discernible changes at a 25% replacement level [42, 43]. Studies have proven that fly ash can improve bond durability through its chloride-binding capability as well as its ability to refine pore structures [44, 45]. The alteration of ITZ through fly ash use becomes visible using advanced characterization tools, which comprise SEM, nano-indentation, and X-ray micro tomography [46-48]. The relationship between fly ash parameters such as loss on ignition (LOI) fineness, together with the Ca/Si ratio, and bond-slip behavior still needs significant development from the current stage of research [49-51]. Research to date mainly investigates single influencing factors, such as replacement ratios, without considering the joint effects of fly ash material characteristics combined with curing procedures and chemical admixtures [52-54]. A minimal LOI value below 6% will allow fly ash to absorb air-entraining admixtures and reduce bond capacity according to the research [55, 56]. Cross-study comparisons become impossible due to variations in testing protocols, which include cube against cylinder specimen shapes combined with different loading rates and bar surface conditions [57-59]. The evaluation of adhesive breakdown under multiple environmental conditions, such as freeze-thaw cycles and chloride penetration, remains limited to a few investigations [60, 61]. This study bridges the existing research gaps through an investigation of fly ash properties obtained from different sources that include classification as Class F and Class C. Laboratory tests of bond performance through different stages of cure time, between 7-28 days, while exposing samples under multiple environmental conditions. Researchers developed prediction models that reveal the connection between fly ash characteristics and the strength of bonds. Low-carbon fly ash ($\text{LOI} \leq 10\%$) of high fineness ($>400 \text{ m}^2/\text{kg}$) enhances bond strength measurements by 10-15% at a 30% replacement level, but high-carbon fly ash ($\text{LOI} > 10\%$) leads to bond strength decreases of up to 25%.

The study uses experimental testing to assess the bond strength performance of reinforcing steel and concrete using fly ash as a substitute in ratios ranging from 0 to 30%. The study looks at the interfacial transition zone (ITZ) microstructure to see how fly ash parameters impact bond strength via fineness and loss on ignition (LOI) attributes. The study specifies the most effective fly ash replacement amount that maintains a reasonable balance between material durability, workability, and sustainability considerations. The study looks at how different replacement levels impact mechanical qualities such as compressive, tensile, and bond strength to see if fly ash performs well as a component of cement in reinforced concrete applications.

2 Methodology

2.1 Introduction

This project was aimed at studying the effect of fly ash on the bond properties between the reinforcing steel and concrete for purposes of building construction, and it was done at the Concrete Engineering Laboratory of Sarhad University,

Peshawar, Pakistan. Grade 53 of Ordinary Portland Cement (OPC) was acquired from a local supplier in Peshawar for its deserved workability. As per the ASTM standards, the OPC was checked for quality before its use. Preliminary tests to assess the properties of the cement were conducted, and relevant tests conducted at the laboratory were based on sample requirements and included the standard consistency of water content and the initial and final setting times of cement, by the provisions of ASTM C187 and ASTM C191. The specific weight was done according to ASTM C188, and it indicates the weight of a cement sample by comparing it to the weight of the same volume of water. The particle distribution was then tested per ASTM C204 for the cement to get maximum output. The output showed that all of the tests done on the OPC met the requirements in the ASTM standards, thus making it available for use in the experimental works. This was achieved through quality testing of the properties of the cement as per the relevant standard for providing a reliable basis for comparing geopolymer concrete with conventional concrete based on Ordinary Portland Cement (OPC).

2.2 Research Methodology Flow Chart

The study methodology is skillfully outlined in Figure 1, vividly illustrating the three phases. A comprehensive breakdown of the steps and techniques to complete this examination will be provided. The first phase involves the characterization of aggregates, steel reinforcement, and fly ash. This next phase encompasses the casting and curing of concrete samples according to ACI standards. The third phase involves testing to verify compressive strength and pull-out strength according to standards.

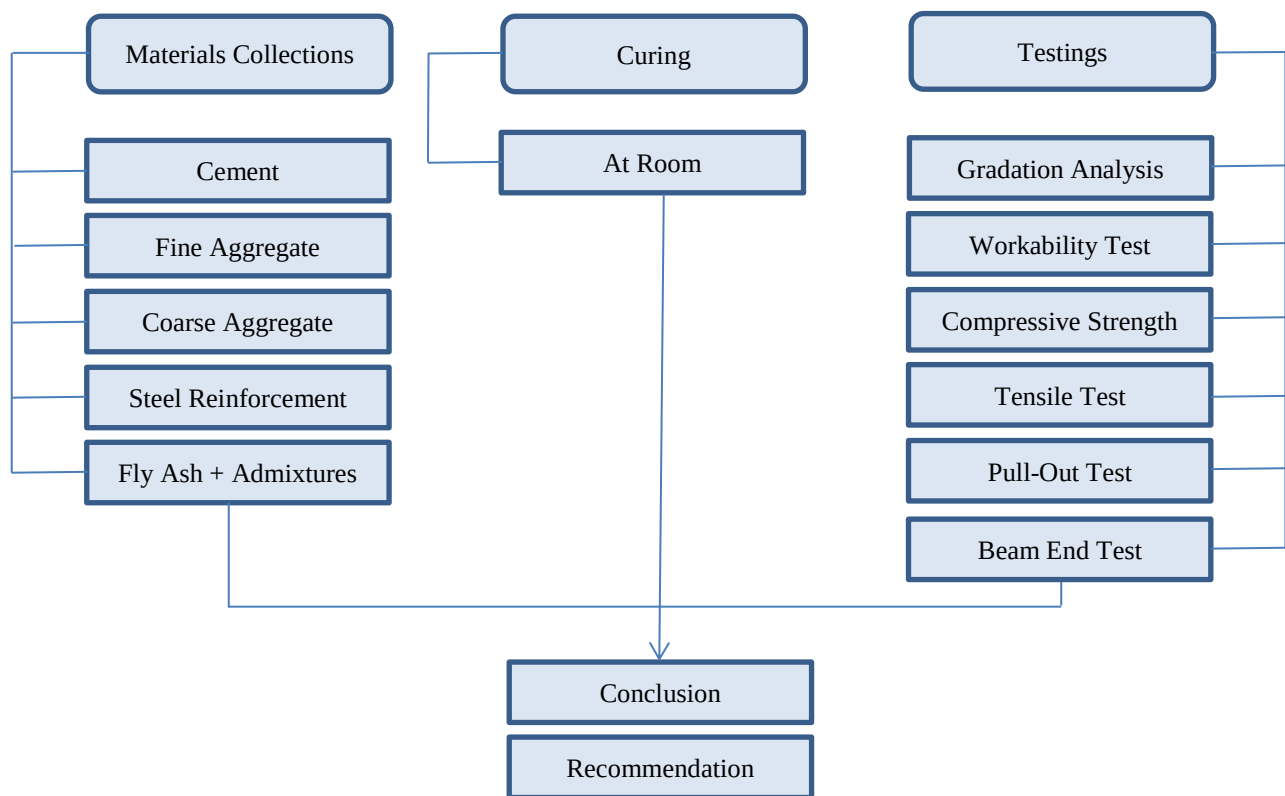


Figure. 1- Research Methodology Flow Chart

3 Materials

This material section outlines the key materials used in the experimental study, assuring the clarity and rigor of our findings. These materials contain the following:

3.1 Cement

we chose locally sourced 53-grade Ordinary Portland Cement (OPC) because of its strength and durability, making it more favorable for high-performance concrete applications. Due to its ideal cohesive and adhesive physical properties, which augment its capacity to bond to other materials, OPC is commonly accepted for use in concrete production [62-64]. The cement selected conformed to ACI standards and represented quality and reliability. All standard tests were performed according to ASTM guidelines[65]. Table 1 presents the detailed properties of the cement.

Table 1- Properties of cement

Specimen	Symbols	Results	LIMITS
Sp. Gravity (ASTM C188)	SG	3.17	3.1 to 3.25
Fineness (ASTM C184)	F	91.5	>90
Silica (ASTM C150)	SiO ₂	20.9	20 to 25%
Alumina(ASTM C150)	Al ₂ O ₃	4.3	4-8%
Iron Oxide(ASTM C150)	Fe ₂ O ₃	3.3	3 to 6%.
Calcium Oxide(ASTM C150)	CaO	63	60 to 67%
Loss on Ignition (ASTM C150)	LOI	1.5	≤ 5%
Sulfur Trioxide (ASTM C150)	SO ₃	2.7	<3%
Magnesium Oxide (ASTM C150)	MgO	2.2	<4%

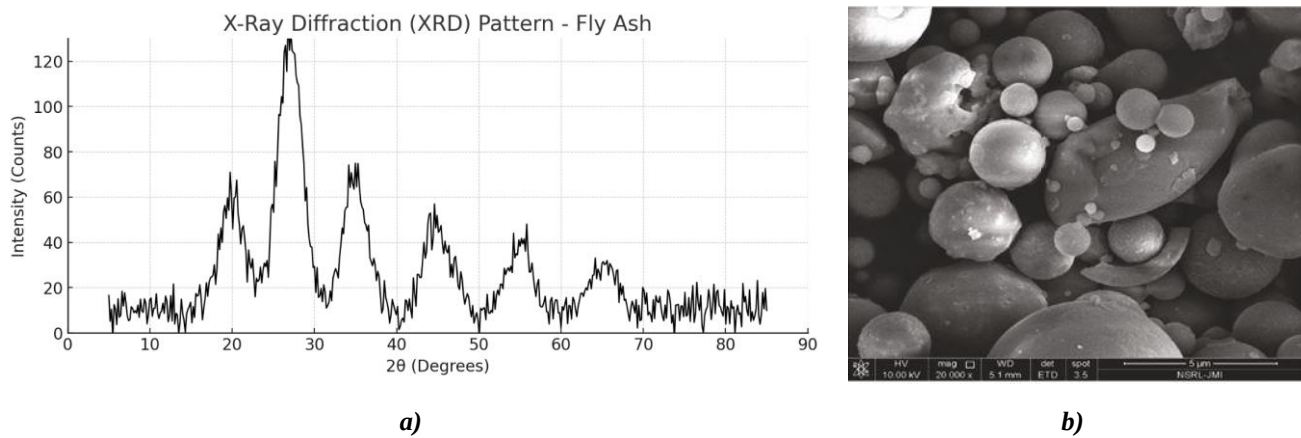
The physical and chemical properties of a cement specimen analyzed through ASTM standardized tests appear in Table 1. Quality measurements outlined by specifications have been verified in testing, which demonstrates material fitness for building use. The cement fulfills ASTM C150 requirements through specific gravity (SG) measurements at 3.17, representing the allowed 3.1 to 3.25 range, and fineness (F) reaching 91.5, above the min 90 standard, and by maintaining chemical composition within the recommended limits: silica (SiO₂) at 20.9%, calcium oxide (CaO) at 63%, and alumina (Al₂O₃) at 4.3%. The cement's quality parameters, including loss on ignition at 1.5%, sulfur trioxide at 2.7%, and magnesium oxide at 2.2%, show levels distinctly lower than their corresponding thresholds, thus reducing the potential durability issues. Analysis results prove that this cement meets all industrial guidelines while demonstrating structural readiness.

3.2 Fly-Ash

Local Class F Fly Ash collected from Peshawar, Pakistan, underwent X-ray diffraction (XRD) and scanning electron microscopy (SEM) evaluation to meet ASTM C618 requirements and demonstrate suitability as a concrete additive. The chemical makeup of the fly ash shown in Table 2 consists mainly of siliceous-aluminous compounds where silica (SiO₂: 64.2%) along with alumina (Al₂O₃: 15.2%) and iron oxide (Fe₂O₃: 3.3%) combine to amount to 82.7% of the material surpassing the 70% necessity for Class F fly ash. This fly ash meets the requirements for Class F status due to its 5.4% CaO content which differentiates it from self-cementing Class C fly ash. The material shows a low level of unburned carbon combined with minimal alkali content (LOI: 2.3% K₂O: 0.4% MgO: 1.5%), which reduces concrete issues related to air-entrainment and alkali-silica reactions (ASR). XRD results (Figure 2-a) confirm that fly ash contains an amorphous structure manifested by the broad hump appearing between 20 and 35° 2θ which supports its pozzolanic reactivity in concrete applications. The material's amorphous characteristic allows the reactive process to take place smoothly between fly ash and calcium hydroxide molecules for forming dense concrete microstructures through C-S-H gels. SEM imaging shows (Figure 2-b) that the material consists of spherical porous particles, which allow improved workability by minimizing inter-particle aggregate friction. Standard testing system validation per ASTM C618 confirms that the fly ash contributes to sustainable construction methods through its ability to lower cement requirements and waste reduction in addition to improved concrete strength properties. Moreover, Class F fly ash provides waste management and addresses environmental issues through sustainable construction practices [66].

Table 2-Characteristics of Fly Ash

Specimens	Standards	Symbols	Values
Silica	ASTM-C618	SiO_2	64.2
Alumina	ASTM-C618	Al_2O_3	15.2
Iron Oxide	ASTM-C618	Fe_2O_3	3.3
Calcium Oxide	ASTM-C618	CaO	5.4
Loss on Ignition	ASTM-C618	LOI	2.3
Potassium Oxide	ASTM-C618	K_2O	0.4
Magnesium Oxide	ASTM-C618	MgO	1.5

**Figure. 2-a) X-ray diffraction (XRD) Pattern of fly ash, b) Scanning Electron Microscopy (SEM) of fly ash**

3.3 Admixtures

An alkaline solution consisting of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was prepared to activate Class-F fly ash. Sodium hydroxide (NaOH) flakes were obtained from Khyber Bazaar located in Peshawar. A sixteen molar (16M) solution of NaOH was prepared according to standard ACI 201.2R-01 by dissolving the flakes of the compound in distilled water without shaking the solution for twenty-four hours for complete dissociation with water. Sodium silicate (Na_2SiO_3) from Karkhano market, Peshawar, served as a soluble silica source for accelerating the polymerization.

The Selection of 16M NaOH conforms to the ACI 201.2R-01 specifications and accepts pertinent findings from geopolymer concrete studies to enhance properties involving strength, durability, and workability. The degree of alkalinity is controlled by molarity such that enhanced geopolymerization is accompanied by enhanced compressive strength development. The use of 16M NaOH not only aids in the practical application of geopolymer concrete products but also enhances the properties of chemical sulfate resistance. Laboratory studies suggest that the selection of 16M NaOH provides not just the most prosperous mechanical properties but also the most desirable results for long-term use in geopolymer construction, but it does slightly lower workability compared to 18M or 20M solutions.

3.4 Super Plasticizer

The available naphthalene-based superplasticizer conforming to ASTM C494/C494M was used in the concrete mix design to improve the workability of fresh concrete while reducing water demand. This additive effectively lowers the water requirement without affecting mix consistency, cohesiveness, or setting characteristics to result in improved casting, compaction, and early-age handling—all important in systems with low water-to-binder ratios. A series of trial mixes were carried out by varying the superplasticizer dosage anywhere between 0.5% and 2.0% by weight of binder for selection of the

best suitable dosage that will provide maximum flowability while preventing bleeding and segregation. Workability was evaluated using standard slump flow and visual stability index (VSI) testing methods. The optimum dosage level was found to be 1.5% by weight of binder, which corresponded to a dosage of 12.6 lb/yd³. This quantity ensured a uniform dispersing of binder particles, facilitating the development of a mix with better workability and increased cohesion. Over time, optimized use of the superplasticizer resulted in denser microstructure, reduced porosity, and a more refined pore distribution. In terms of compressive strength at different curing ages—3, 7, 14, and 28 days—the optimized mix design was found to be much superior. It showed not only the durability performance improvements but also lowered crack susceptibility and increased resistance to aggressive environmental conditions. Such improvement makes the optimized mix design consistent with applications where mechanical integrity and durability are needed for longer periods.

3.5 Steel Bar

The research examined deformed steel bars that fit the 16 mm (5/8 inches) nominal diameter in their bond behavior with geopolymer concrete. Deformed steel bars used for testing had a nominal tensile strength rate of 72.5 ksi (500MPa).

The selection of the 16mm deformed steel bar and its practicality and relevance in structural applications assured a reliable study of bond behavior in geopolymer concrete. The 72.5-ksi (500-MPa) tensile strength is considered sufficient for standard reinforcement requirements, making a balance between structural relevance and ease of testing. The selection adds to the applicability of the findings for construction and engineering practice.

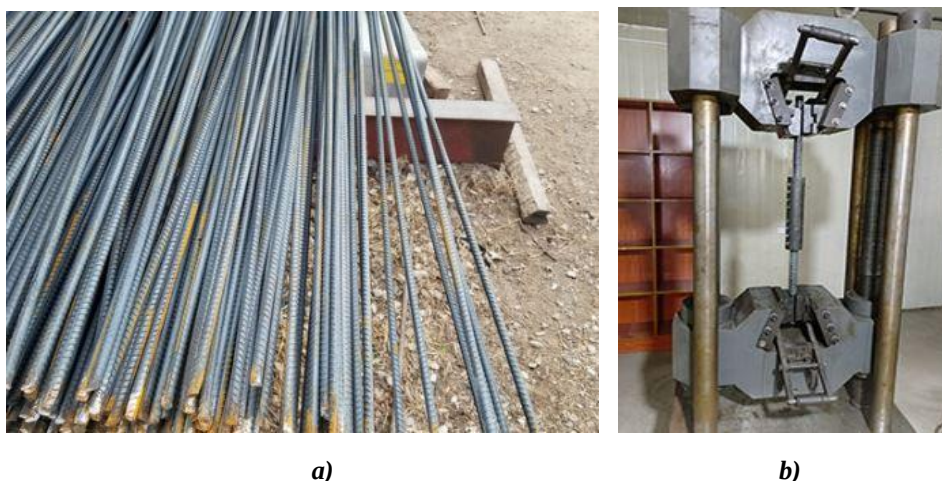


Figure. 3 - a) Deformed Steel bar, b) Universal testing machine

3.6 Aggregates

The project obtained riverbed fine aggregate while the coarse aggregate consisted of appropriately sized crushed angular stones. This document presents the required information about aggregate components in the table shown below.

Table 3-Physical characteristics of coarse and fine aggregates

S. No	Description	References	Results
1	Sp. Gravity of Fine Aggregate	ASTM C128	2.6
2	Sp. Gravity of Coarse Aggregate	ASTM C127	2.3
3	F.M of Fine Aggregate	ASTM C136	2.33
4	F.M of Coarse Aggregate	ASTM C136	3.07

Table 3 shows essential physical data of coarse and fine aggregates needed for successful concrete mix designs. Results from the standardized ASTM tests confirm quality standards for consistency purposes. Specific gravity rates for fine aggregates (e.g., sand) come in at 2.6 per ASTM C128 test standards, thus demonstrating typical densities of natural sand materials for concrete workability and strength objectives. A medium-fine sand classification results from the fine aggregate's

fineness modulus reading of 2.33, which follows ASTM C136 standards, permitting efficient particle placement while minimizing material voids within the mix. The specific gravity measurement for coarse aggregates (gravel or crushed stone) stands at 2.3 according to ASTM C127, showing it has a lower density than fine aggregates due to its pore structure. A moderate grading pattern emerges from the fineness modulus of 3.07, indicating balanced workability as well as structural stability according to ASTM C136. Standard specifications demonstrate these values and show each aggregate is suitable for concrete use by proving durability while guaranteeing proper hydration and preventing segregation. Concrete strength outcomes, together with shrinkage control and extended performance, rely on precise aggregate grading techniques and density levels.

4 Mixing, curing, and casting

In this research, concrete mixes were ready for the presence of fine aggregate and water, coarse aggregates, and with 0, 10, 20, and 30% proportions, Type F fly ash was all the mixtures subjected to pullout test cubes and compressive strength with the use of cylinders. Mixing according to ASTM C192/C192M standards included making sure that all the materials mixed well with each other towards a homogeneous concrete mixture [65]. Specimens were cast and cured under controlled conditions. Curing was done in the first 24 hours at 25°C under a relative humidity of 60-70% per ASTM C511 to obtain good cement hydration [67]. The specimens will then be marked, de-moulded, and put into clean water for conditioning before testing as soon as curing is finished. The concrete cubes and cylinders were kept until they were ready for testing after the curing duration. Pullout test studies were performed under and concerning Aci 318-19 [68] for testing of bonding between steel and concrete, and compression tests were per ASTM C39/C39M-20 [67] to acquire "compressive strength." It was indeed a very systematic mode of acquiring accurate data to study the performance of concrete mixes affected by "Type F" fly ash.



Figure. 4- illustrates the curing and molding process

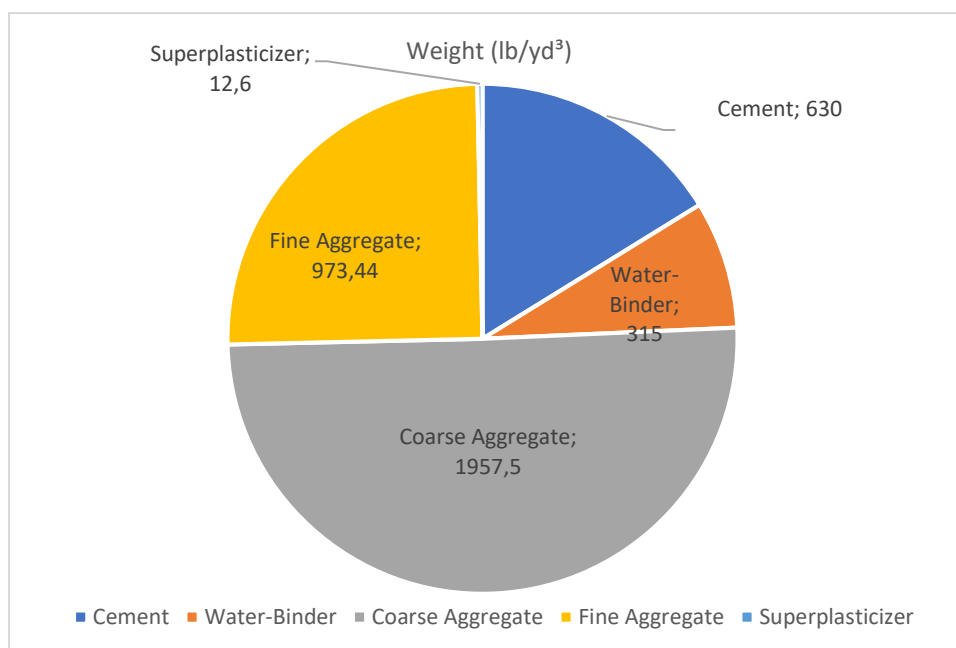
5 Mix Design as Per ACI

Such an "ACI" code offers indispensable parameters for the whole concrete mix design scenario as in ACI 318 [68]. Following these guidelines will ensure a long-lasting and reasonably performing scheme for your endeavor. Well, let us have a very simplified overview of the steps in concrete mix design per ACI guidelines: ·

- Target Strength of concrete = 20 MPa or 3000 psi
- $W/b = 0.5$
- W/b = Water to Binder Ratio
- Slump= 1.1 Inch
- Max Size of Aggregate = 3/4" water required for 1.1 slump would be 315 lb/yd³

Table 4-Calculations for mixed design

Calculation Steps	Details	Value
Cement Content Calculation	Weight of Cement = Weight of Water / Water-Cement Ratio	630 lb/yd ³
	Weight of Water-binder	315 lb
	Water-binder Ratio	0.5
Coarse Aggregate Estimation	Fineness Modulus of Coarse Aggregate	3.07
	Vol. of Dry Robbed CA	0.5 or 0.6
	Dry Robbed "U.W." of Coarse aggregate	145 lb/ft ³
	Oven Dry Weight of Coarse Aggregate	1957.5 lb/yd ³
Fine Aggregate Content Estimation	The volume of Dry Fine Aggregate	27 ft ³ –21 ft ³
	The volume of Fine Aggregate	6 ft
	Oven Dry Weight of Fine Aggregate	973.44 lb/yd ³
Total Batch Estimation per yd³	Water-binder Volume	5.05 cft
	Cement Volume	3.256 cft
	Coarse Aggregate Volume	11.0 cft
	Total Volume	21 cft
Estimated Batch per yd³	Water-binder	315 lb
	Cement	630 lb
	Coarse Aggregate	1957.5 lb
	Fine Aggregate	973.44 lb
Ratio Calculation	Ratio of Cement	1
	Ratio of Fine Aggregate	1.54
	Ratio of Coarse Aggregate	3.1
Final Ratio		1:1.54:3.1

**Figure. 5- Concrete Mix Design Composition (Per yd³)**

Each material element of a concrete mix design adopts its respective weight distribution (in lb/yd³), which becomes evident in the pie chart and supports the significance of each component. As the main binding ingredient, cement contributes 630 lb/yd³ to the mix, while its proportioning at a 0.5 water-binder ratio controls workability and provides ideal strength conditions. The water-binder content weighing at 315 lb/yd³ creates the needed workable mix consistency and also allows the concrete to hydrate properly. The concrete's bulk strength and dimensional stability derive from the large 1957.5 lb/yd³ amount of coarse aggregate, which also reduces shrinkage and minimizes binder requirements. The quantity of 973.44 lb/yd³ fine aggregate completes void sizes among coarse materials to increase workable mixture quality and material density maintenance, thus minimizing bleeding events and segregation occurrences. Despite its small weight of 12.6 lb/yd³, the superplasticizer improves mix flowability substantially while keeping water content constant. The optimized concentration of the superplasticizer maintains a consistent distribution of binder particles, which in turn creates better bond strength and a denser arrangement. This well-proportioned mixture design delivers better mechanical strength alongside durability and prolonged performance capabilities, fit for use in structural projects and durable infrastructure developments.

6 Testing

6.1 Sieve Analysis

A sieve analysis was conducted to determine the particle size distribution of fine and coarse aggregates used in the concrete mixes. Fine aggregates were tested using sieves No. 4 through No. 200, while coarse aggregates were analyzed using larger sieves, including 3, 2.5, 1.5, 3/4, 1/2, 3/8, and 1/4 inch sizes[64]. Aggregate samples were placed in a sieve stack and mechanically shaken. After shaking, the retained material on each sieve was weighed, and cumulative percentages were calculated. The results, provided in the data Table 5, helped assess aggregate grading, ensuring material suitability for the concrete mix. This process is essential for optimizing workability, strength, and overall concrete quality.

Table 5- Grading results of Fine and Coarse Aggregates

Sieves #	Weight Retained (gm)	% retained	Cumulative% passing	Cumulative% Retained
3	0	0	100	0
2.5	0	0	100	0
1.5	0	0	100	0
1	0	0	100	0
3/4	269	26.9	73.1	26.9
1/2	582	58.2	14.9	85.1
3/8	121	12.1	2.8	97.2
1/4	11	1.1	1.7	98.3
			Total	307.5
Fines Modulus (Fine Aggregate) = $\sum$ Cumulative % Retained / 100				3.07

Sieve Analysis (Coarse Aggregate)				
Sieves #	Weight Retained (gm)	% retained	Cumulative% passing	Cumulative% Retained
4	0	0	100	0
8	3.2	0.64	99.36	0.64
16	8.7	1.74	97.62	2.38
25	14.18	2.836	94.784	5.216
50	178.2	35.64	59.144	40.856
100	239	47.8	11.344	88.656
200	37.12	7.424	3.92	96.08
pan	19.6			
			Total	233.828
Fines Modulus (Coarse Aggregate) = $\sum$ Cumulative % Retained / 100				2.33

6.2 Workability

We carried out the slump test for the workability of concrete, using the method set out in ASTM C143[69]. This study was performed at the Concrete Laboratory of the Civil Engineering Department, Sarhad University of Science and Technology. It consists of mixing fresh concrete, placing it in a conical mold, pulling the mold out upright, and determining the drop in height of the sample.

Each test involved putting three equal layers of resin in the mold. After each layer was delivered, it was tamped 25 times with a standard rod to achieve the same compaction all around. When tamping the last layer was finished, there was a very brief pause of 3 to 4 seconds before carefully lifting the mold's main column straight up. To find out how workable the concrete was, its height was lowered, or “slumped,” and then checked. The value is tabulated in Table 6.

Table 6. Slump Values

S.No	Ratio	identifications	Slump in inches
1	0%	Concrete with 0% Fly-Ash	1.1
2	10%	Concrete with 10% Fly-Ash	0.9
3	20%	Concrete with 20% Fly-Ash	0
4	30%	Concrete with 30% Fly-Ash	0

6.3 Compression Test

The compressive strength test was conducted to assess the development of strength within fly ash concrete and its overall performance. Cylindrical specimens were prepared by keeping a concrete mix ratio (1:1.54:3.1) so that all batches remain uniform concerning material composition. It kept the uniform density in all the samples by vigorous tamping of the molds with a tamping rod. Following 24 hours of set time, the specimens were de-molded and immersed in a water tank for continued hydration at later ages.

The number of complete specimens cast into cylinders was 12 for each curing period (7, 14, and 28 days) for a precise mean compressive strength result. The compressive strength test was conducted as per ASTM C39/C39M using a UTM[67]. Each specimen underwent the universal testing machine (UTM) individually, and a uniform compressive load was applied until failure. The compressive strength (σ_c) value was calculated using the expression:

$$\sigma_c = \frac{P}{A} \quad (1)$$

where: P = Maximum load applied (N), A = Cross-sectional area of the specimen (mm²).

From test results it show the use of fly ash enhances the long-term compressive strength due to pozzolanic action, which increases strength with time. The compressive strength of 10% fly ash replacement is noted to be 23.6 MPa, as contained in Table 7. The study results prove that fly ash makes concrete durable and performance-oriented, and henceforth, it seems to be a salt material for construction.

Table 7- Compressive strength results at 28 days

Fly-Ash Replacement (%)	Compressive Strength(MPa)	Compressive Strength(Psi)
0	22	3190
10	23.6	3442
20	21.5	3117.5
30	19	2755

6.4 Tensile Strength Test

The tensile strength test has been done to determine how the fly ash concrete resists cracks and bond failure due to applied tension. These cylindrical specimens have been prepared using the concrete ratio of 1:1.54:3.1, and thus it has achieved batch uniformity in the material composition. To get the same consistency in density, concrete was compacted using a tamping rod. Specimens were de-molded after 24 hours of setting time and placed in a water tank for 28 days of continuous hydration. A total of 12 cylindrical specimens were cast to test parameterization for specific tensile strength. The splitting tensile test was carried out according to ASTM C496/C496M by a Universal Testing Machine (UTM)[70]. Loading them with the same load at the time of failure due to tensile. The tensile strength (σ_t) has been defined using the formula below:

$$\sigma_t = \frac{2P}{\pi dL} \quad (2)$$

Where: P = Maximum applied load (N), d=Diameter of the specimen (mm), L=Length of the specimen (mm)

Results of the tests showed that the addition of fly ash improved internal cohesion, thereby making more tensile strength. The redesign of 10% replacement fly ash gains a tensile strength value of 4.2 MPa, which is 15% more than that of the control concrete sample. This was indicated to have an increase in strength when compared to 4.0 MPa. All these findings speak about using fly ash as a tool for the overall development of concrete, thus providing a way to adapt it structurally durably.

Table 8- Tensile Strength results at 28 days

Fly-Ash Replacement (%)	Tensile Strength(MPa)	Tensile Strength(Psi)
0	4	580
10	4.2	609
20	3.8	551
30	3.5	507.5

6.5 Pull-out Test

The pull-out test procedure was selected to evaluate the bond between the reinforcement steel and the concrete matrix based on fly ash percentages of 0%, 10%, 20%, and 30%. The pull-out test was conducted using a hydraulically operated UTM capable of producing a pull-out force of 3000 psi concerning bond strength measurement. The sample arrangement was consolidated on a specially designed steel frame for testing, which simulated the bonding conditions in the field. The frame consisted of rigid steel with two plates, fastened with high-strength bolts. The upper plate was attached to the loading arm of the UTM, while the lower plate contained a hole to extract the embedded rebar during the actual pull-out test. The concrete specimens were thus placed in the test set-up in such a way as to guarantee uniform load application and accuracy in the measurement of bond performance during the test. Bond strength is determined as:

$$\tau = \frac{P}{\pi dL} \quad (3)$$

where P = applied maximum load, d = diameter of the steel reinforcement bar, and L = length embedded in concrete.

The results indicated that with the rise in fly ash content up to a certain limit of 10%, the bond strength exhibited a gradual increase. The control sample (0% fly ash replacement) had a bond strength value of 13.5 MPa, while 10% fly ash exhibited a marginally improved bond strength value (13.9 MPa). The 20% fly ash mix decreases in bond strength to 11 MPa. The lowest bond strength for 30% fly ash was reported at 9.7 MPa, and this was attributed to better microstructure densification, leading to lower porosity and hence more adhesion.

The improvement in bond strength has been attributed to the formation of CaSiH gel, which itself fills in and improves the bonding of the cement matrix and consequently enhances mechanical interlocking between concrete and steel. The reduction in micro-cracking provided further support for this stress transfer process, enabling bond behavior to be fostered. These findings suggest that fly ash in concrete will ensure structural performance in the long run while being an important alternative for minimizing environmental hazards contributed by cement-based materials. This study provides enough

evidence to prove that fly ash improves bond strength (10%), and therefore, it may be considered a way to increase the durability and performance of reinforced concrete structures.

Table 9-Pull-out test results

Fly-Ash Replacement(%)	Pull-out Strength(MPa)	Pull-out Strength(Psi)
0	13.5	1957.5
10	13.9	2015.5
20	11	1595
30	9.7	1406.5

6.6 Beam End Test

Bond strength testing between reinforcement steel and concrete matrix was carried out on bare beam ends on the concrete specimens with reinforcement embedded at one end. The preparation of the specimens was done at various percentages of fly ash replacement (0, 10, 20, and 30) to check how fly ash was affecting the bond performance. The test set-up consisted of a special loading frame. The use of a hydraulic universal testing machine (UTM) capable of applying a 3000 psi pulling force was employed for pullout failure. Thus, the application of load on the reinforced concrete samples was secured in the testing apparatus, making sure that it was well aligned and simulated the real bond conditions.

The test apparatus consists of a rigid steel frame with two steel plates firmly bolted together with high-strength bolts. The upper steel plate is attached to the loading arm of the UTM, while the lower plate has a borehole to allow for rebar pullout during testing. The bond strength was determined from the expression:

$$\tau = \frac{P}{\pi dL} \quad (4)$$

where P is the applied load, d is the diameter of the reinforcement bar, and L is the embedment length.

As observed from the beam-end test outcome, bond strength was increased in progressive order with an increase in fly ash. The control concrete showed a bond strength of 12.0 MPa; with 10% fly ash, its bond strength became 13.5 MPa, which was only slightly higher. With 20% fly ash replacement, bond strength was observed to decrease to 11.76 MPa. The lowest bond strength recorded thus far was achieved by the mix with 30% fly ash replacement, which amounted to 9 MPa.

The enhanced bonding performance due to pozzolanic activity with fly ash helps in refining the microstructure due to the formation of additional C-S-H gel, thus strengthening the interface between concrete and its reinforcement. A dense cementitious matrix reduces micro-cracking and improves stress transfer, promoting mechanical interlock. Thus, in addition to being beneficial to structure and environment, this paper shows a good solid case for increasing fly ash use as a sustainable alternative in concrete mixes since it increases bond strength. Table 10 shows the results of the test.

Table 10- Results of the beam end test

Fly-Ash Replacement(%)	Beam-End Test Strength(MPa)	Beam-End Test Strength(Psi)
0	12	1740
10	13.5	1957.5
20	11.76	1705.2
30	9	1305

7 Results

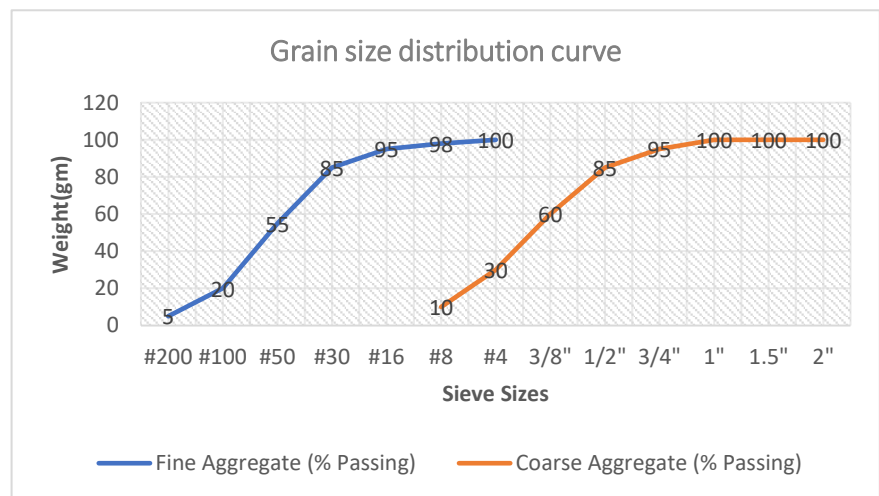
All cast samples of concrete mixtures were inspected using UTM to compare their structural characteristics. Furthermore, the specimens were examined by the guidelines established by the ASTM. The field study on concrete cylinders was carried out in the concrete laboratory of SUIT's Civil Engineering department in Peshawar. The following findings were obtained.

7.1 Sieve Analysis

The fineness modulus (FM) of the fine aggregate measured during the sieve analysis was 3.07, which is in line with the correct FM range (2.3–3.1) for good-quality fine aggregates. A good sand mix is found here, which can provide good workability and a balanced connection between paste and aggregates in concrete. The smooth gradation with only a few gaps revealed by the cumulative percentage passing indicates that very little void space is left in the mix. The fineness modulus for the coarse aggregates came out to be 2.33, a value appropriate for structural concrete blends. Experiments revealed that most of the particles stayed on the 1/2 and 3/4 inch sieves, indicating that the bulk of the aggregates were medium-sized coarse. The gradation makes it possible for hardened concrete to interlock properly and become stronger. All in all, the standard grading was met by both types of aggregates, which helps guarantee that the concrete will be workable and durable. These features are necessary for achieving even compaction, reduced mixing of different materials, and strong reinforced concrete performance over time.



a)



b)

Figure. 6 - a) Mechanical Sieve Shaker Machine used for gradation, b) Grain size distribution Curve

The grain size distribution curves in Figure 6- b) display the passed particle percentage of standardized sieves versus logarithmic particle measurement in both fine and coarse aggregates. The steep slope of the fine aggregate curve (sand) indicates high quantities of material smaller than 0.6 mm and between 0.6 mm and 1.18 mm, while the remaining coarse aggregates exceed 1.18 mm. The coarse aggregate curve (gravel) exhibits a progressive increase in the larger size range (>4.75 mm) where it retains 10% of the material at the 9.5 mm sieve and releases 90% at the 19 mm sieve, thus demonstrating a balanced big particle mixture. The intersection of these curves at the 4.75 mm sieve demarcates the boundary between fine and coarse fractions. The fineness modulus of fine aggregate and the nominal maximum size of coarse aggregate can be determined from this figure to verify adherence to standards like ASTM C33. A proper grading of fine aggregates should produce a smooth, continuous curve, while proper grading of coarse aggregates should achieve balanced distribution to minimize voids and optimize packing efficiency, which leads to improved concrete properties and durability. The illustration demonstrates why correct grading remains essential to decrease cement requirements, alongside segregating prevention and creating economical concrete mixes with superior performance.

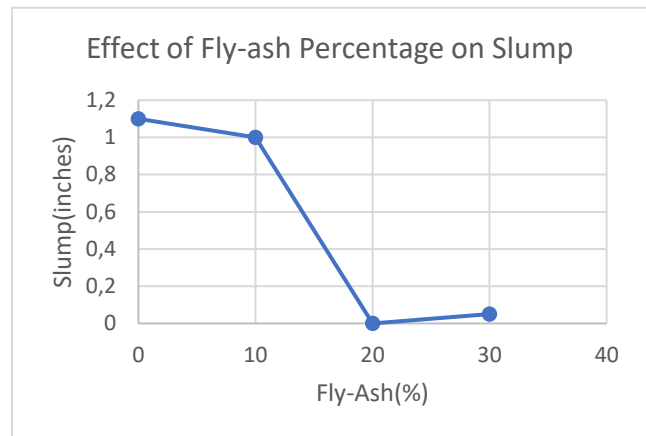
7.2 Workability Test

The experimental study aimed to quantify workability in respect to gradual fly-ash substitution (varying 0-30% fly ash by mass of cement) influence and showed that the control mix with 0% fly ash had recorded a minimum slump of 1.1 inches (2.79 cm), which is an indication of moderate workability suitable for conventional placement. Gradual replacement of fly ash exhibited an enormous slump loss: 10% fly ash replacement reduced this to almost 0.9 inches (2.29 cm) with the 20% and 30% fly ash mixes, with zero slump into a non-flowable and cohesion-dominated state. This is attributed to combined synergistic effects from fly ash's high specific surface area and pozzolanic reactivity, thus increasing the demand for interstitial water, hence resulting in less free water available for flow behavior particle lubrication. Fly ash and slump share

an inverse correlation, as corroborated by empirical observations and confirmed in Figure 7b. Figure 7a underlines the procedural legitimacy of slump test compliance to the specification. These results are meaningful for mix optimizations from the aspect of placement, placing designs of stringent workability while maintaining mechanical performance. With this in mind, adjusting the water-cement ratio could counter the stiffening action of the fly ash, producing a mix containing a high-range water-reducing admixture, such as poly-carboxylate-based superplasticizers, or tuning the aggregate grading for enhanced particle pack density. All these enhancements represent avenues for achieving concrete's rheological behavior objectives in practice while maintaining the durability and structural integrity of the hardened concrete matrix.



a)



b)

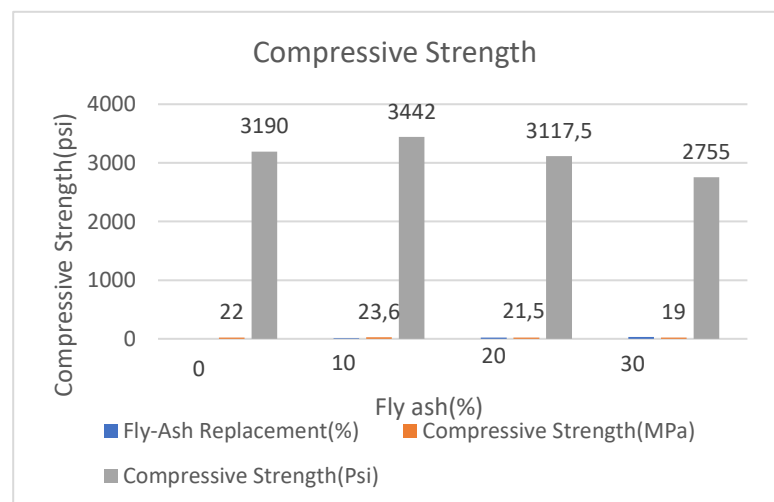
Figure. 7- a) Slump test, b) Slump vs Fly-ash Graph

7.3 Compression Test

The compressive strength test of fly ash concrete was performed to assess the effect of fly ash on the mechanical performance. 150 mm diameter × 300 mm high cylindrical specimens were cast for uniformity in batch preparation, using mix ratio (1:1.5:3 cement: sand: coarse aggregate). The compaction was thorough, with the specimens demoulded after 24 hours and cured in a temperature-controlled water tank (23±2°C) until the testing at 7, 14, and 28 days of casting. The tests were conducted according to ASTM C39/C39M using UTM, where compressive strength (σ_c) has been obtained from the formula: Peak failure load (P) divided by cross-section area (A) of the specimen.



a)



b)

Figure 8 - a) Sample of Concrete, b) Compressive strength result- 28 days

The 28-day compressive strength results (Table 7, Figure 8b) did indicate an apparent non-linear relationship between fly ash content and strength. As for other 1:1.54:3.1 concrete, the control mix (0% fly ash) measured 22 MPa (3,190 psi). On replacing the control mix with 10% fly ash, the strength improved to 23.6 MPa (3,442 psi), which is a 7.3% improvement attributed to the pozzolanic reaction leading to the secondary formation of C-S-H, thereby densifying the matrix. But higher replacement percentages did not translate into higher performance, as with 20% fly ash the strength had dropped to 21.5 MPa (3,117.5 psi); while further decreasing to 19 MPa (2,755 psi) for 30% replacement. Such behavior indicates poor particle packing at these high replacement percentages, where excessive amounts of fly ash act largely as inert fillers, diluting the cement binder.

The best performance was noted for 10% of the replacement, which is an indication of the suggestion that fly ash promotes latent long-term durability in terms of time for pozzolanic reactions, with larger proportions establishing the importance of informed cement-pozzolan ratios to avoid weakening the matrix. For this reason, the findings favor 10% fly ash as an environmentally friendly strength enhancement additive and cement-reducing material beyond which caution is advised; however, further optimization is warranted concerning structural applications.

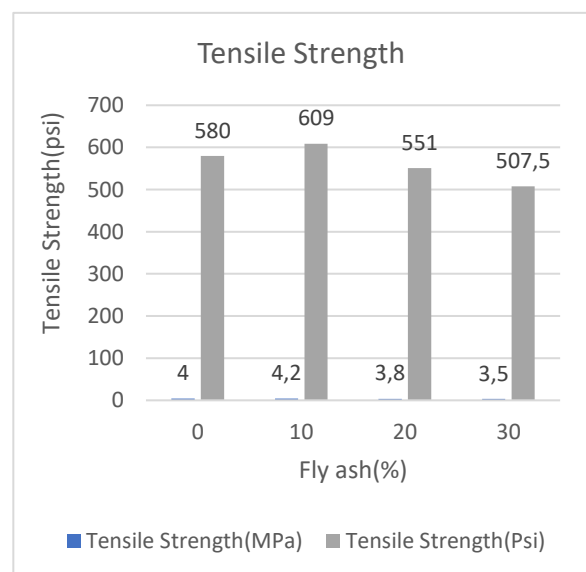
7.4 Tensile Strength

The splitting tensile test (ASTM C496/C496M) evaluated fly ash concrete's tensile strength in resisting crack and bond failure under tension. Cylindrical specimens were made from a batch employing a cement-sand-coarse aggregate mix ratio of 1:1.54:3.1 to ensure compositional consistency across batches. Specimens were tamped for uniform density, demolded after 24 hours, and cured in a temperature-controlled water tank ($23 \pm 2^\circ\text{C}$) for 28 days for complete hydration. A total of twelve specimens were tested using a Universal Testing Machine (UTM), while tensile strength (σ_t) was calculated from the applied load, diameter, and length of the specimen using the expression $\sigma_t = 2P/(\pi dL)$.

The results (Table 8, Figure 9-b) indicate that there exists a nonlinear relation between the fly ash content and the tensile strength. The plain mixture (0% fly ash) had a tensile strength in approximate terms of 4.0 MPa (580 psi), and this has been agreed upon for the M20 grade concrete. With the addition of 10% fly ash replacement, the strength improved to a maximum of 4.2 MPa (609 psi), representing a 15% improvement due to increasing internal cohesion afforded by the pozzolanic activity of fly ash, refinement of the interfacial transition zone (ITZ), and enhanced secondary calcium silicate hydrate (C-S-H) formation. But higher percentage replacement led to lower performance, i.e., bond strength at 20% replacement came down to 3.8 MPa (551 psi), while at 30% replacement, the value dropped to 3.5 MPa (507.5 psi). This was attributed to excess fly ash, acting as an inert filler, hampering the consolidation of particles to yield less effective binders, resulting in lower strength of the matrix.



a)



b)

Figure.9 -a) Sample of Concrete, b) results of tensile strength

Results showed that fly ash serves dual purposes: to improve tensile resistance due to microstructural densification at 10% replacement that is then outdone at higher replacement levels due to lack of a full pozzolanic reaction and increased water demand. A specimen under test is shown in Figure 9a, which has its maximum tensile strength at 10% fly ash treated graphically in Figure 9-b. These findings drew attention to the need for optimizing the fly ash content concerning two objectives, sustainability and structural performance, as one way to achieve durability may be to replace 10% of cement with fly ash.

7.5 Pull-out Test

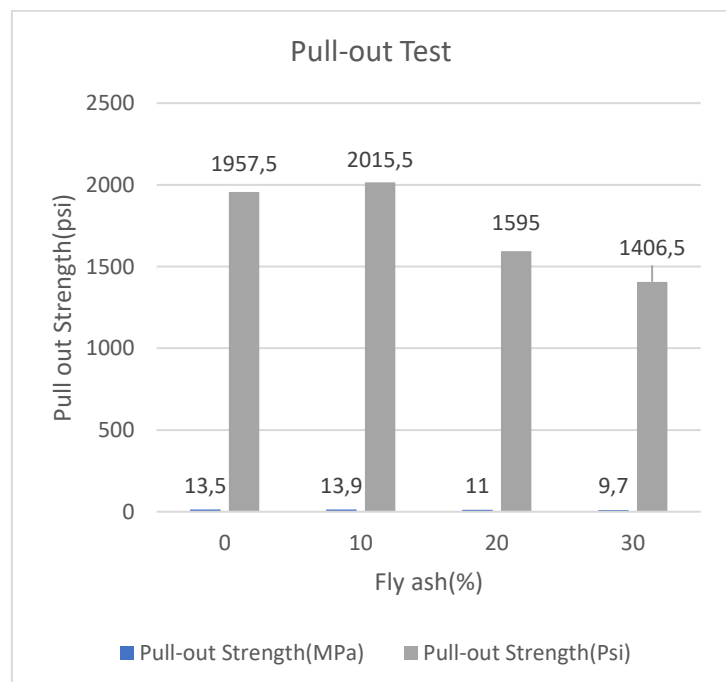
In using the pull-out test, the interfacial bond strength between steel reinforcement and fly ash-modified concrete was intra-corporeally assessed for evaluating adhesion under axial tension. Specimen preparation adopted fly ash replacement levels of 0%, 10%, 20%, and 30% corresponding to the test on the hydraulically actuated Universal Testing Machine (UTM). It also built a steel structure that distributed the same load in a test simulation of real-life bonding conditions. The bond strength (τ) is calculated by the ratio of the maximum pull-out load (P) to the product of the rebar circumference (πd) and the embedding length (L).

The results revealed a non-linear relation between the content of fly ash and bond performance. The control mix (0% fly ash) yielded a reference bond strength of 13.5 MPa (1,957.5 psi). As expected, it was close to conventional reinforced concrete. In replacing 10% fly ash, bond strength improved slightly, recording 13.9 MPa (2,015.5 psi). It was, therefore, observed that because of pozzolanic activity, fly ash improved interfacial adhesion. This indicated that by secondary C-S-H gel formation, which densified the concrete matrix, porosity was reduced, and the mechanical interlock contributed to the steel-concrete interface's component. Greater fly ash replacements were associated with progressive solvent losses in bond strength (20% replacement reduced bond strength to 11.0 MPa (1,595 psi)); a 30% replacement yields the lowest value of 9.7 MPa (1,406.5 psi).

However, the low value as noted affirms the effect of strengthening at 10% substitution of fly ash on the improvement of the interfacial transition zone (ITZ) due to microstructural densification that lessens micro-cracking incidence and enhances stress transfer. Hence, in more than 10% substitution, the unreacted fly ash particles, acting as inert filler, dilute the cementitious binder and diminish the cohesive forces at the interface. Results include lower adhesion and higher interfacial slippage during load.



a)



b)

Figure 10-a) Universal testing machine, b) results of pull-out test

As shown in Figure 10-b, the relationship of bond strength is parabolic, and this underlines the critical balance between the pozzolanic benefit and filler limitation of fly ash. These findings argue for a 10% fly ash substitution for optimal bond performance in reinforced concrete thus providing a sustainable measure toward reduced cement consumption while at the same time providing structural integrity. Greater replacement levels necessitate other economics like hybrid pozzolan blends or superplasticizers to cater to losses in adhesion while still ensuring compliance with engineering requirements. Thus, what the study does is to emphasize the need for calibrated application of fly ash to ensure durability and high performance in reinforced concrete systems.

7.6 Beam End Test

The bond strength between fly ash-modified concrete and reinforcement steel has been further studied using a beam-end test to simulate interfacial adhesion under actual service conditions. Specimens were prepared with different levels of fly ash replacement—0%, 10%, 20%, and 30%—with steel embedded at one end. The experiment was done using a hydraulic Universal Testing Machine (UTM) made to apply pull force to samples amounting to 3,000 psi and embedded into a rigid steel frame to hold them in alignment with physically accurate pressure dynamics. The following equation was used to calculate bond strength (τ): $P/(\pi dL)$.

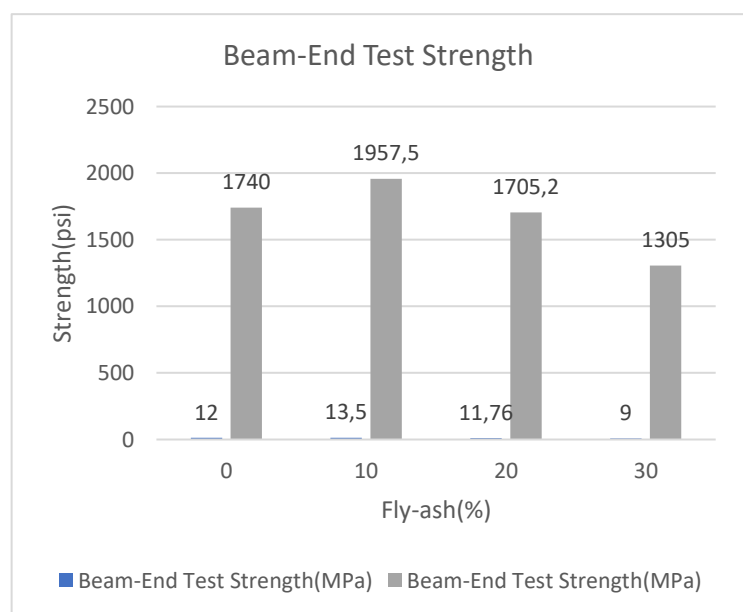
Results showed a nonlinear relationship between fly ash and bonding performance. The control mix, which was without fly ash (0%), recorded a bond strength of 12.0 MPa (1,740 psi), which would conventionally serve as the benchmark for concrete. Bond strength increased to 13.5 MPa (1,957.5 psi) when 10% fly ash was substituted, indicating a 12.5% improvement due to the pozzolanic activity of fly ash; which, in turn, enhanced the secondary formation of the calcium silicate hydrate (C-S-H) gel that densifies interfacial transition zones (ITZs), reduces porosity, and augments mechanical interlocking of steel with the concrete matrix. On the other hand, the continued increase in the percentages did not improve the values. attained 20% fly ash replacement reduced bond strength to 11.76 MPa (1705.2 psi), while using 30% replacement yielded the lowest value of 9.0 MPa (1,305 psi).

The lower substitution of 10% indicates that fly ash can improve the ITZ by dense microstructures, thereby eliminating micro-cracking and increasing the efficiency of stress transfer at this point. However, any increases to the substitution above 10% would add unreacted fly ash particles acting as an inert filler in the cementitious binder, leading to the dilution of cohesive forces at the steel-concrete interface, hence causing weaker adhesion and an increased interfacial slippage when loaded. The evidence is shown in the sharply declining value at 20-30% replacement.

As shown in Figure 11-b, the parabolic trend captures the kind of critical tipping point when the pozzolanic good qualities of fly ash turn to limitation as part of cement.



a)



b)

Figure 11. (a) A universal testing machine, (b) results of beam end test strength

These findings would reconfirm that replacing 10% of fly ash would be the most strategic maximum efficiency point where bond performance in reinforced concrete can be improved, offering advantages from the sustainability viewpoint because it reduces the consumption of cement. Greater substitutions would require countermeasures such as optimal gradation or the use of superplasticizers to maintain structural reliability. The work highlights the necessity for carefully calibrated use of fly ash in designing durable, high-performance concrete systems while calling for its use in green construction practices.

8 Conclusion

In this research, an attempt has been made to conduct a systematic study of steel reinforcement in concrete bonding influenced by Type-F fly ash with testing as part of a larger experimental program. The most important parameters evaluated in this work to look for an optimum level of fly ash substitution will be compressive strength, tensile strength, and bond strength.

- A 10% replacement level of fly ash as partial cement replacement shows the most promising results, wherein the compressive strength of concrete is 23.6 MPa, tensile strength is 4.2 MPa and bond strength is 13.9 MPa. Further refinements occurred due to the ongoing process of pozzolanic reaction, and refinement incorporated with microstructure improved interfacial adhesion.
- With the increase of percentage replacement (20-30%), a gradual decrement in the set of developed mechanical properties was observed; however, the mixture with 30% replacement revealed a slump value of 0. This adverse phenomenon can be attributed to an undue increase in fly ash not affecting cement hydration and an increase in loss of cohesion between the particles.
- More associated with the increased bond strength attainable with a 10% blend of fly ash is the formation of a secondary C-S-H gel, which made the cementitious matrix denser and reduced the porosity at interfaces.
- Aggressive replacement with fly ash generated negative effects on mechanical performance and workability, paralleled with the otherwise optimal level of replacement to ensure faster development of strength while providing satisfactory durability.
- Such experimental findings illuminate the active role of fly ash as both pozzolanic material and microstructural densifier in support of its application in high-performance concrete.
- Sustainable use of fly ash as a cement substitute achieves a reduction in cement consumption, which translates to a reduction in CO₂ emissions and improves the beneficial reuse of industrial by-products.
- The replacement, with 10% fly ash substitution, is an effective method of producing durable high-performance concrete in line with sustainable construction and circular economy objectives across the globe.
- This research sets a primacy for future investigations as to how the enhancement of properties of fly ash interventions can be evaluated concerning bond properties in conventional and geopolymer concrete systems.
- The experimental results have been obtained using Type-F fly ash and locally available aggregates, so other combinations of materials will give different results from region to region.
- The tests were carried out in a laboratory, and its long-term permanence of fly ash-modified concrete under real-exposed environments requires evaluation for ingress of chlorides and freeze-thaw cycles.
- Replacement levels are from 0% to 30% fly ash, without the incorporation of a hybrid binder system that contributed to supplementary cementitious materials, like silica fume or ground granulated blast-furnace slag.
- Future studies would involve the synergistic uses of fly ash and other pozzolanic materials to ensure no deterioration of performance arising from prolonged exposure of fly ash cementitious composites too harsh.

9 Recommendation

The following recommendations stem from experimental results to improve fly ash-modified concrete practical applications as well as future research projects.

- The overall recommended optimal dosage, at which about 10% of OPC is replaced with fly ash, enhances bond strength, compressive strength, and tensile strength while keeping workability within acceptable limits.
- Higher levels of replacements ($\geq 20\%$) may also lead to compromise in the mechanical properties and, therefore, need to be carefully optimized through advanced mix design procedures.

- The loss of workability with increasing fly ash content hence warrants the use of high-range water-reducing admixtures or superplasticizers to attain the desired flow properties.
- Consideration should be given to adjusting the water-binder ratio and optimizing overlay gradation to minimize the stiffening effect of fly ash.
- Further, the mechanical and durability performance of 10% fly ash-modified concrete establishes its suitability for reinforced concrete structures, particularly for green infrastructure and high-performance applications.
- Further studies should evaluate its long-term durability under field conditions, including chloride ingress resistance, sulfate attack, freeze-thaw cycles, and carbonation.
- For promoting mechanical performance and durability, the interaction of fly ash with other SCMs such as silica fume, GGBFS, and meta-kaolin should be considered in the future.
- The hybrid binder systems may also counteract the strength diminution observed at high fly ash replacement, hence enhancing the sustainability benefits.
- In view of the possibility of carbon reduction and waste reutilization, the inclusion of fly ash should be promoted in infrastructural mega-projects and sustainable building activities.
- The policy frameworks should promote the use of fly ash-based concrete as a green alternative to conventional cementitious materials.
- Future studies need to test the structural behavior of fly ash-modified concrete on dynamic loading operations such as seismic resistance and fire performance.
- Long-term field studies are planned to measure durability, microstructural evolution, and service life performance in different environmental situations.
- Future evaluation of the effect of various curing conditions and those of accelerated aging of the mechanical and bond properties of fly ash-modified concrete is mandated.
- This essentially can be a guideline to optimize fly ash-based concrete for the sustainable and high-performance construction domain.

10 Authors Contribution

Investigations were conducted by Adnan and Muhammad Anas, the methodology was developed by both Adnan and Muhammad Anas. Writing, review, editing, and supervision were overseen by Adnan and Muhammad Anas, and the Introduction and software were done by Adnan. The completed paper has been seen and approved by all authors.

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