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EXPERIMENTAL STUDY ON PARTIAL CEMENT SUBSTITUTION IN CONCRETE WITH POFA AND FLY ASH

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ABSTRACT

As the concrete production and consumption across the globe continue to increase, the significant carbon dioxide accumulation in the atmosphere due to the emissions from cement manufacturing has become a cause of global concern. This opened the doors to researching the various supplemental cementitious materials to reduce the quantity of cement required in concrete production. Some such industrial by-products are palm oil fuel ash (POFA) and fly ash. POFA and fly ash, thought to be useless industrial by-products, are found to have pozzolanic properties. The studies performed on the utilization of POFA and fly ash to enhance the mechanical properties and durability of concrete have shown promising results. Furthermore, the usage of POFA and fly ash is eco-friendly and economical.

Keywords: POFA, fly ash, mechanical properties, regression analysis, and sustainability.

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1. INTRODUCTION

The imperative need for conservation of natural resources and reduction in CO_2 emissions, coupled with ever-rising demand for concrete, has led people to search for alternative solutions. Throughout the past few decades, many researchers have studied the use of Agro waste and industrial waste ashes as alternative components in concrete. These ashes include palm oil fuel ash (POFA), rice-husk ash, bagasse ash, fly ash, GGBS, Alccofine, etc. These ashes are used as mineral admixtures or fillers and aggregates in concrete, as their utilization generally improves the properties of concrete, also reducing costs and negative impact on the environment. [1]

POFA is a by-product generated during the combustion of palm oil fuel in power plants and boilers. It is a fine, powdery material composed primarily of oxides of silicon, aluminium, calcium, and iron. POFA is a byproduct of the palm oil industry. The fruit and copra of the palm oil tree are used to extract palm oil, leaving behind waste materials such as empty fruit bunches, palm oil fibres, and shells. These waste materials are burned as biomass fuel to generate steam, powering the extraction process in palm oil mills. The remaining residue, known as POFA, constitutes approximately 5% of the total waste material. [2] While POFA was initially considered waste, recent research has highlighted its potential as a valuable resource [3]. Its high silica content makes it suitable for various applications, such as manufacturing construction materials (like bricks and tiles), producing adsorbents for water treatment, and serving as a component in cement and concrete. [4] The calcium hydroxide produced during the hydration process of concrete can react with the silica oxide content in POFA. This pozzolanic reaction results in an increase in C-S-H, a gel component, and a decrease in calcium hydroxide. [5]

Fly ash is a fine-grained residue that is collected from the flue gas emitted by coal-fired power plants. [6] It is composed primarily of amorphous silica, alumina, and iron oxide, along with trace amounts of other elements. Due to its high content of silica and alumina, fly ash has been widely used in various applications, including construction materials, cement, and geotechnical engineering. Fly ash can delay the setting time of concrete. Also, the excess calcium hydroxide produced during the hydration process is reduced by pozzolanic reactions, resulting in a stronger C-S-H gel. [7] Recent studies revealed that many industrial waste materials or by-products are disposed of in open lands, hurting the immediate vicinity by deteriorating the nearby groundwater streams and soil.[8] Such harmful effects can be avoided by incorporating the use of these by-products in construction materials, hence promoting sustainability. [9]

2. MATERIALS

The materials employed in this investigation are: OPC, coarse and fine aggregates, FA, POFA, tap water, and superplasticizer. The characteristics of each material are outlined in the following section.

Cement

Ordinary Portland cement (OPC), locally available 53-grade cement conforming to IS: 12269:2013, was used in this research. Cement serves as a binder, reacting with water to create a hydraulic binder that binds the other constituents of concrete.

Fly ash (FA)

Fly ash, a byproduct of coal-fired power plants, is composed primarily of alumina, silica, and iron oxide. Its addition to concrete enhances its workability, reduces heat generation, and improves its durability against chemical exposure. The FA used in this experiment is class F-type fly ash.

Table-1. Composition of fly ash [10].

Constituents	Concentration (wt. %)
SiO_2	59.03
Al_2O_3	25.86
Fe_2O_3	5.81
TiO_2	1.71
CaO	1.07
MgO	0.68
K_2O	1.89
Na_2O	0.07
P_2O_5	0.72
SO_3	0.14
LOI	1.80

Palm Oil Fuel Ash (POFA)

POFA is a detrimental waste that has pozzolanic properties, making it a possible replacement material in concrete. POFA is rich in silica and alumina, essential constituents of cement that enhance the concrete's structural integrity.

Table-2. Composition of POFA[11].

Constituents	Concentration (wt.%)
SiO_2	53.82
Al_2O_3	5.66
Fe_2O_3	4.54
CaO	4.24
MgO	3.19
Na_2O	0.1
K_2O	4.47
SO_3	2.25
P_2O_2	3.01
LOI	10.49

Fine Aggregate

Aggregate passing through a 4.75mm sieve was used in the experiments. River sand from zone-Ⅱ, obtained locally, was employed as the fine aggregate.

Coarse Aggregate

Aggregate retained on the 10mm sieve but passing through the 12.5mm sieve was used at approximately 40%, while aggregate retained on the 20mm sieve but passing through the 22.5mm sieve was used at around 60%. The maximum and minimum aggregate sizes were 20mm and 10mm, respectively. Both sizes were used to ensure proper compaction and achieve good workability.

Water

Water plays a crucial role in the hydration of concrete, the chemical reaction that binds the concrete together and gives it strength and durability.

Chemical Admixture

In this research work, a superplasticizer was used to enhance the workability of the concrete without increasing the water-cement ratio.

The specific gravity of the above materials is mentioned in the table below:

Table-3. Specific gravity of materials.

Materials	Specific Gravity
Cement	3.14
Superplasticizer	1.1
FA	2.2
POFA	2.2
Fine Aggregates	2.65
Coarse Aggregates	2.87

3. SCOPE

The scope of this study involves the following aspects.

- **Mix design optimization:** Trial and error analysis of multiple mix designs replacing different proportions of fly ash and POFA, to establish the optimum percentages of both the materials that balance strength and workability.
- **Laboratory testing:** Carrying out laboratory experiments to determine the mechanical properties of the concrete with the above-determined proportions.
- **Comparative analysis with the standard mix:** Evaluating the performance of replacement mix concrete relative to conventional cement-based concrete and concrete incorporating other supplementary cementitious materials.
- **Environmental impact analysis:** Exploring how the use of discarded fly ash and POFA can contribute to a more sustainable concrete production process by

reducing greenhouse gas emissions, landfill waste, and environmental footprint.

- **Field applications and case studies:** Examining real-world examples of fly ash and POFA utilization in construction projects and analysing case studies to understand the challenges and best practices for their implementation.
- **Mix design:** Concrete mix was prepared by replacing 10% and 15% of the total weight of cementitious material with POFA and fly ash, respectively. An optimum water-cement ratio is maintained to ensure proper strength and workability.

Table-4. Material proportioning for different mix designs [12].

Material	Standard Mix	Replacement Mix
Cement	450 kg	374.55 kg
Water	177kg	159kg
Fine Aggregate	639.18kg	624.3kg
Coarse Aggregate	1174.91kg	1132.75kg
Superplasticizer	Nil	4.99 kg
Fly Ash	Nil	74.91kg
POFA	Nil	49.94 kg

3.1 Preparation of Specimens

The specimens prepared for this experiment are cubes of dimensions 150 mm × 150 mmx150mm, cylinders of dimensions 150 mm × 300 mm, and prisms of dimensions 100 mm × 100 mm ×500 mm. The moulds were initially tightened to avoid leaks after filling with the concrete. A thin layer of grease was applied to the moulds before the concrete was poured. After 24hrs of casting, the specimens were demoulded and placed in the curing tanks.

3.2 Test Methods

3.2.1 Workability

The Consistency of concrete is known as how simple it is to mix the concrete, and the ease of placing the concrete. There are numerous testing methods for determining the workability of concrete; one among them is the slump cone test. Initially, the slump cone is applied with a thin layer of grease to avoid the sticking of concrete to the mould, then the concrete is placed in 3 layers, and 25 blows from a tamping rod are used to compress each layer.

3.2.2 Compressive strength (CS)

Cube specimens measuring 150mm x 150mm x 150mm were subjected to compressive strength (CS) tests. These tests were conducted at 7, 28, and 56 days of curing, adhering to IS 516:1959. The average compressive strength of three specimens was recorded for each mix.

3.2.3 Split tensile strength (STS)

Split tensile strength (STS) tests were conducted on a compressive testing machine. Cylinder specimens were placed horizontally and subjected to a gradually applied load. These tests were performed at 7, 28, and 56 days of curing. The load was applied until the specimen failed, and the maximum load recorded was used to calculate the split tensile strength. This test is a common method for assessing the tensile strength of concrete, as it provides a more direct measure of its ability to resist tensile forces.

3.2.4 Flexural strength (FS)

Flexural strength (FS) tests were performed on prism specimens. Following IS 516:1959, the specimens were marked for testing. The tests were conducted at 7, 28, and 56 days of curing.

3.2.5 Experimental analysis

Concrete, a cornerstone of modern construction, is renowned for its strength, versatility, and durability. Its ability to withstand heavy loads, adapt to various shapes and sizes, and endure harsh environmental conditions has made it an indispensable building material. However, the growing demand for cement, a key ingredient in concrete, has raised significant environmental concerns due to its high carbon footprint. The production of cement involves the calcination of limestone, a process that releases substantial amounts of carbon dioxide into the atmosphere. This contributes to climate change and exacerbates environmental degradation. To address these challenges, the construction industry is actively exploring alternative materials that can partially replace cement, enhance concrete properties while promote sustainability. These supplementary cementitious materials (SCMs) offer a promising solution to reduce the environmental impact of concrete production while maintaining or even improving its performance. By incorporating SCMs into concrete mixes, it is possible to reduce the overall carbon footprint, improve workability, enhance durability, and increase resistance to various environmental factors.[13]

Fly Ash, a waste product from burning coal, and POFA, a by-product obtained from the processing of palm oil, are some such viable SCMs. The usage of fly ash improves the workability of fresh concrete, and the strength and durability of hardened concrete[14]. The utilization of POFA is found to offer high resistance to acid and sulphate attacks and increased durability. Owing to its high pozzolanic properties, POFA offers an additional source of calcium silicate hydrate (C-S-H) during the hydration process. [15]

While fly ash and POFA offer promising benefits, their successful integration into concrete necessitates a thorough understanding of optimal

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replacement ratios and their impact on mechanical properties. Research on glass powder's effects on concrete has yielded inconsistent results, influenced by factors such as particle size, replacement percentage, and curing conditions. Thus, the purpose of this experimental analysis is to methodically evaluate the impact of fly ash and POFA on concrete's mechanical properties during its complete curing period.

The findings of this study will contribute to a deeper understanding of the subtle applications of fly ash and POFA in concrete mixtures and highlight their potential as an environmentally friendly, high-performance, and sustainable building material.

4. RESULTS AND DISCUSSIONS

4.1 Workability

The workability of the concrete mix is evaluated by the slump cone test. For the conventional concrete (CC), the slump value is 120mm. As the quantity of fly ash increases, the consistency of concrete also increases, while the replacement with POFA shows a reduction in workability as the percentage rises. From trial and error, it is determined that replacement at 15% fly ash and 10% POFA (a total of 25% replacement in total cementitious material) shows the best workability, i.e., 105 mm. The density of the replacement mix is 2524.7 kg/m^3

4.2 Compressive Strength

The compressive strength test results of concrete are shown in Figure-1 for CC and the substitute mix. For CC, the compressive strength was 27.35 MPa at 7 days, and the substitute mix had a compressive strength of 25.03 MPa at 7 days, which is well above 60% of the target mean compressive strength at 28 days, thus conforming to IS: 10262-2019. The compressive strength at 28days for CC was 38.33MPa, while the substitute mix had 36.58MPa. While at 56 days, the compressive strengths of CC and substitute mix were 39.99MPa and 39.62MPa, respectively. While it is seen that at 28 days, though the target compressive strength was not achieved, the difference in compressive strengths of the two mixes is almost negligible in the long run, i.e., at 56 days, making POFA and fly ash plausible substitute materials.

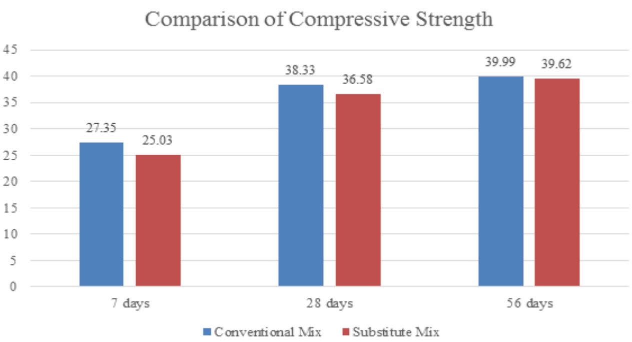

Figure-1. Comparison of compressive strength between CC and substitute mix.

4.3 Split Tensile Strength (STS)

The results for the STS of concrete are shown in Figure-2 for CC and substitute concretes. For CC, the STS was 2.45MPa at 7 days, while the same for the substitute mix was 2.32MPa. Here, it was observed that the CC mix offers more STS than the replacement mix. The same trend was observed at both 28 days and 56 days. The STS at 28 days for CC and substitute mixes are 2.73MPa and 2.60MPa, respectively. At 56 days, the CC mix had STS of 3.18MPa while the substitute mix showed STS of 2.96MPa.

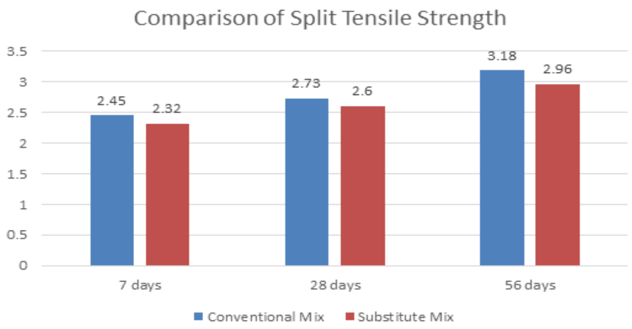

Figure-2. Comparison of split tensile strength between CC and substitute mix.

4.4 Flexural Strength (FS)

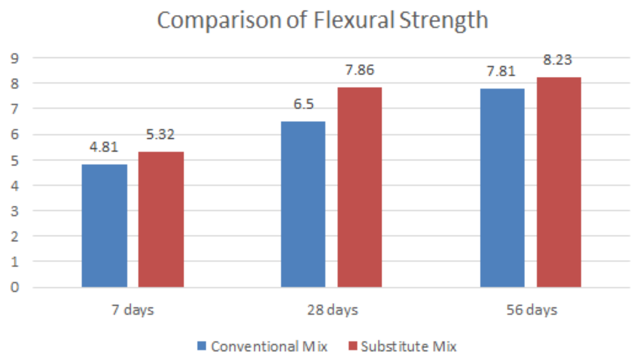

Figure-3. Comparison of flexural strength between CC and substitute mix.

The flexural strength (FS) test measures the concrete's resistance to bending stresses. It is essential for evaluating concrete performance under different bending loads. FS can be determined for both reinforced and unreinforced beams. The FS results of the following experiment are shown in Figure-3. For CC, the FS was 4.81MPa at 7 days, while the same for the substitute mix was 5.32MPa. The FS at 28 days for CC and substitute mixes are 6.5MPa and 7.86MPa, respectively. At 56 days, the CC mix had STS of 7.81MPa while the substitute mix showed STS of 8.23MPa. It is observed that the substitute mix exhibits significantly greater flexural strength at all instances compared to the conventional concrete mix.

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COMPARISON OF REGRESSION ANALYSIS OF COMPRESSIVE STRENGTH AND SPLIT TENSILE STRENGTH

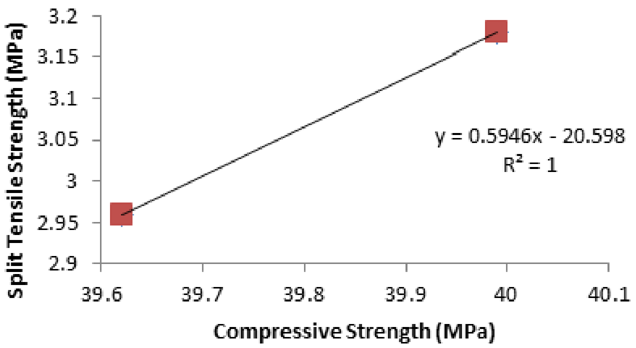

Figure-4. Relation between compressive strength and split tensile strength at 56 days curing.

The relation coefficient obtained from the above Figure-1. It shows that the relationship between compressive strength and split tensile strength of the substitute mix is consistent. Furthermore, it shows that there is almost no difference between compressive strength and split tensile strength of the substitute mix compared to that of the standard mix. The values that are taken are at 56 days of curing of specimens. The relationship between compressive strength (f_{ck}) and split tensile strength(f_t) is given below.

Linear Regression Analysis

f_t=0.5946(f_{ck})-20.598 (56th day)

COMPARISON OF REGRESSION ANALYSIS OF COMPRESSIVE STRENGTH AND FLEXURAL STRENGTH

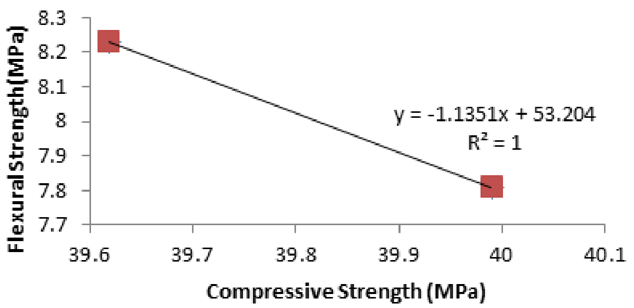

Figure-5. Relation between compressive strength and flexural strength at 56 days curing.

The relation coefficient obtained from the above Figure-1. It is observed that there is no difference in the values of compressive and flexural strengths of the substitute mix when compared to the standard mix. The values that are taken are at 56 days of curing of specimens. The relationship between compressive strength (f_{ck}) and flexural strength (f) is given below.

Linear Regression Analysis

f= -1.1351(f_{ck})+53.204 (56th day)

All the graphs of regression analysis (both above and below) further show that there is almost no difference in the mechanical properties of the substitute mix and standard mix.

COMPARISON OF REGRESSION ANALYSIS OF SPLIT TENSILE STRENGTH AND COMPRESSIVE STRENGTH

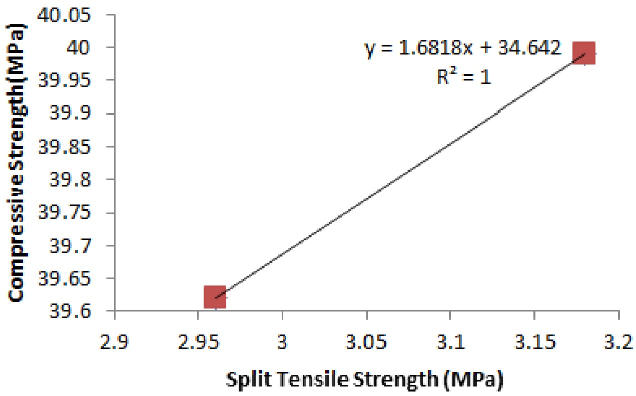

Figure-6. Relation between split tensile strength and compressive strength at 56 days curing.

The relationship between split tensile strength (f_t) and compressive strength (f_{ck}) is given below.

Linear Regression Analysis

f_{ck}= 1.6818(f_t)+34.642 (56th day)

COMPARISON OF REGRESSION ANALYSIS OF SPLIT TENSILE STRENGTH AND FLEXURAL STRENGTH

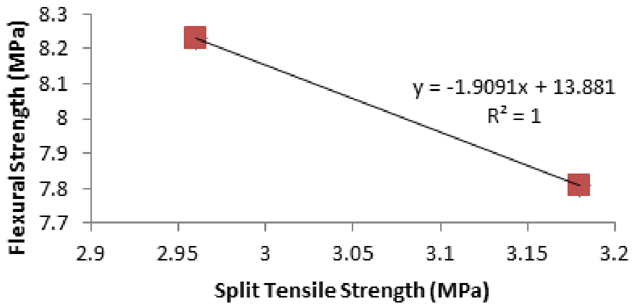

Figure-7. Relation between split tensile strength and flexural strength at 56 days curing.

The relationship between split tensile strength (ft) and flexural strength (f) is given below.

Linear Regression Analysis

f= -1.9091(f_t)+13.81 (56th day)

COMPARISON OF REGRESSION ANALYSIS OF FLEXURAL STRENGTH AND COMPRESSIVE STRENGTH

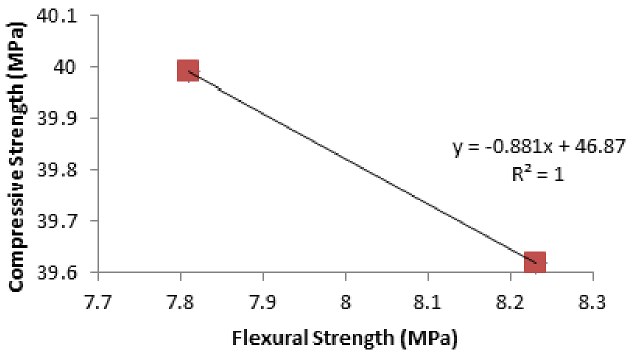

Figure-8. Relation between flexural strength and compressive strength at 56 days of curing.

The relationship between flexural strength (f) and compressive strength (f_{ck}) is given below.

Linear Regression Analysis

f_{ck}= -0.881(f)+46.87 (56th day)

COMPARISON OF REGRESSION ANALYSIS OF FLEXURAL STRENGTH AND SPLIT TENSILE STRENGTH

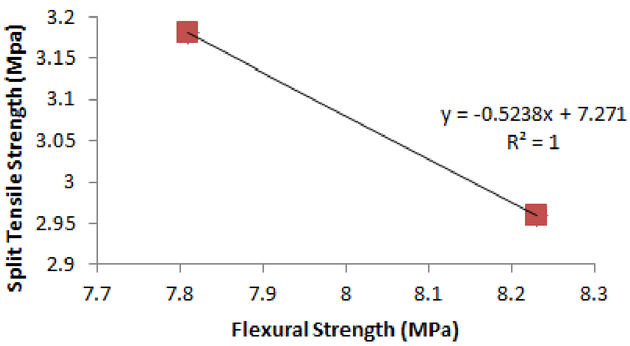

Figure-9. Relation between flexural strength and split tensile strength at 56 days curing.

The relationship between flexural strength (f) and split tensile strength (f_t) is given below.

Linear Regression Analysis

f_t= -0.5238(f)+7.271 (56th day)

5. CONCLUSIONS

The experimental investigation utilized M30 grade concrete, incorporating supplementary cementitious materials such as fly ash and POFA at replacement levels of 15% and 10% respectively. The concrete was cured for 7, 28, and 56 days.

a) Using industrial by-products and waste materials as alternatives to cement in concrete can help mitigate waste disposal issues and produce concrete with comparable or even enhanced strength properties.
b) Compressive Strength (CS) of concrete decreases slightly at the initial stages due to the addition of POFA and fly ash, but is almost the same at 56 days. At 28 days, a 4.5% decrease in compressive strength in the substitute mix was observed.
c) The decrease in Split Tensile Strength (STS) found in the substitute mix is also negligible. A 4.5% reduction in STS was observed in the substitute mix at 28 days
d) Incorporating fly ash and POFA into the concrete showed a significant increase in the Flexural Strength. The substitute mix experienced a 21% increase in flexural strength after 28 days.
e) From the results, it can be concluded that using both POFA and fly ash at the same time as SCMs in the concrete is feasible.

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