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Experimental Studies on the Mechanical and Microstructural Properties of Sustainable Concrete Incorporating Palm Oil Industrial Waste

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Abstract

Diving into the world of concrete, normal concrete is widely used in construction but poses environmental challenges due to significant carbon dioxide emissions from cement production. Incorporating oil palm shells (OPS) and palm oil fuel ash (POFA) into concrete offers a sustainable alternative, utilizing waste products from the palm oil industry and reducing environmental impact. Experimental studies have examined the use of OPS and POFA as partial replacements for coarse aggregate and cement in concrete, with curing periods of 7, 28, and 56 days. The mechanical, durability, and flexural properties of these beams were tested and compared with conventional concrete. Additionally, some advanced techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier Transform Infrared (FTIR) spectroscopy, and Energy-Dispersive X-ray Spectroscopy (EDS) were employed to analyze the microstructural properties of proposed concretes. However, the results affirm that replacing cement and aggregates with oil palm waste is particularly advantageous for mass concreting. The SEM analysis exhibited that the OPS concrete has a heterogeneous microstructure with irregular pore distribution and varied particle sizes, influencing its mechanical properties and durability.

Keywords: Flexural Behavior, Mechanical properties, Palm Oil Fuel Ash (POFA), Microstructural properties, Scanning Electron Microscopy (SEM)

INTRODUCTION

Malaysia faces the challenge of managing vast palm oil wastes and the pressing need for sustainable construction materials. Approximately 15 million tons of oil palm shell (OPS) and palm oil fuel ash (POFA) are generated annually. This study investigates their integration into concrete to mitigate environmental concerns and reduce reliance on conventional materials [1]. It also explores using palm kernel shells as a partial coarse aggregate replacement, emphasizing compressive strength and water absorption capacity. Findings suggest palm kernel shells can be a cost-effective substitute, offering insights into sustainable construction practices [2]. The study delves into utilizing OPS as a sustainable replacement for coarse aggregate in concrete, prompted by substantial agricultural waste from the palm oil industry in countries like Malaysia and Indonesia. The research focuses on three objectives: examining the properties of concrete with varying OPS replacement percentages, establishing the relationship between concrete densities and OPS replacement percentages, and investigating the correlation between compressive strength and OPS replacement levels. OPS undergoes thorough cleaning before incorporation to ensure viability [3].

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Laboratory tests, including workability assessments, density evaluations, and compressive strength tests, are conducted on both normal weight concrete (NWC) and OPS concrete with replacement percentages ranging from 10% to 40% at intervals. Two water/cement (w/c) ratios (0.45 and 0.5) are employed, and curing is performed at 7, 14, and 28 days. Preliminary results reveal nuanced effects on workability, densities, and compressive strength, emphasizing the need for a detailed understanding of OPS integration into concrete mix designs. This research aims to contribute valuable insights into the sustainable use of OPS in concrete, balancing environmental considerations and structural performance [4]. The study also explores the use of improved POFA as a pozzolanic material for producing high-strength concrete. POFA is graded to achieve a median particle size of about 10 mm, replacing varying percentages (10%, 20%, and 30%) of Portland cement Type I. Results indicate that high-strength concrete, exceeding 90 MPa, can be achieved with ground POFA replacement up to 30%. At 28 days, concrete with 10%, 20%, and 30% ground POFA replacement exhibited compressive strengths of 81.3, 85.9, and 79.8 MPa, respectively, with the highest strength observed at 20% replacement [5]. Additionally, the paper discusses the use of ultrafine POFA (U-POFA) in high-strength concretes, highlighting its chemical and physical characteristics, as well as its engineering and fluid transport properties compared to ordinary Portland cement-based high-strength concrete. The investigation suggests that high-volume POFA in high-strength concrete, with improved fineness and heat treatment, can enhance durability, retard water absorption, and provide better performance in challenging environmental conditions. This makes high-strength concrete incorporating POFA a promising choice for applications such as hot weather, underwater concreting, and corrosive or aggressive environments [6]. In the broader context of utilizing pozzolanic materials in concrete, this study contributes experimental results on high-volume POFA in concrete. Concrete specimens with 50%, 60%, and 70% POFA are produced at different water-cement ratios (0.38, 0.42, and 0.48) with superplasticizer. Workability, slump, and strength properties are investigated and compared with a control concrete containing 100% ordinary Portland cement (OPC) [7]. Enhancing and predicting the modulus of elasticity (MOE) in palm kernel shell concrete (PKSC) involves scanning electron microscopic (SEM) analysis of palm kernel shell (PKS) and explores the influence of varying sand and PKS contents, along with mineral admixtures, and compressive strength and MOE. Increased sand content coupled with reduced PKS content enhances compressive strength and static MOE. The highest MOE recorded in this study, 11 kN/mm², replaces 30% of the coarse aggregate with OPS. An M30 grade concrete mix incorporates 0.2% electro-chemical resistance (ECR) glass fiber to the concrete volume. To reduce greenhouse gas emissions from the cement industry, cement is replaced with ground granulated blast furnace slag (GGBS) up to 30% [8, 9]. Additionally, GGBS and POFA are introduced as partial replacements for cement in M30 grade concrete. To enhance ductility, 0.5% electrically higher acid corrosion resistance (ECR) type glass fibers are added to the concrete volume. Replacement percentages for POS, GGBS, and POFA range from 10% to 50%. The study also examines the flexural performance of reinforced concrete beams incorporating POS as a replacement for natural aggregates in coarse aggregate. This substitution addresses solid waste disposal challenges and contributes to natural resource conservation. To further reduce CO_2 emissions from the cement industry, cement is partially replaced with GGBS and POFA, with the addition of 0.5% glass fibers tested under four-point bending. The investigation includes deflection characteristics and the ductility Index [10, 11].

MATERIAL USED AND ITS PROPERTIES

The current research primarily investigates the mechanical and durability properties of sustainable concretes incorporating OPS and POFA. This involves using palm oil fuel ash (POFA) as a partial replacement for cement and palm oil shells (OPS) as a partial replacement for natural coarse aggregates. The proposed concrete mixes feature varying percentages of OPS and POFA replacing natural coarse aggregates and cement are detailed in Section 3. The characteristics of the materials used in preparing these OPS and POFA concretes are thoroughly discussed in subsequent sections.

Binder Materials

Cement is a vital binding material widely used in constructing infrastructure, roads, and bridges. It primarily consists of calcium, silica, aluminum, and iron. Its production involves grinding raw materials to produce clinker, which is further ground with gypsum. This process yields various types of cement, such as ordinary Portland cement (OPC), Portland pozzolana cement (PPC), and white cement. When hydrated with water, cement forms a paste that sets and hardens, influencing the compressive strength, durability, and workability of concrete [12–14]. In this study, 53-grade Ordinary Portland Cement (OPC) was used as the main binder material. Its physical and chemical properties are discussed in Tables 1 and 2. Given cement's ecological impact, ongoing research in construction has shifted towards sustainable practices. One such material used as a partial replacement for cement in this research is Palm Oil Fuel Ash (POFA), sourced from RUCHI SOYA INDUSTRIAL Ltd. (Oil Palm Division) in Andhra Pradesh.

Palm Oil Fuel Ash (POFA) is a byproduct derived from the combustion of palm oil waste, specifically the husk and kernel shell. It is rich in amorphous silica and various minerals and is characterized by its black color and fineness, ranging from 900 to 1100 m²/kg, obtained on a 150 µm sieve. The fineness and pozzolanic properties of POFA make it a valuable additive in concrete, enhancing strength and durability while reducing environmental impact by utilizing waste [15–18]. Researchers suggest that incorporating POFA in concrete mixtures can improve workability and long-term performance, making it a promising and sustainable partial alternative to cement in the construction industry. The physical and chemical properties of POFA are provided in Tables 1 and 2.

Table 1. Physical properties of Binder materials.

S.N.	Properties	Cement	POFA
1	Specific gravity	3.14	2.2
2	Initial setting time (in minutes)	50	N.S
3	Final setting time (in minutes)	475	N.S
4	Normal consistency (%)	34	N.S
5	Bulk density(kg/m^3)	1865	966
6	Specific surface area (m^2/kg)	340	980

Table 2. Chemical properties of Binder materials.

Characteristic	Mass content %	
	Cement	***POFA***
Silicon dioxide(SiO_2)	20.4 [1]	63.4 [2]
Aluminum oxide(Al_2O_3)	4.68 [4]	2.5 [1]
Iron oxide(Fe_2O_3)	4.19 [4]	7.1 [5]
Calcium oxide(CaO)	64.2 [2]	4.9 [4]
Magnesium oxide(MgO)	2.4 [6]	4.5 [4]
Phosphorus pentoxide(P_2O_5)	0.28 [4]	2.322 [6]
Potassium oxide(K_2O)	0.4 [7]	3.23 [5]
Methacrylic anhydride($C_8H_{10}O_3$)	0.2 [7]	0.15 [2]
Sulfur trioxide(SO_3)	2.11 [1]	0.3 [3]
Titanium dioxide(TiO_2)	0.11 [6]	0.25 [3]
Manganese oxide(MnO_2)	0.09 [5]	0.072 [6]
Loss of ignition (LOI)	1 [2]	10.1 [7]

Fine Aggregate

Fine aggregate, commonly known as sand, plays a pivotal role in determining the strength variation within concrete mixes by filling the voids between adjacent coarse aggregates. Adequately graded fine aggregate is essential for achieving optimal particle packing, leading to the formation of dense and cohesive concrete. In the current study, local river sand is used as the fine aggregate. This sand is graded as Zone-II according to IS 383:2016 and passes through a maximum sieve size of 4.75 mm. The physical properties of the collected fine aggregate are detailed in Table 3.

Table 3. Physical properties of fine aggregate (FA), Coarse Aggregate (CA), and Palm Oil Shells (POS).

S.N.	Property	FA	CA	POS
1	Specific gravity	2.71	2.73	1.24(SSD)
2	Finess modules	3.16	7.93	N.S
3	Grade of Zone	II	N.S	N.S
4	Size (mm)	4.75(DOWN)	12.5	0.7-4.75

Coarse Aggregate

Coarse aggregate, primarily composed of crushed stone, is essential for providing volume and structural integrity to concrete mixes. The properties of concrete, such as workability, strength, and durability, are significantly influenced by the shape, size, and surface characteristics of the coarse aggregate. Selecting a well-graded mixture of coarse aggregate ensures effective dispersion within the concrete, thereby enhancing its mechanical properties. In the current research, two types of coarse aggregates were used: natural coarse aggregates sourced from nearby mining operations and POS from the palm oil industry. The physical properties of these coarse aggregates are detailed in Table 3. The maximum size of the coarse aggregate used in this study was 12.5 mm.

Palm Oil Shells (POS)

Palm Oil Shells (OPS), an industrial by-product of palm oil production, can be used as a lightweight aggregate to partially replace coarse aggregate in concrete. For this study, OPS were sourced from a nearby palm oil industry (Ruchi Soya Industries Ltd.). The maximum size of the shells was approximately 4.75 mm. To address their water absorption capacity, the shells were soaked in water for 3-4 hours. After soaking, the shells were spread out on a flat surface and left to dry under atmospheric conditions until they reached a saturated surface dry (SSD) condition [19, 20]. The physical and chemical properties of OPS are detailed in Tables 3 and 4.

Table 4. Chemical properties of Palm oil Shell (OPS) aggregates.

Characteristic	Mass content%
Silicon dioxide(SiO_2)	16.83 [8]
Aluminum oxide(Al_2O_3)	5.8 [9]
Iron oxide(Fe_2O_3)	3.75 [8]
Calcium oxide(CaO)	64.6 [9]
Magnesium oxide(MgO)	2.03 [8]
Phosphorus pentoxide(P_2O_5)	0.04 [8]
Potassium oxide(K_2O)	0.19 [8]
Methacrylic anhydride ($C_8H_{10}O_3$)	0.03 [8]
Sulfur trioxide(SO_3)	4.83 [8]
Titanium dioxide(TiO_2)	0.14 [8]
Manganese oxide(MnO_2)	0.11 [8]
Zinc oxide (ZnO)	1.95 [10]
Loss of Ignition (LOI)	3.8 [10]

Super Plasticizer

Superplasticizers are high-range water reducers that play a crucial role as additives in concrete technology. These additives significantly enhance the workability of concrete by dispersing cement particles and reducing water content without compromising strength. They are capable of producing high-strength and high-performance concretes at lower water-cement ratios, allowing for water reductions of 10% to 30% when used in concentrations ranging from 0.5% to 1.5%. In the current study, HI-FORZA 369, a PCE-based superplasticizer, was used at 1% of the weight of cement, as per IS 9103:1999. This superplasticizer has a specific gravity of approximately 1.22.

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MIX DETAILS

This current study investigates the mechanical and durability properties of OPS and POFA concretes. Various mix proportions were proposed to cast concrete, utilizing sustainable materials such as POS and POFA at different percentages in conventional concrete. This resulted in the production of OPS concrete, POFA concrete, and a combination of POFA and POS materials. OPS concrete involves using POS material as a partial replacement for coarse aggregate at discrete percentages of 0%, 10%, 20%, 30%, 40%, and 50%. POFA concrete, on the other hand, incorporates POFA material as a partial replacement for cement at discrete percentages of 0%, 10%, 20%, and 30%. To address extreme exposure conditions, a water-cement ratio of 0.45, as per IS 456:2000, was adopted for all proposed mix proportions. The design of these mix proportions followed Indian standard codes IS 456:2000 and IS 10262:2019, ensuring adherence to crucial parameters. The suggested mix proportions were further specified in terms of mix ratios, as illustrated in Table 5.

Table 5. Mix Proportions and their Corresponding Mix ratios.

Mix ID	Mix Proportions	Corresponding Mix Ratios
N1	C100%+POFA0%: FA100%:CA100%+POS0%	1:1.9:3.3
P1	C100%+POFA0%: FA100%:CA90%+POS10%	1:1.8:1.9:0.10
P2	C100%+POFA0%: FA100%:CA80%+POS20%	1:1.8:1.7:0.20
P3	C100%+POFA0%: FA100%:CA70%+POS30%	1:1.8:1.5:0.30
P4	C100%+POFA0%: FA100%:CA60%+POS40%	1:1.8:1.3:0.40
P5	C100%+POFA0%: FA100%:CA50%+POS50%	1:1.8:1.10:0.50
F1	C90%+POFA10%: FA100%:CA100%+POS0%	1:0.1:1.8:3.1
F2	C80%+POFA20%: FA100%:CA100%+POS0%	1:0.25:1.8:3.1
F3	C70%+POFA30%: FA100%:CA100%+POS0%	1:0.4:1.8:3.1
A1	C80%+POFA20%: FA100%:CA80%+POS20%	1: 0.25: 2.27: 2.16: 0.251

EXPERIMENTAL PROGRAM

The experimental program in this research was primarily designed to investigate the effects of partially substituting sustainable materials, such as Palm Oil Fuel Ash (POFA) in cement and Palm Oil Shells in coarse aggregates, on the characteristics of concrete. The focus was on improving both the mechanical and durability properties of the concrete. Fresh concrete properties, including workability, and mechanical properties such as compressive strength, split tensile strength, and flexural strength, were examined. Additionally, durability properties such as water permeability, water absorption, and resistance to chemical attacks were evaluated through the testing of a required number of cast specimens in the form of cubes, cylinders, and prisms. These proposed mix proportions were assigned distinct mix IDs such as N1, P1, P2, P3, P4, P5, F1, F2, F3, and A1. However, after years of extensive research in sustainable concretes, one mix proportion with the mix ID (A1) was identified as having the optimum percentage of replacement among all the mix proportions.

RESULTS AND OBSERVATIONS:

Workability

Workability is a crucial characteristic of concrete in its fresh state, referring to its ability to blend, place, and compact effortlessly without segregation or excessive bleeding. It significantly affects both the ease of handling and the quality of the finished concrete products. Several factors influence the workability of concrete, including the water-cement ratio, aggregate characteristics, admixtures, and the use of supplementary cementitious materials. The workability of concrete mixes is commonly assessed using the Slump Cone test, which provides a practical way to measure the consistency and flowability of fresh concrete mixes. In the current research, the results of the slump cone test for the proposed concrete mixes of OPS and POFA were compared to the conventional concrete mix N1, as illustrated in Figure 1, 2, and 3.

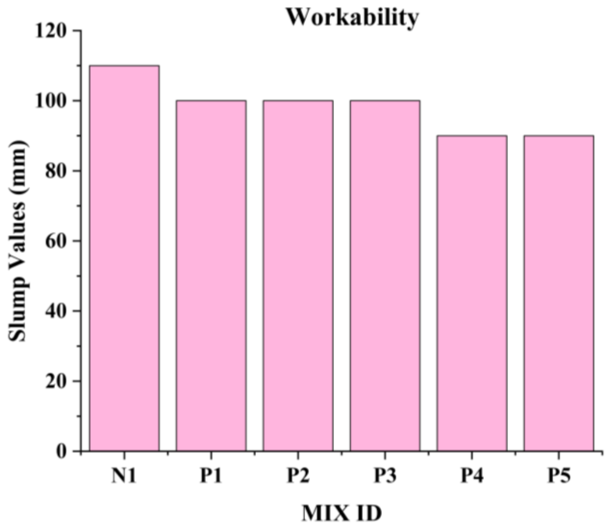

Figure 1. Comparison in workability of conventional and OPS concretes.

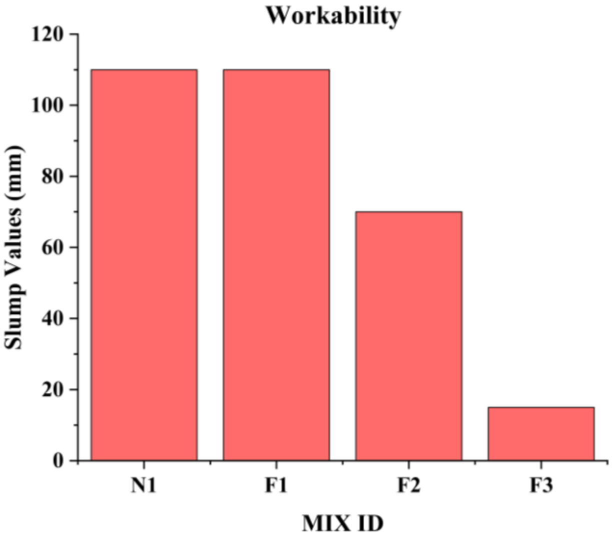

Figure 2. Comparison in workability of conventional and POFA concretes.

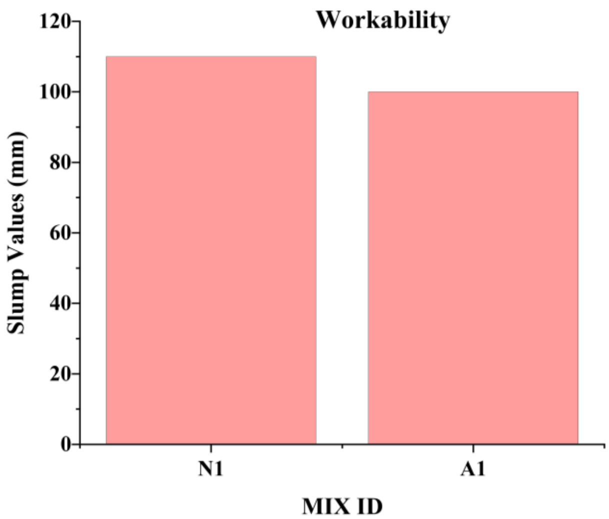

Figure 3. Comparison in workability of conventional and A1 concretes.

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For OPS concrete, multiple mix trials were conducted to achieve the desired slump value.

- *Trial mix 1:* Slump 15 mm, POS in SSD condition, 0.5% superplasticizer.
- *Trial mix 2:* Slump 20 mm, POS in SSD condition, 0.7% superplasticizer.
- *Trial mix 3:* Slump 25 mm, POS in SSD condition, 1% superplasticizer, 15% water reduction.
- *Trial mix 4:* Slump 25 mm, POS in SSD condition, 1% superplasticizer, 15% water reduction, slump cone top at 120 mm.
- *Trial mix 5:* Slump 70 mm, POS in SSD condition, 1% superplasticizer, 15% water reduction.
- *Trial mix 6:* Slump 100 mm, POS in SSD condition, 1% superplasticizer, 10% water reduction.

Trial mix-6 is suitable for the design slump, with 10% POS replacing coarse aggregate.

Mechanical Properties

To ascertain the mechanical properties of hardened concrete, the current research necessitated conducting various types of tests, including compressive strength, split tensile strength, and Flexural strength.

Compressive Strength

Compressive strength stands as a critical mechanical characteristic of hardened concrete, serving as a key standard to assess material resilience under applied compressive loading conditions. To validate the compressive strengths of proposed concrete mix proportions, the current study cast three cube specimens measuring 150mm×150mm×150mm according to IS: 516:1959 for each specific proposed mix proportion. These specimens underwent curing in water for distinct intervals of 7, 28, and 56 days. Upon completion of the curing period, the concrete samples were subjected to vertical loading to obtain compressive strength values for the corresponding concrete mixes and curing intervals. The results of compressive strengths for various concrete mixes were compared with conventional concrete mix N1 at their respective curing intervals. Compared to conventional concrete mix N1, sustainable concretes (P1, P2, P3, P4, P5, F1, F2, F3) exhibited diminishing strength values, as depicted in Figures 4 and 5, at curing intervals of 7, 28, and 56 days. OPS concrete with 20% replacement of POS showed a compressive strength of 28 MPa at 28 days. POFA concretes achieved their target strength at later curing ages due to the presence of unburnt carbon in higher percentages in the concrete matrix constituents. The desired optimum replacement percentage for POFA in cement was found to be 20% by weight of cement, achieving optimal performance with good workability and a compressive strength of 36.5 MPa at 56 days of curing. Additionally, a desired optimum mix proportion, mix A1, was designed with a 20% replacement of POFA in cement and 20% POS in coarse aggregate. The compressive strength results for mix A1 showed approximately 26.67 MPa and 33.22 MPa at curing intervals of 28 days and 56 days, respectively, compared to conventional concrete mix strength, as illustrated in Figure 6.

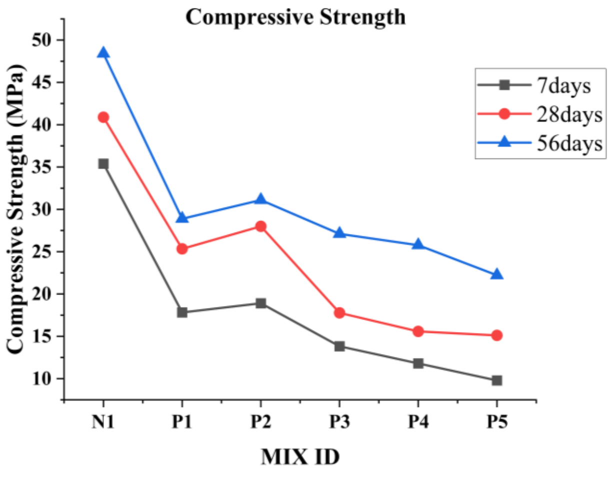

Figure 4. Comparison in compressive strength of conventional N1 and OPS concretes.

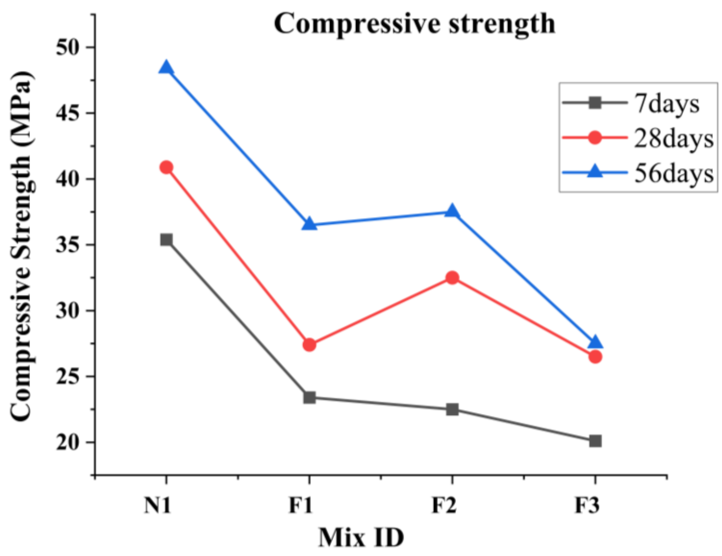

Figure 5. Comparison in compressive strength of conventional N1 and POFA concretes.

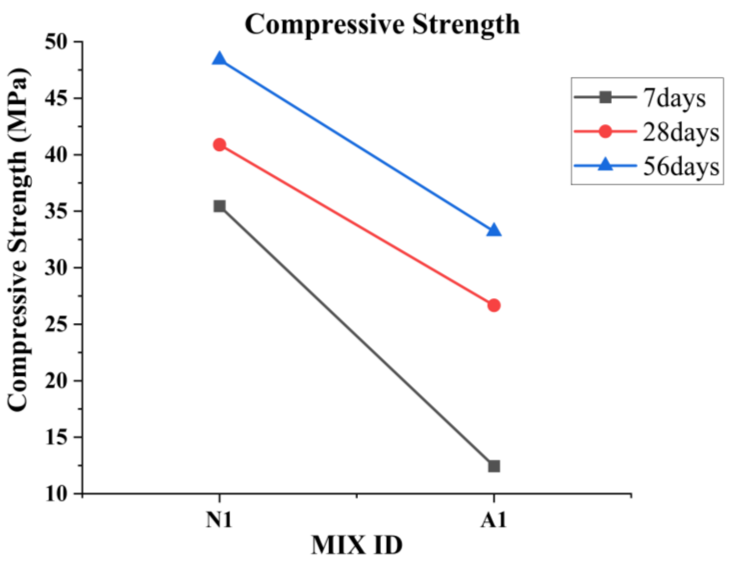

Figure 6. Comparison in compressive strength of conventional N1 and A1 concretes.

Split Tensile Strength

Split tensile strength is a critical parameter used to assess concrete resistance against cracking, primarily influenced by the concrete curing period. Extended curing durations foster improved bonding between the CSH gel and aggregate, thereby reducing the formation of microcracks on the concrete surface. The test for split tensile strength involves cylinder specimens of standard size, measuring 300mm in height and 150mm in diameter. The results of split tensile strength for OPS concrete and POFA concretes were compared to the results of conventional concrete mix N1, as depicted in Figures 7 and 8. For instance, concrete mix proportion (P1), containing a 10% replacement of POS, exhibited higher tensile strength values of 1.84 MPa, 2.26 MPa, and 2.55 MPa for curing intervals of 7, 28, and 56 days, respectively. Similarly, concrete mix proportion (F2), containing a 20% replacement of POFA, displayed higher tensile strength values of 2.4 MPa, 2.54 MPa, and 3.10 MPa for curing intervals of 7, 28, and 56 days, respectively. However, the optimum mix A1 showed lower tensile strength compared to conventional concrete mix N1, with values of 0.85 MPa, 1.41 MPa, and 2.01 MPa for curing intervals of 7, 28, and 56 days, respectively, as illustrated in Figure 9.

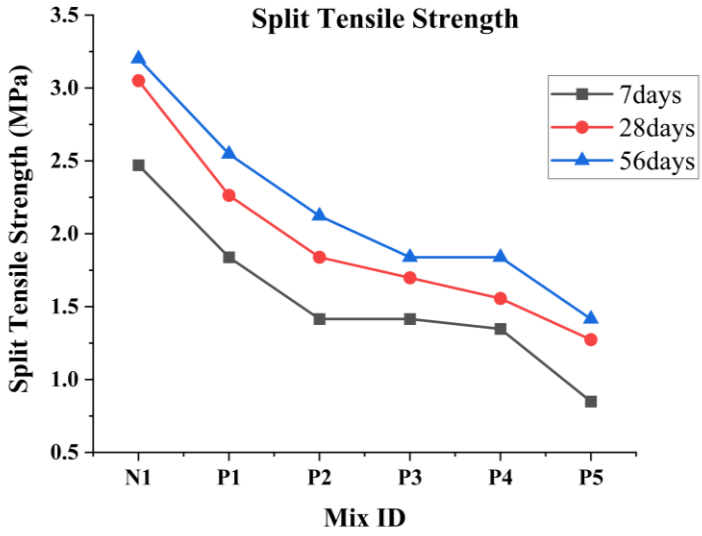

Figure 7. Comparison in split tensile strength of conventional N1 and OPS concretes.

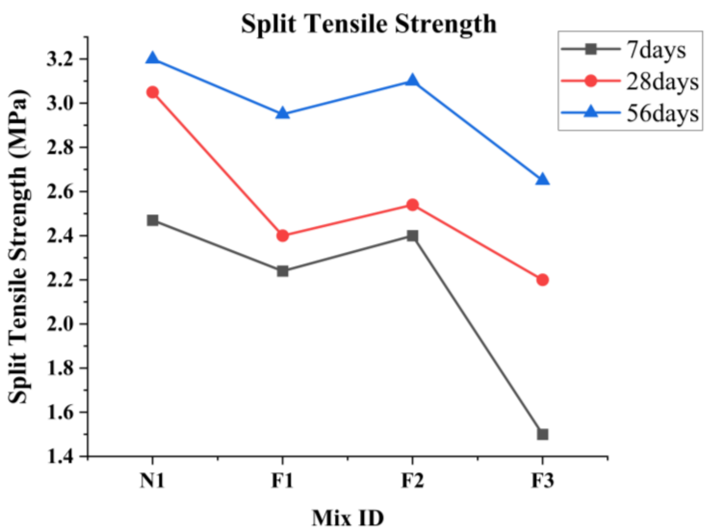

Figure 8. Comparison in split tensile strength of conventional N1 and POFA concretes.

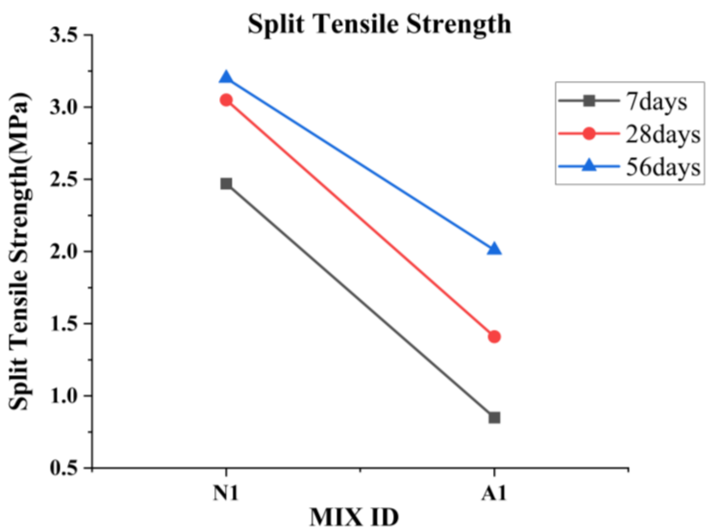

Figure 9. Comparison in split tensile strength of conventional N1 and A1 concretes.

Flexural Strength

Flexural strength is a mechanical characteristic that determines a concrete's ability to withstand bending or deformation under externally applied loads. The test for flexural strength involves subjecting a prismatic concrete sample to a bending force at a constant rate until it reaches failure. The ultimate load and corresponding deformation measured during this test are then used to evaluate the flexural strength of the concrete specimen. In this current research, the modulus of rupture or flexural strength for distinct proposed concrete mix proportions was assessed. Prismatic concrete specimens with dimensions of 500mm × 100mm × 100mm were cast for all mix proportions. The results of flexural strength for proposed conventional N1, OPS, and POFA concretes were compared, as illustrated in Figures 10, 11, and 12. For example, mix proportion (P2), containing a replacement of 20% POS, exhibited higher flexural strengths of 3 MPa, 6.5 MPa, and 11 MPa for curing intervals of 7, 28, and 56 days, respectively. Similarly, mix proportion (F2), containing a 20% replacement of POFA, achieved higher flexural strengths of 6.3 MPa, 7.85 MPa, and 8.8 MPa for curing intervals of 7, 28, and 56 days, respectively. The optimum mix A1 attained flexural strengths of 2 MPa, 6.5 MPa, and 11.5 MPa for curing intervals of 7, 28, and 56 days, respectively.

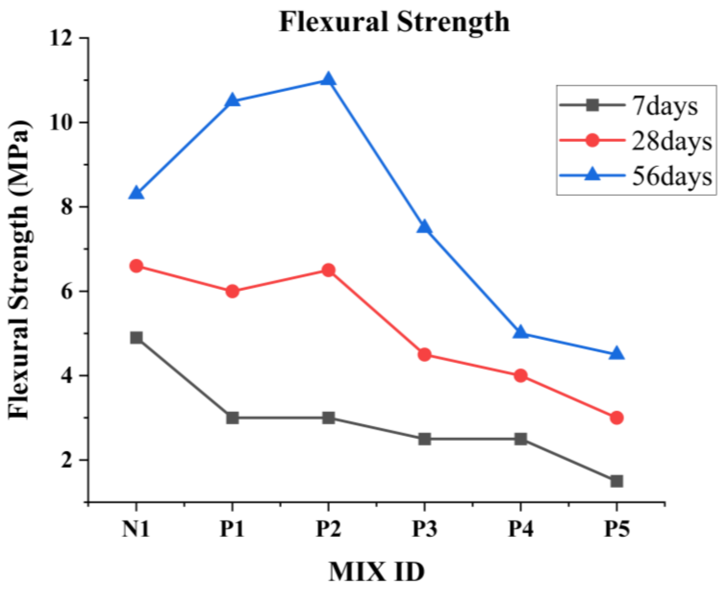

Figure 10. Comparison in Flexural strength of conventional N1 and OPS concretes

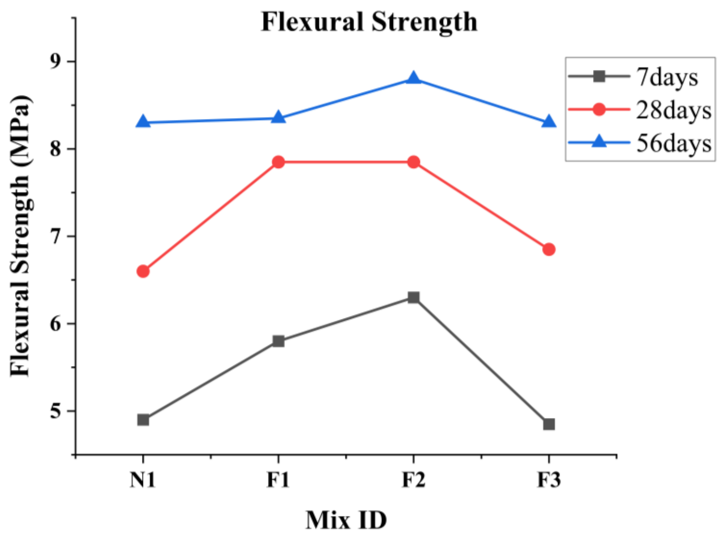

Figure 11. Comparison in Flexural strength of conventional N1 and POFA concretes.

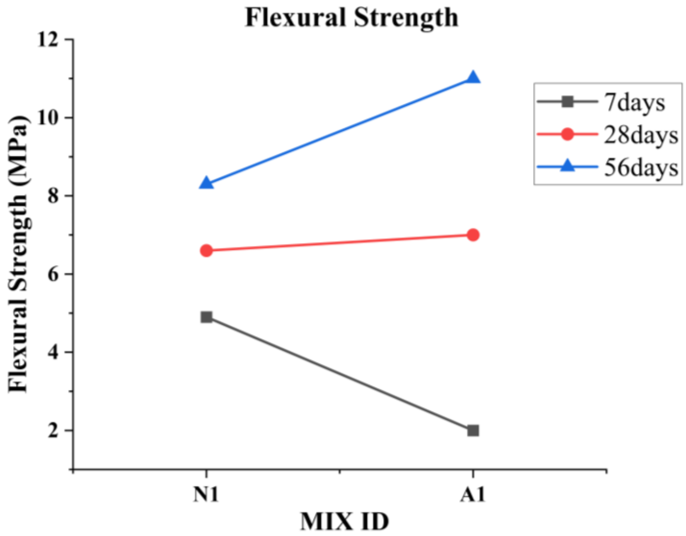

Figure 12. Comparison in Flexural strength of conventional N1 and A1 concretes.

Durability Properties

Durability studies of concrete involve various tests, including water absorption, water permeability, and three types of chemical attacks. Standard size cubes measuring 100 mm × 100 mm × 100 mm are used for all chemical attack tests. These cubes undergo a curing period of 28 days with portable water, followed by chemical water curing for an additional 28 days and 56 days.

Water Absorption

The water absorption test is pivotal in assessing the durability and lifespan of concrete structures. It's instrumental in determining concrete's suitability for various applications and ensuring the long-term integrity of structures. Initially, cube specimens undergo a 28-day curing period in a curing tank. Subsequently, the dry weight of each specimen is measured. Next, the cube specimens are soaked in water for 24 hours. Afterward, excess water is removed using a dry cloth, and the weight of each specimen is measured again. The percentage of water absorbed by the concrete can be calculated using Eq.1. The results of the water absorption capacity for concrete mix A1 are presented in Table 6.

$$\text{Water Absorption (\%)} = \left(\frac{\text{Saturated Weight} - \text{Dry Weight}}{\text{Dry Weight}}\right) \times 100 \tag{1}$$

Table 6. Results of water absorption test for A1 concrete Mix.

Mix ID	Dryweight (W1)	Saturated Weight(W2)	Water Absorption (%)
A1	7.672 7.654	7.872 7.895	2.6 3.14

Water Permeability

Concrete is renowned for its durability and exceptional resistance to compression. However, its vulnerability to water can lead to significant deterioration over time. The water permeability test is conducted to measure the depth of water infiltration into concrete specimens. This test involves curing two specimens of concrete mix A1 in potable water for 28 days, followed by breaking the concrete sample in half to ascertain the depth of water immersion, as depicted in Figure 13. Splitting is preferred for measuring depth, as it provides more accurate and reliable results compared to drilling or chiseling. The depth of water penetration is measured using a ruler or vernier caliper after the specimen has been divided. In this test, the depth of water penetration is limited to 25 mm. The findings revealed that the water penetration depth for concrete with an M30 grade was measured at 18 mm. These measured depths were compared with the established standard, which dictates that the depth should not exceed 25 mm. Since the obtained values were below this threshold, it can be concluded that the permeability test confirms the durability criteria, indicating the concrete's effective resistance to water penetration.

Figure 13. Measuring the depth of water penetration into concrete specimens at water permeability. test.

Chemical Attacks

Acid Resistance (H_2SO_4)

Concrete can undergo chemical reactions with acidic substances such as sulfuric or hydrochloric acid, particularly in industrial environments where acids are used or produced as byproducts. This interaction is especially critical as acids initiate destructive reactions upon contact with concrete. For instance, acids dissolve calcium hydroxide, a byproduct of cement hydration, which leads to the deterioration of concrete's structural integrity as water-soluble chemicals and calcium ions (Ca2+) are formed. Additionally, acids can dissolve calcium silicate hydrate (C-S-H) gel, a vital component that binds the material together, resulting in decreased cohesiveness and strength of concrete. The severity of acid attacks depends on various factors, including the type and concentration of acid, duration of exposure, porosity of the concrete, and presence of protective coatings. Utilizing acid-resistant coatings or supplementary cementitious materials (SCMs) can mitigate the impact of acid attacks. Moreover, proper design and construction techniques are essential to ensure adequate coverage of reinforcing with concrete. In the experimental setup, 100×100×100 mm cubes of OPS concrete underwent a 28-day curing phase before being submerged in a solution containing 4% H2SO4 for 28 and 56 days. Routine inspections and maintenance are crucial for early detection of degradation signs and prompt action to prevent further damage. After the curing period, the specimens exhibited a mass decrease of 1.56% and 3.48%, and their compressive strength, as depicted in Figure 14, indicated vulnerability to damage, with corners appearing very brittle. To ensure the long-term durability of concrete structures in acidic environments, it is imperative to comprehend the chemical processes involved and implement appropriate preventive measures.

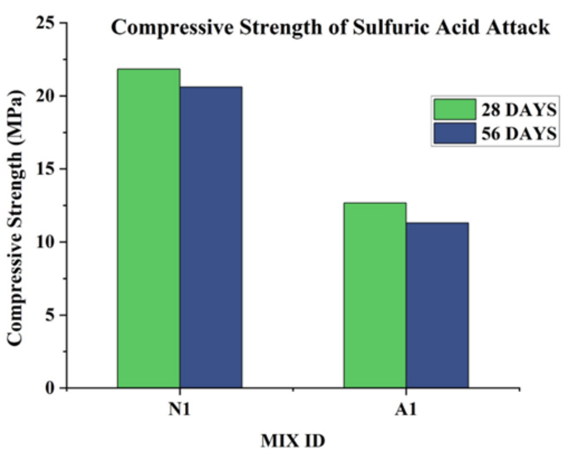

Figure 14. Comparison in Compressive strength of conventional and A1 concretes subjected to Sulfuric Acid Attack.

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Sulphate Attack ($MgSO_4$)

A study was conducted to assess the impact of sulfate on OPS concrete. Sulfate, commonly found in soil or groundwater, can interact with concrete, potentially affecting its structure. Test specimens, comprising 100×100×100mm cubes made of OPS concrete, were utilized to measure both compressive strength and changes in mass. Each set of specimens comprised three cubes, which underwent a curing period of 28 days before being immersed in a solution. The immersion duration in the solution extended to 28 days and 56 days for the purpose of curing. A solution was prepared by diluting a 5% concentration of MgSO4 in clean water to the required proportions. Following the curing process in the solution, the concrete's strength decreased by 30% to 60% compared to normal water curing. These results are depicted in Figure 15.

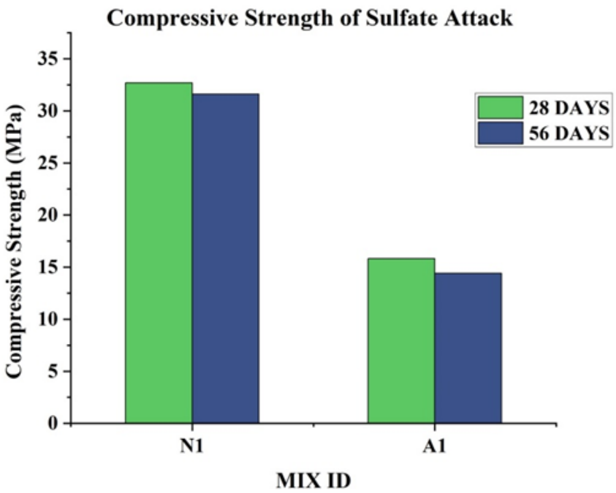

Figure 15. Comparison in Compressive strength of conventional and A1 concretes subjected to Sulphate Attack.

Chloride Attack (NaCl)

This test examined the effect of chlorine on OPS concrete, particularly relevant for marine constructions subject to chloride assault. Chloride penetration can lead to reinforcement corrosion. Specimens undergo a 28-day curing phase before being submerged in a solution containing 3.5% NaCl for 28 and 56 days. The chloride exposure gradually damages the concrete, resulting in a decrease in strength compared to curing in portable water. The strength decreases ranges from 4% to 7% after curing in the chloride solution. These findings are illustrated in Figure 16.

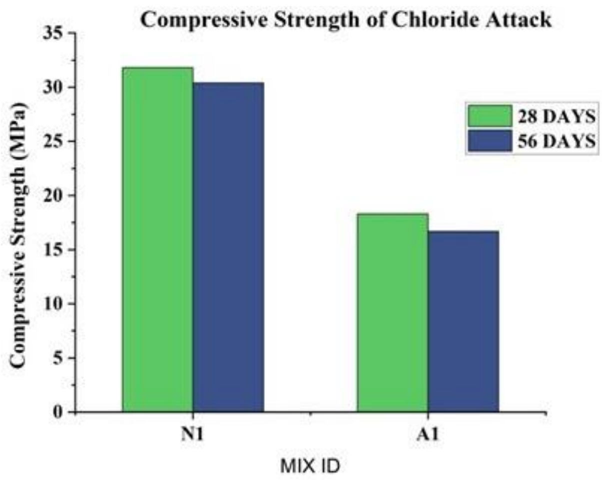

Figure 16. Comparison in Compressive strength of conventional and A1 concretes subjected to Chloride Attack.

Microstructure Analysis

Scanning Electron Microscopy

The microstructure of POFA concrete can be analyzed using scanning electron microscopy (SEM), a tool that enables investigation into the bonding mechanism between POFA particles and the cementitious matrix. SEM produces high-resolution images, as depicted in Figure 17, showcasing the distribution of POFA particles within the POFA concrete.

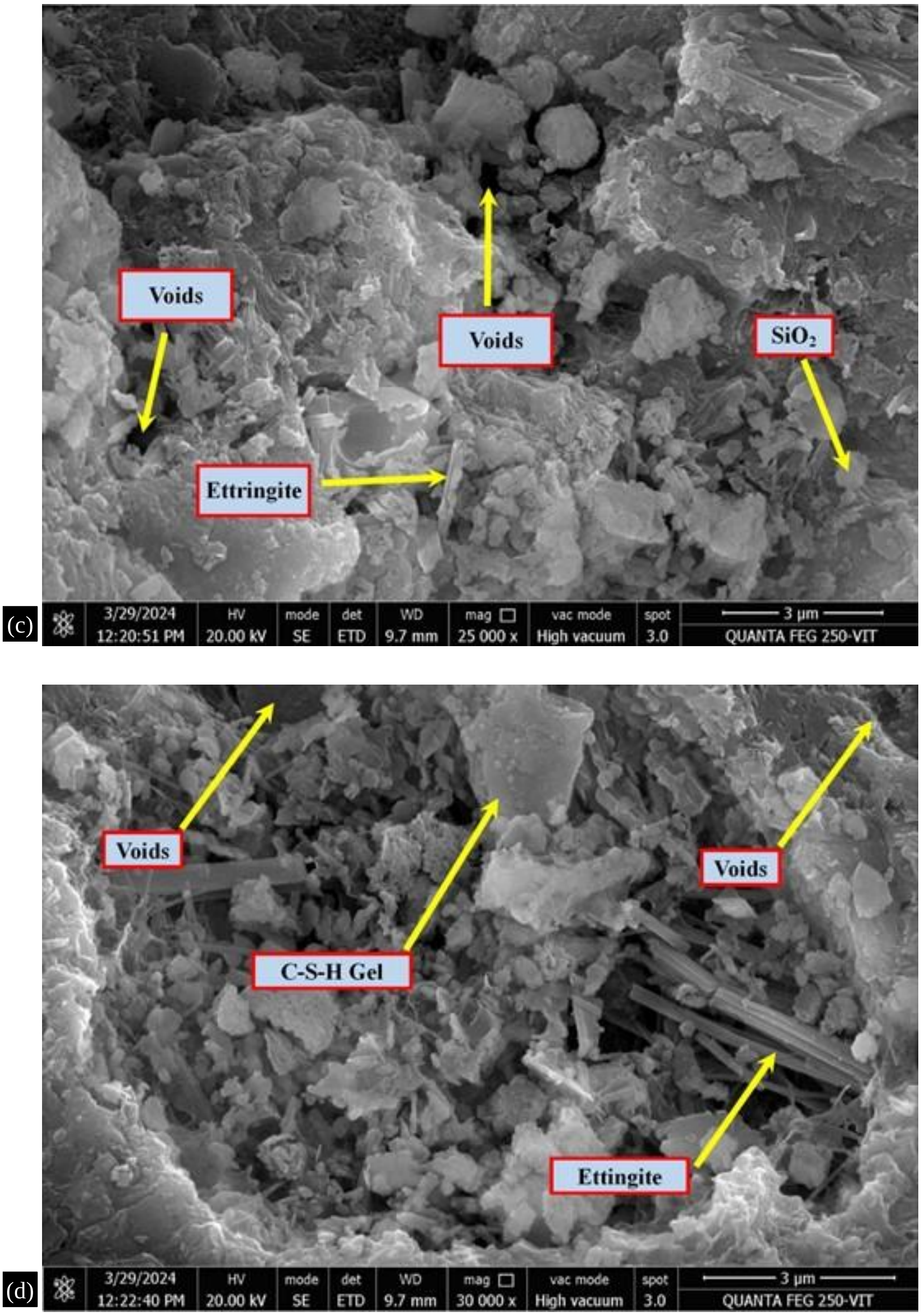

Figure 17. Scanning Electron Microscopy (SEM) images of A1 concrete.

X-ray Diffraction

X-ray diffraction (XRD) analysis is a method used to ascertain the molecular and atomic structure of crystalline materials. In this process, a beam of X-rays is directed at the sample, and its resulting diffraction pattern is examined. This pattern provides insight into the arrangement of atoms or molecules within the sample. Through X-ray diffraction analysis, the crystalline phases of minerals present in oil palm shells, such as silica and calcium carbonate, can be identified. This is demonstrated in Figure 18.

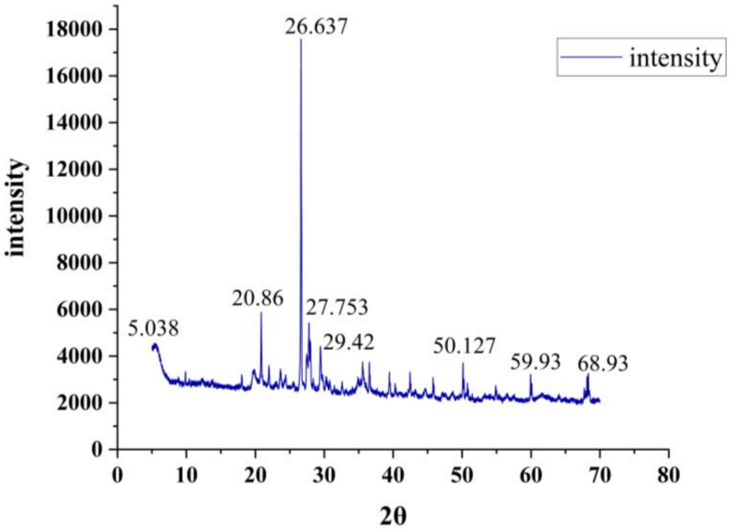

Figure 18. X-ray diffraction analysis on OPS based concrete.

Fourier Transform Infrared (FTIR)

FTIR spectroscopy is a non-destructive analytical method employed to identify functional groups within a material based on their distinctive infrared absorption spectra. In the realm of concrete, FTIR offers insights into the chemical composition and bonding characteristics of cementitious phases, supplementary materials, and additives. The FTIR spectrum of a concrete sample captures the vibrational modes of molecular bonds, facilitating the identification of hydration products like calcium silicate hydrates (C-S-H), calcium hydroxide ($Ca(OH)_2$), and ettringite, as well as organic compounds from additives such as polymers or chemical admixtures. Through analysis of FTIR spectra from various concrete samples, researchers can gauge hydration levels, detect anomalies or contaminants, and understand the reaction mechanisms within the concrete matrix. Additionally, FTIR spectroscopy can be augmented with techniques like attenuated total reflection (ATR) to examine surface properties of concrete specimens, offering further insights into surface hydration and modification treatments, as demonstrated in Figure 19.

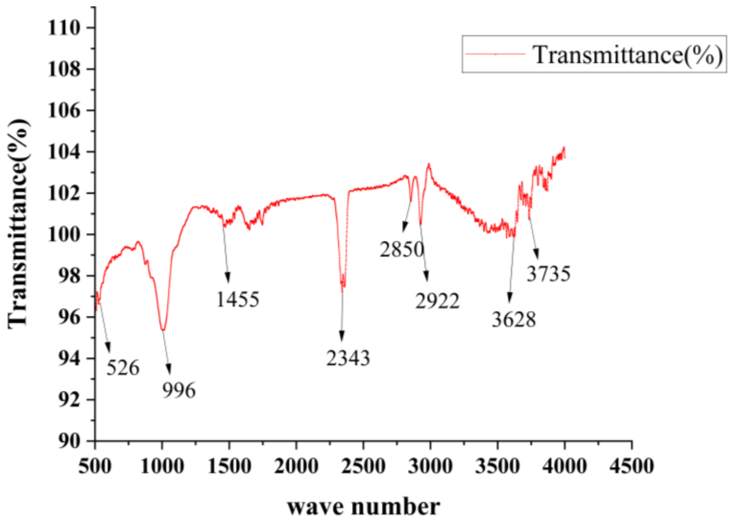

Figure 19. Fourier Transform Infrared spectroscopy on OPS based concrete.

Energy-Dispersive X-ray Spectroscopy (EDS)

Energy-Dispersive X-ray Spectroscopy (EDS) is a method utilized to examine the elemental composition of materials by detecting the characteristic X-rays emitted when the material is subjected

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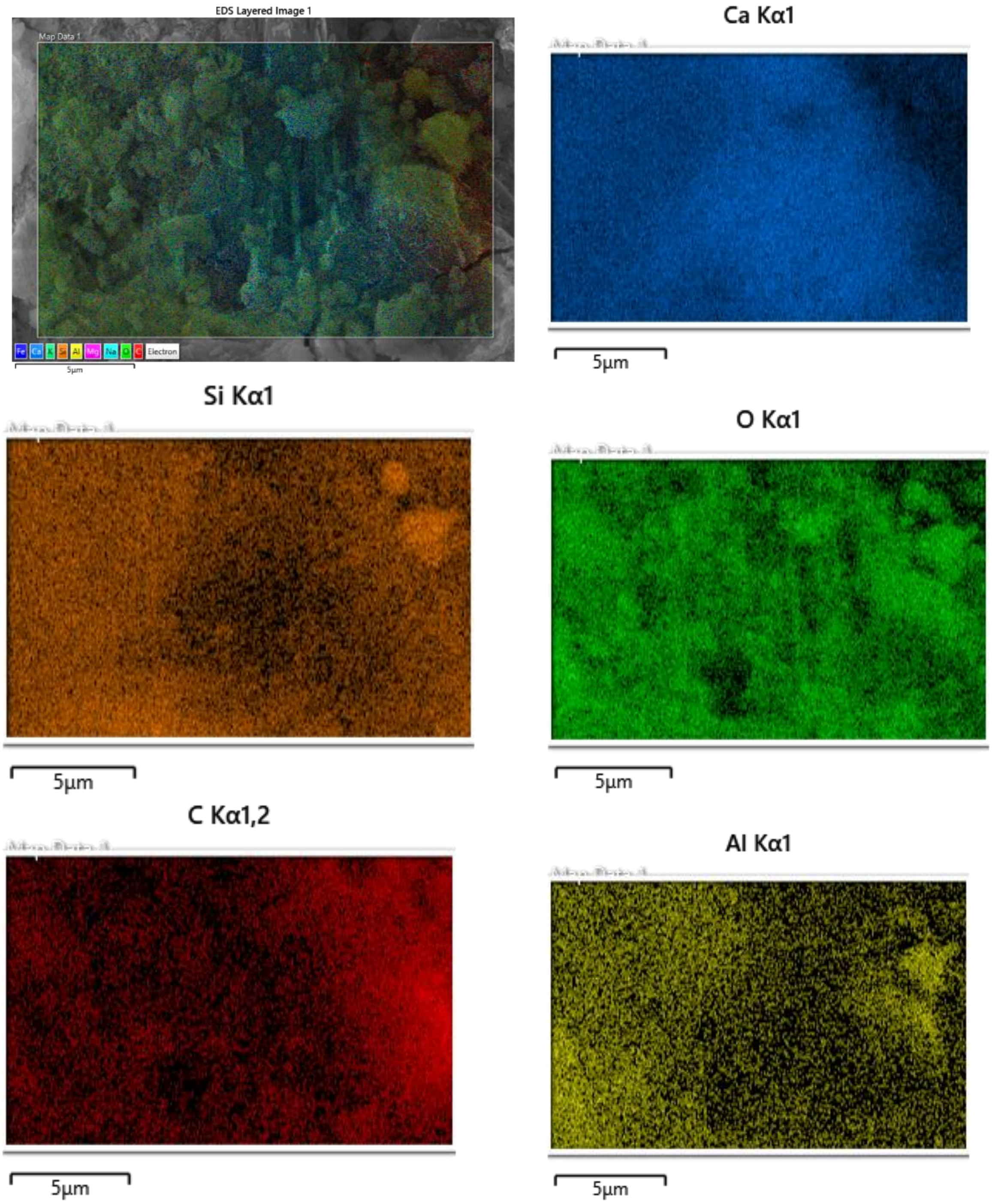
to high-energy electron bombardment. In the context of concrete, EDS offers valuable insights into the distribution and concentration of elements like calcium, silicon, aluminium, iron, and sulphur, among others. This technique allows for the determination of the elemental composition of concrete phases, aggregates, and supplementary materials, aiding in the evaluation of the uniformity of the concrete matrix and the identification of any segregation or impurities. Furthermore, when coupled with scanning electron microscopy (SEM), EDS enables the generation of spatially resolved elemental maps of concrete microstructures, offering insights into phase distribution and interfacial interactions. Through the quantitative analysis capabilities of EDS, researchers can establish correlations between elemental composition, microstructural features, and mechanical properties, thereby facilitating a comprehensive understanding of concrete materials, as depicted in Figure 20**.**



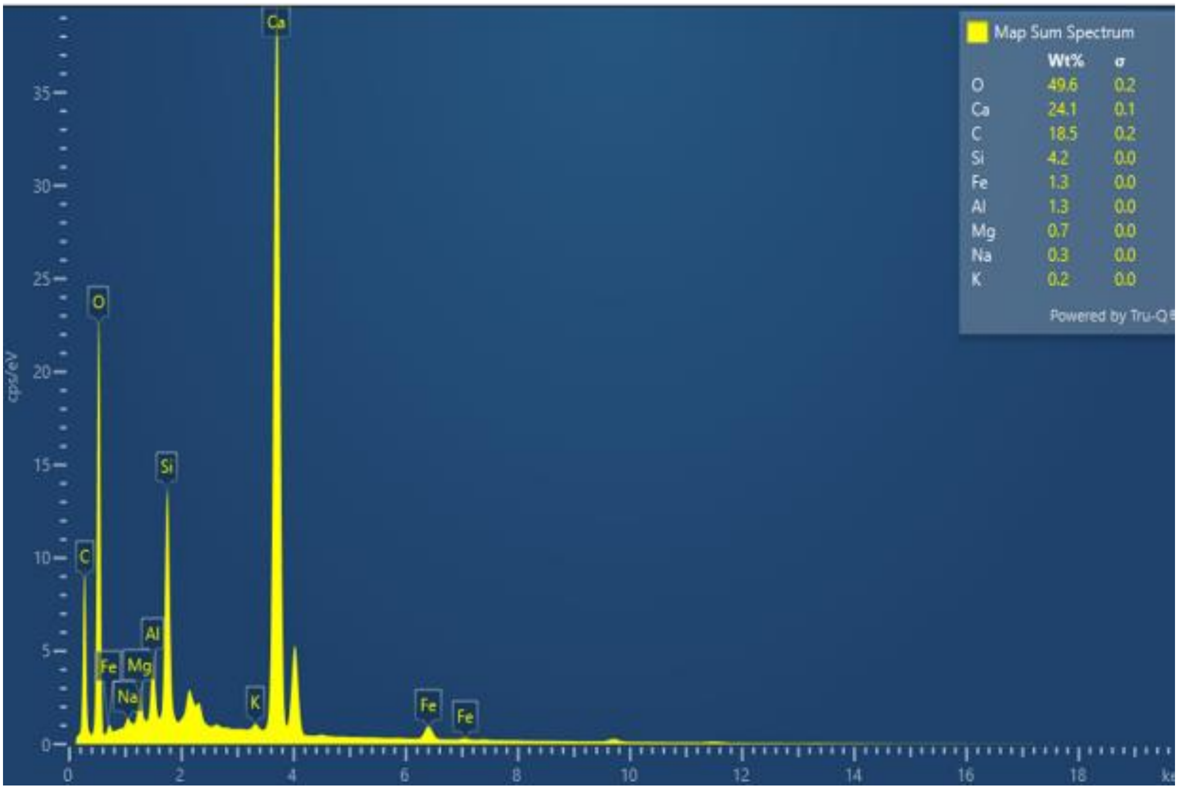


Figure 20. Energy-Dispersive X-ray Spectroscopy on OPS based concrete.

Stress Strain Behavior

Understanding the stress-strain behavior of concrete is critical in construction, offering insights into its performance under different loading scenarios, especially in earthquake-prone regions. This knowledge aids in designing efficient structures capable of withstanding seismic events. Evaluating the ductility of concrete, particularly its ability to deform without failure, relies on identifying the yielding point and plastic deformation. In seismic zones, ductility is vital for structures to absorb and dissipate energy effectively during earthquakes. The least count of the dial gauge used in this assessment is 0.01. Figures 21 and 22 depict the stress-strain behavior of N1 and A1 concretes, respectively.

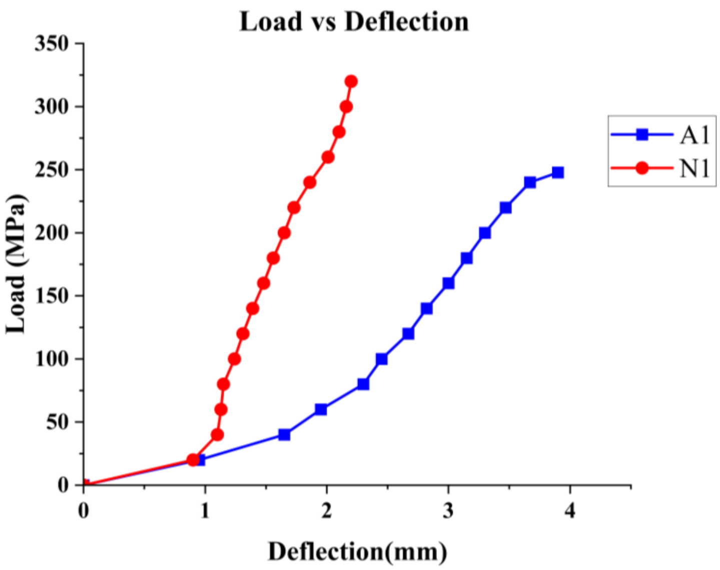


Figure 21. Comparsion of Load versus Deflection behaviour of conventional and A1 concretes.

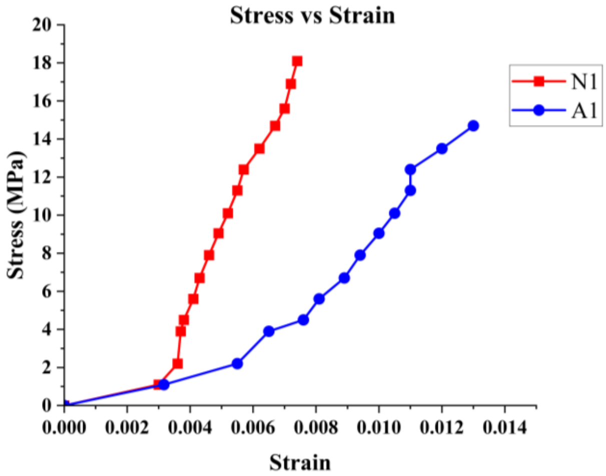


Figure 22. Comparison in Stress versus Strain behaviour of conventional and A1 concretes.

Beam Behavior

In this study, a simply supported RCC beam with a cross-section of 1500×150×150mm was utilized. Figures 23 and 24 present the specific beam details, with one support being a hinge and the other a roller. The beam was subjected to two-point loads. Both conventional concrete and A1 concrete were cast for comparative analysis. Testing was conducted using a loading frame after a 28-day curing period. The beam was marked at equal intervals along its length to facilitate the measurement of crack lengths and distances between multiple cracks. Figure 25 illustrates the comparison of load vs mid-span deflection between A1 concrete and conventional concrete. The X-direction represents mid-span deflection, while the Y-direction denotes load in KN. The curves exhibit nonlinear behavior until the final failure of the beam samples. During significant loading, the concrete layer in the tension zone of the beams demonstrated its ability to withstand load until reaching the concrete's flexural capacity at the beam's bottom. Thus, the rate of deflection expansion served as an indicator of the initial occurrence of cracking in the beams.

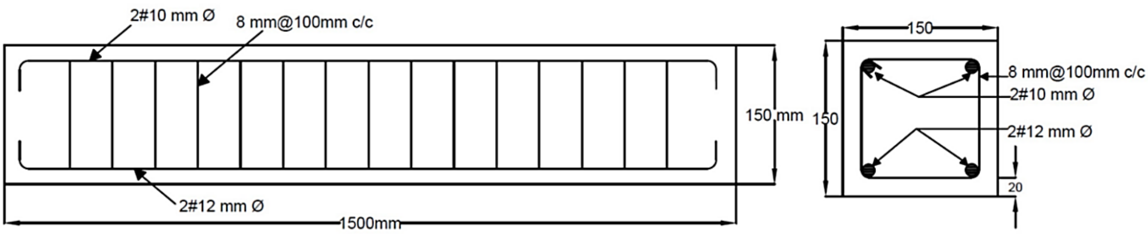


Figure 23. Reinforcement detailing of a test beam.

(a)

Figure 24. Experimental setup for test beams with different concrete mixes. (a) Conventional concrete(N1) (b) Optimum mix concrete(A1).

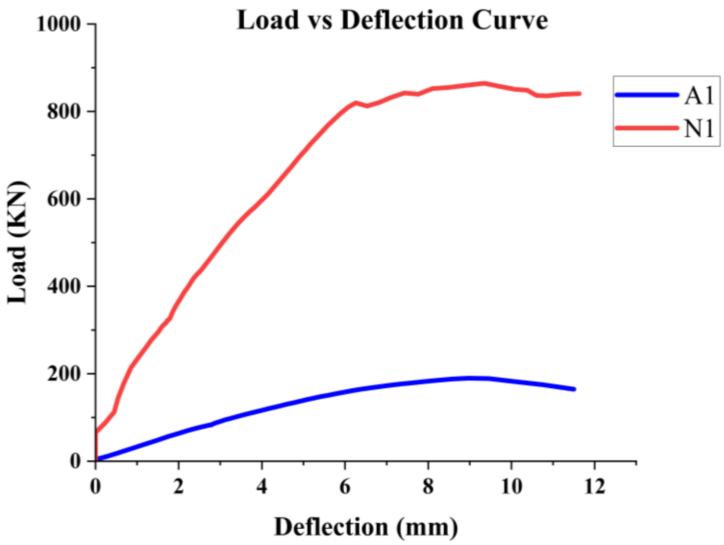


Figure 25. Comparison in Load versus Deflection behaviour of N1 and A1 concretes.

CONCLUSIONS

The research was designed to investigate the effects of partially substituting sustainable materials, such as Palm Oil Fuel Ash (POFA) in cement and Palm Oil Shells in coarse aggregates, on the characteristics of concrete. The focus was on improving both the mechanical and durability properties of the concrete. The fresh concrete properties, including workability, and mechanical properties such as compressive strength, split tensile strength, and flexural strength, were assessed during the study. Additionally, durability properties such as water permeability, water absorption, and resistance to chemical attacks were evaluated through the testing of a required number of cast specimens in the form of cubes, cylinders, and prisms. Several mix proportions were proposed and designated with distinct mix IDs such as N1, P1, P2, P3, P4, P5, F1, F2, F3, and A1. The results obtained from present experimental investigation, the following main highlights and conclusions can be obtained:

- OPS concrete exhibits a mean strength approximately 8% lower than conventional concrete.
- Replacement of 20% cement with POFA and 20% coarse aggregate with POS demonstrates suitable workability and strength.
- In OPS concrete, a maximum coarse aggregate size of 12.5mm is used to create lightweight concrete (LWC), while POS and POFA contribute to industrial lightweight concrete (ILWC).
- To address POS's high water absorption, soaking and drying in SSD conditions are employed for desired workability.

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- POFA concrete achieves target strength over long-term curing, with less than a 5% deviation from conventional concrete.
- Flexural strength of OPS concrete exceeds conventional concrete by 10-30%, attributed to the presence of more fibers in the shells.
- The compressive strength of OPS concrete is 8% lower than conventional concrete, with an optimum replacement percentage of 20%. POFA concrete's compressive strength is 5% lower than conventional concrete but achieves target strength over long-term curing.
- Several Micro-strucutral studies such as SEM analysis, XRD analysis, FTIR spectroscopy and Energy-Dispersive X-ray Spectroscopy were conducted on OPS concrete. The X-ray diffraction (XRD) analysis revealed the existence of a crystalline phase in the sustainable lightweight concrete synthesized from industrial waste derived from palm oil production. The Fourier-transform infrared (FTIR) spectroscopy indicated a reduction in carbonation bonding within the concrete mixes, which correspondingly diminishes the strength properties of the mixture.
- Whereas the SEM analysis exhibited that OPS concrete has a heterogeneous microstructure with irregular pore distribution and varied particle sizes, influencing its mechanical properties and durability. Additionally, the EDS analysis detected silicon, calcium, and aluminum as key elements, indicating the presence of typical cementitious and pozzolanic materials from palm oil industrial waste.
- The reinforced concrete beam with OPS concrete has demonstrate lower flexural strength but increased ductility and enhanced crack resistance compared to conventional concrete beams and exhibited a distinct load-deflection behaviour due to decreased stiffness.

Acknowledgment

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