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Experimental investigation on the viability of palm oil fuel ash as a sustainable additive in high performance concrete

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ABSTRACT

The usage of by-products stems from industry offers a promising avenue for promoting clean production, waste minimization, and reducing greenhouse gas emissions, thus fostering environmental sustainability. This study delves into the performance evaluation of palm oil fuel ash (POFA) in concrete, aiming to assess its impact on strength, flowability, durability, and microstructure. The findings indicate that incorporating POFA into concrete mixes, up to a 12% dosage enhances compressive, flexural, and splitting tensile strengths. However, higher POFA content leads to decreased workability. Notably, the study divulges a significant control over chloride ingress with the addition of POFA, suggesting its potential to mitigate degradation in aggressive environments. Microstructural analysis of the specimens further highlights the promising role of POFA in enhancing concrete performance under adverse conditions, affirming its viability as a sustainable alternative in construction materials.

Keywords: Palm oil fuel ash; By-products; Additive; Waste minimization; Sustainability.

1. INTRODUCTION

The construction sector poses a substantial impact on environmental sustainability due to its extensive consumption of resources and continuous release of harmful gases like CO_2 into the atmosphere. To address this challenge and foster sustainability in building construction, researchers are turning to unconventional renewable resources [1–4]. Palm oil fuel ash (POFA), a byproduct of the palm oil industry stems from burning waste materials such as shells and fibres in power plants. POFA is an unavoidable material which has been produced from the oil industry over several decades. Palm oil fuel ash can effectively replace certain quantity of cement in construction, thereby reducing the environmental impact of cement manufacturing and the issues related to its transportation [5–10].

The quantity of POFA produced is steadily increasing alongside the rise in palm oil production, imposing its utilization to avoid environmental challenges associated with waste accumulation. As society becomes increasingly aware of the environmental impacts of industrial and agricultural activities, there is a growing interest in finding sustainable solutions to utilize waste materials effectively [11–16]. In the realm of construction, this interest has sparked a movement towards incorporating industrial and agricultural waste materials into concrete production to enhance sustainability. However, this movement is not only driven by environmental concerns but also by the urgent need to address the harmful residues that pose threats to human health and the environment [17–21].

Industrial and agricultural processes generate significant amounts of waste, ranging from byproducts of manufacturing to residues from farming activities. If not managed properly, these residues can pollute water sources, contaminate soil, and release harmful gases into the atmosphere [22–26]. Numerous studies highlight the benefits of incorporating agricultural waste materials into concrete, showcasing their superior properties compared to traditional cement, which emits high levels of CO_2. POFA, being environmentally friendly and

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requiring less energy during production, offers a sustainable alternative. Moreover, the usage of POFA with cement can reduce production costs but also minimize waste accumulation in landfills, thereby improving the environment [27–33].

Despite its potential, the use of POFA in concrete production requires careful consideration, as studies have shown a decrease in compressive strength when high percentages of cement are replaced with POFA, appropriate mix design should be done to obtain and maintain the quality of the concrete with suitable grades [34–42]. However, current research aims to enhance concrete properties while leveraging POFA's ability to prevent and reduce chloride attacks, further demonstrating its promise as a sustainable solution in construction. Besides, the efforts to minimize waste generation through resource efficiency, recycling, and sustainable practices are critical for reducing the environmental footprint of industrial and agricultural activities.

2. MATERIALS AND TESTING METHODS

POFA is partially substituted for cement in concrete and different mixes were prepared. POFA has been substituted in the weight % of cement by 4 to 20% in the mortar. The samples were designated as PFA-4 to PFA-20 concerning the POFA content. The performance of POFA has been test verified.

2.1. Portland cement

Portland cement of grade 53 has been used throughout the study to examine the enactment of POFA with cement. Table 1 furnishes the composition of Portland cement.

2.1.2. Palm Oil Fly Ash

Table 2 provides a chemical composition of Palm Oil Fly Ash. SiO_2 may impart pozzalanic properties to POFA. However, the constituents of Palm Oil Fuel Ash are critically influenced by the raw material used in the industry.

Table 1: Composition of portland cement (%).

CONSTITUENT	% OF COMPOSITION
CaO	62.97
SiO_2	23.06
Al_2O_3	5.86
Fe_2O_3	3.97
MgO	2.91
Na_2O	0.21
K_2O	0.19
SO_3	0.22
LOI	0.89

Table 2: Chemical properties of POFA.

CONSTITUENT	% OF COMPOSITION
CaO	9.47
SiO_2	62.6
Al_2O_3	4.83
Fe_2O_3	3.59
K_2O	4.98
Na_2O	0.88
SO_3	0.95
MgO	4.73
LOI	7.97

2.2. Testing methods

(1) Concrete slump test was conducted for the control and POFA added fresh concrete mix by IS 1199-2004 [43].
(2) Compressive, flexural and split tensile strength after 28 days of curing of specimens were calculated as per IS 516-2018 [44].
(3) Ultrasonic pulse velocity (USPV) test was performed as per IS: 13311 (Part 1) for the control and POFA-added concrete specimens [45].
(4) XRD analysis has been performed to study the microstructure properties of POFA concrete. Mix design was carried out as per IS 10262: 2019 [46] and samples were prepared for the mix proportion of 1: 1.67: 3.14 for the water to binder ratio of 0.48.

3. RESULTS AND DISCUSSIONS

3.1. Compressive strength of PFA mixes

The capacity of the material to withstand load is mainly determined by compressive strength. The concrete specimens substituted with POFA were subjected to compressive pressure. It is evident that the addition of POFA to concrete increased its mechanical strength; however, the strength increase may be utilizing POFA up to 12% with cement. Mix PFA-12 attained a compressive strength of 24.5 MPa. Higher substitution of POFA reduces the strength after 28 days of curing, and the tested values are presented in Figure 1.

Mix PFA-12 and PFA-20 gained the highest and lowest compressive strength respectively among all the mixes, whereas had the lowest strength among PFA mixes. The strength of the mixes PFA-4, PFA-8, and PFA-12 gained 4.18%, 9.76% and 13.95% higher compressive strength than the control mix respectively. Mixes PFA-16 and PFA-20 dropped by 6.52% and 11.36%, respectively, after 28 days. Test results indicated that POFA enhances strength attainment in the mix.

3.2. Flexural strength of PFA mixes

Flexural strength is predominantly considered in determining the structural integrity of cementitious composites. The presence of internal voids and capillary channels led to a decrease in the flexural strength of the control mix, indicating a weakening in concrete quality. The bonding capabilities of POFA considerably influenced the strength, with an increase in POFA percentage correlating with an increase in flexural strength. However, replacement of POFA beyond 12% exhibited lower strength development. The flexural strength was examined and the findings are shown in Figure 2.

The flexural strength increase and decrease mirrored those observed in compressive strength variations. Besides, the cracking behaviour of POFA-admixed concrete under flexure was found almost the same as the control mix with slightly higher strength, suggesting that the relative effectiveness of pozzolanic materials

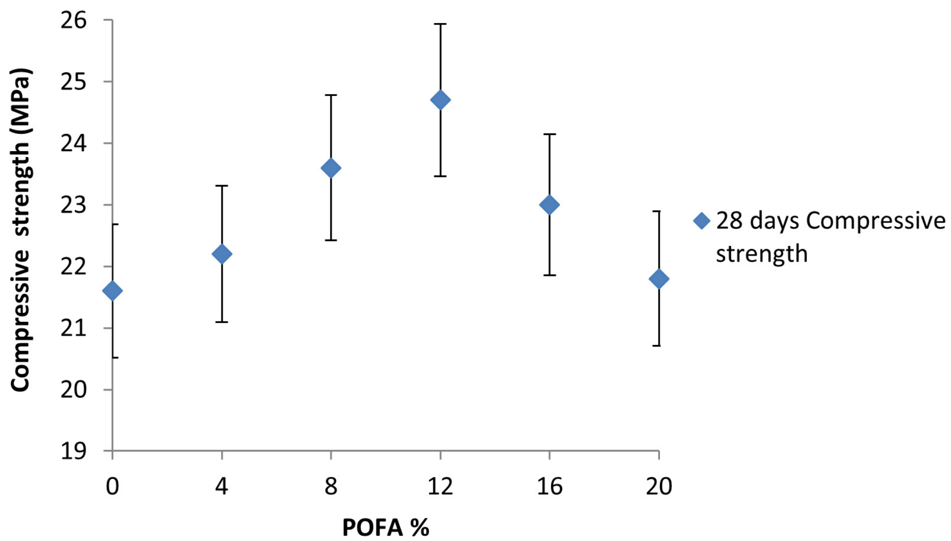


Figure 1: Compressive strength variations of POFA concrete.

primarily enhanced the flexural strength of the concrete matrix. Mixes PFA-4, PFA-8, and PFA-12 gained 2.9%, 10.4% and 16.4% higher flexural strength than control mix respectively. The provided image from the experimental findings (Figure 2) offers visual and quantitative insights into the behaviour of the tested specimens under flexure, further corroborating the observed trends in flexural strength variations.

3.3. Split tensile strength of PFA mixes

Split tensile strength reflects the strength of the bond between concrete elements. In Figure 3, the outcomes of the experimental investigation for POFA concrete are delineated. This investigation spans 28 days of curing and aims to scrutinize the enduring impact of POFA on the splitting tensile strength concrete. The regular concrete serves as a reference point for assessment, with the discrepancies in the tensile strength of POFA concrete depicted as percentages relative to the control mix.

Notably, compared with control concrete, up to 12% incorporation of POFA into the mix showed an escalation of splitting tensile strength by around 21% at the 28-day mark. However, beyond 12%, the increase in tensile strength surpassed that of mix PFA-12, Mixes PFA16 and PFA-20, surpassing that of mix PFA-12 by 13.4% and 29.6% respectively. This declining trend mirrors the observations made regarding compressive and flexural strength.

The primary reason behind the reduced tensile strength in higher replacement percentage of POFA in concrete is mainly governed by the weak bonding between cement pastes and POFA due to less content of cement, leading to concrete failure initiating at the vulnerable interface zone. Additionally, the higher water absorption nature of POFA reduces the normal quantity of water required for the hydration process.

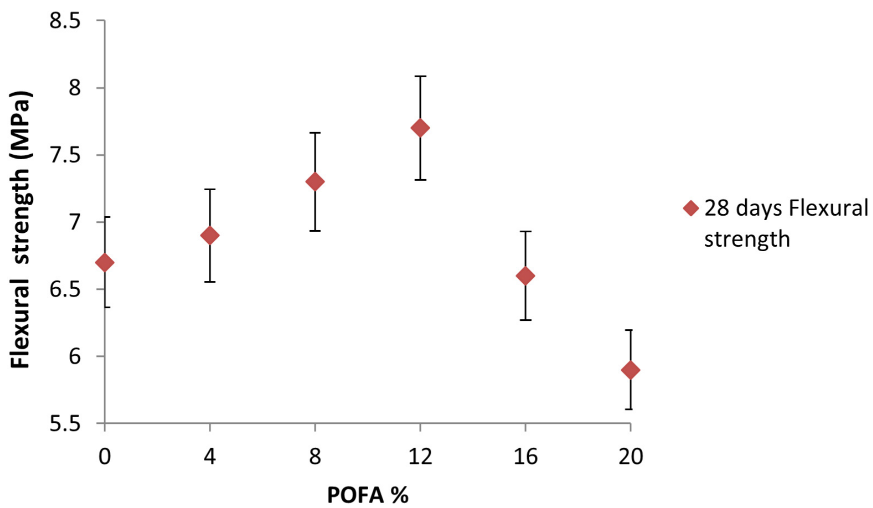


Figure 2: Flexural strength variations of POFA concrete.

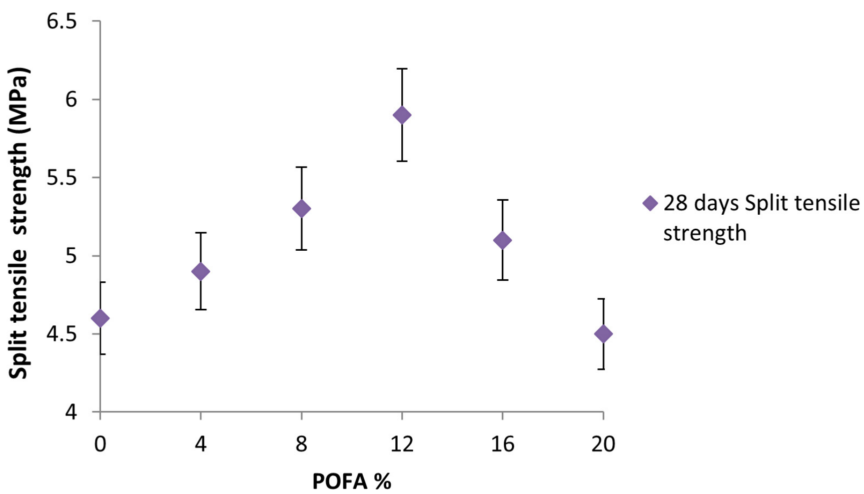


Figure 3: Split tensile strength variations of POFA concrete.

3.4. Workability of PFA mixes

The effect of using POFA on the workability of mixes has been tested. Workability is a substantial property that affects the quality of concrete and in terms of slump, the workability of PFA mixes was calculated. It was observed that an increase in POFA in the mix reduced the workability of the concrete. This is evidenced by the decreasing slump values of the PFA mixes. For instance, when 4%, 8%, 12%, 16% and 20% of cement is replaced with POFA, compared with the control mix the slump values of PFA mixes decreased by 2.15%, 5.38%, 9.68%, 13.98% and 18.28% respectively. Figure 4 illustrates the slump variations of CC and PFA mixes.

The decrease in workability with higher POFA replacement percentages can be attributed to several factors related to the physical characteristics of POFA. Firstly, POFA particles are finer in size. Finer particles have a larger surface area, which necessitates a larger amount of water to coat their surfaces. This reduces the overall W/C ratio in the mix, leading to lower workability. Besides, POFA particles may have higher porosity which allows them to absorb more water. This absorption further contributes to the reduction in the available water for lubricating the concrete mixture, resulting in decreased workability.

3.5. Ultrasonic Pulse Velocity (UPV) of PFA mixes

The impact of replacing cement with POFA on the ultrasonic pulse velocity of concrete specimens and the influence of the curing period have been test verified. If the replacement percentage of cement with POFA increases, there is a corresponding decrease in the UPV of the concrete specimens. The percentages given illustrate the extent of this decrease compared to the control mix. Figure 5 elucidates the UPV values of control and PFA mixes for various curing periods.

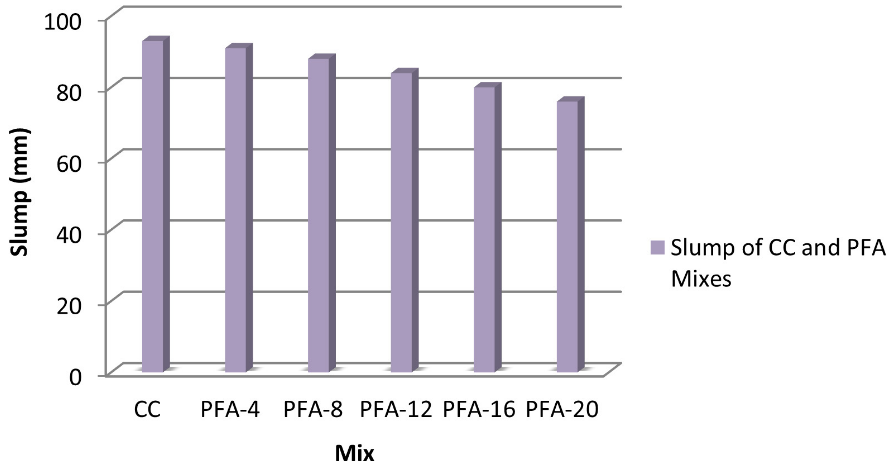


Figure 4: Slump variations of CC and PFA mixes.

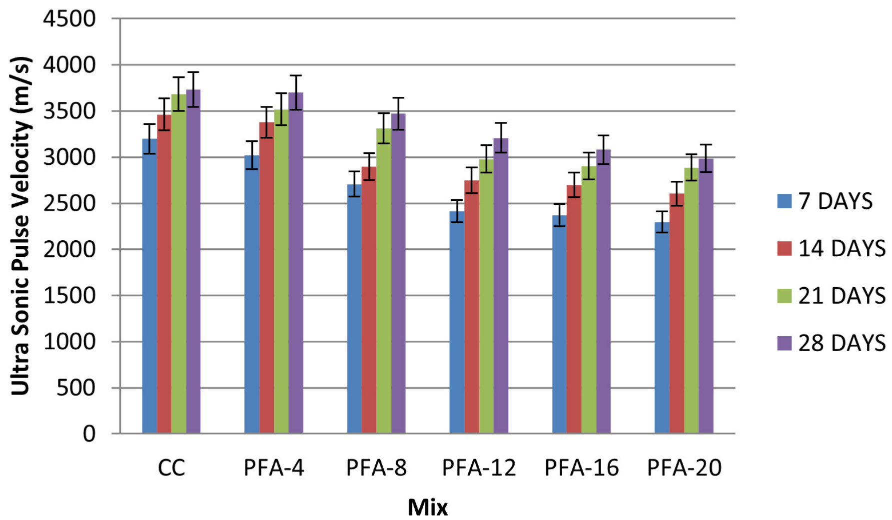


Figure 5: Ultrasonic pulse velocity values of control and PFA mixes.

It was observed that as the curing period increases, the ultrasonic pulse velocity of the specimens also increases. This indicates that over time, the concrete gains strength and density, leading to higher velocities. Irrespective of curing age and POFA content, PFA mixes exhibited higher ultrasonic pulse velocities than the control mix due to the pore-filling effect of POFA the mix, which reduces voids in the concrete specimens.

The decrease in ultrasonic pulse velocity with an increase in POFA content in concrete may be due to the lower density and higher fineness of POFA present in cement. POFA incorporation results in less porous concrete compared to control concrete due to their denser nature which results in higher ultrasonic pulse velocity values. This indirectly indicates that the durability of POFA-added concrete is more than control concrete.

3.6. Probability of corrosion of steel in PFA mix

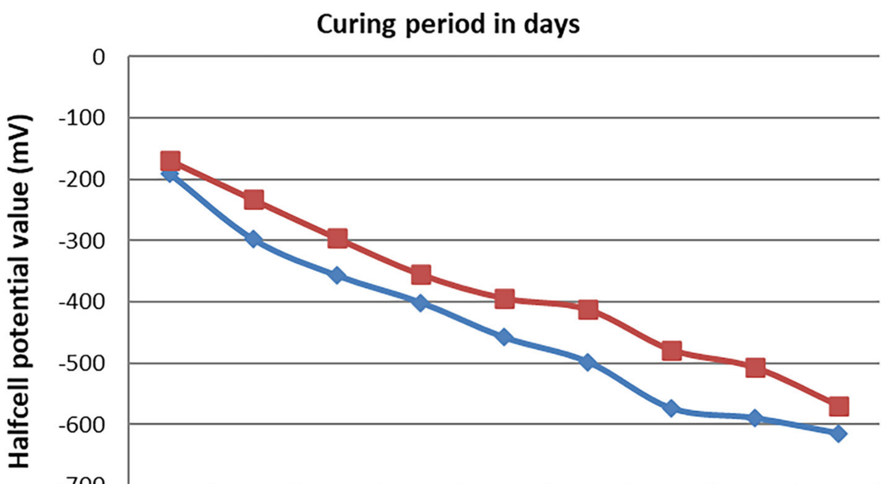
From Figure 6 the Probability of corrosion of steel entrenched in the PFA-12 mix has been assessed in terms of half-cell potential values. PFA-12 mix is found optimal mix, hence it is considered for corrosion study. This method is commonly used in the field of corrosion to evaluate the possibility of corrosion occurring in reinforced concrete structures. The test results provide an indication of the electrochemical activity at the surface of the reinforcement steel within the concrete. A more negative half-cell potential specifies a higher probability of corrosion, while a less negative value suggests a lower probability.

In this context, the passage notes that the half-cell potential values measured for the PFA-12 mix were lower than CC mix. This implies that the probability of corrosion over time in steel embedded in the POFA-12 mix is lesser than in the control concrete. The nonhomogeneous formation of hydrated products in the mix of PFA-12 contributed to corrosion reduction of steel. POFA reacts with $Ca(OH)_2$ in the presence of water to form C–S–H and C–A–H. These hydration products contribute to the densification of microstructure and lessen its overall porosity. Lower porosity restricts the ingress of aggressive agents such as moisture, oxygen, and chloride ions, which are primary contributors to the initiation and propagation of corrosion in reinforced concrete structures. By minimizing the availability of these corrosive agents, the risk of corrosion of embedded steel is significantly reduced.

3.7. X-ray diffraction (XRD) of Control and PFA concrete

The X-ray diffraction (XRD) patterns are illustrated in Figures 7 and 8. Figures show valuable insights into the crystalline composition of OPC and POFA concrete. XRD analysis was carried out for control and PFA-12 mixes. Quartz emerges as the predominant mineral exhibiting a crystalline structure, indicating its significant presence in both materials.

Notably, the XRD analysis of POFA reveals prominent quartz intensity, registering approximately 3500 counts. Additionally, the presence of opal in POFA is identified, stemming from the calcination process of palm oil fibres and shells.



	0	15	30	45	60	75	90	105	120
CC	-191	-298	-357	-401	-458	-498	-574	-590	-615
PFA-12	-169	-233	-296	-355	-394	-412	-478	-507	-569

Figure 6: Probability of corrosion of steel in PFA mix.

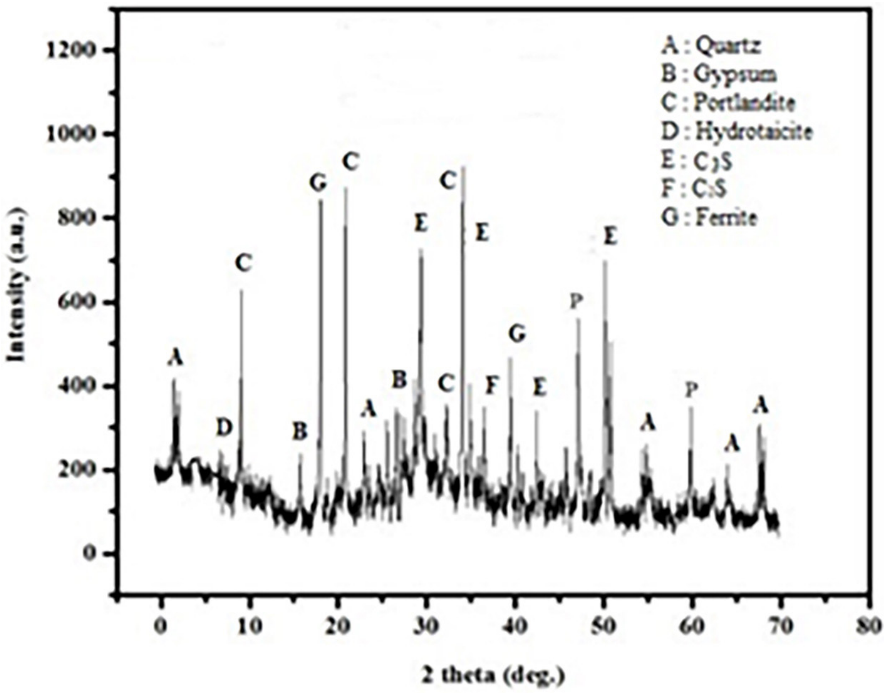


Figure 7: XRD of control concrete.

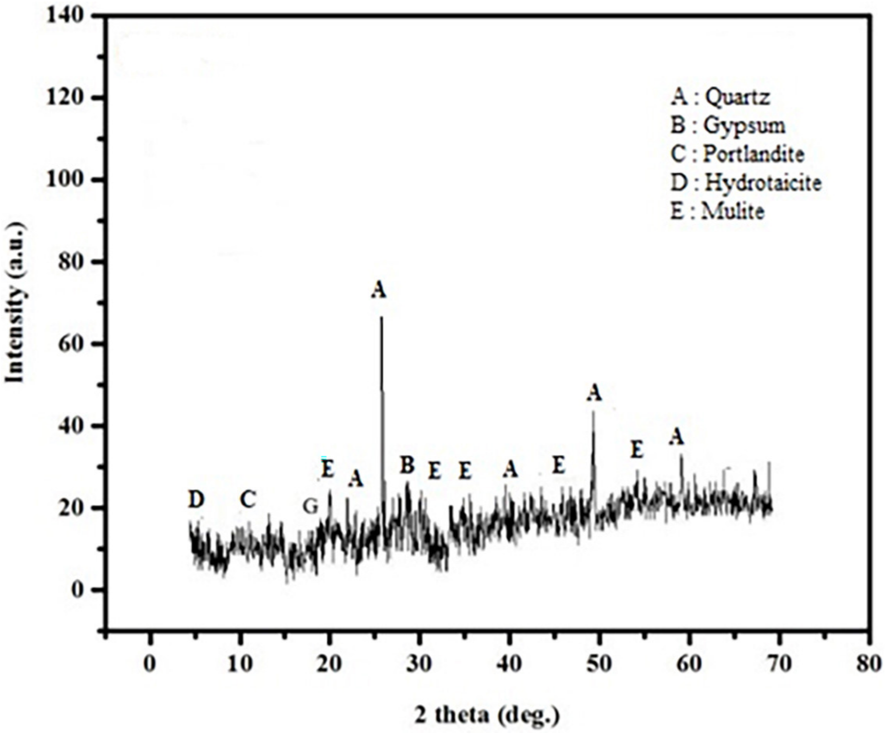


Figure 8: XRD of POFA added concrete.

Both Figure 7 and 8, elucidate distinct diffraction peaks ranging from 16 to 32° . This peak signifies crystalline silica and alumina compounds, respectively, indicating the influence of POFA on the crystalline composition of the concrete. Moreover, the presence of crystalline quartz and mullite phases is noted, further emphasizing the alterations induced by POFA incorporation. The XRD analysis indicates that the incorporation of POFA develops a stable crystalline structure in concrete.

The incorporation of POFA into OPC is imperative to address the low SiO_2 content inherent in OPC. Through the pozzolanic reaction, C–S–H is formed by the reaction of SiO_2 and Al_2O_3 with $Ca(OH)_2$ in the mix. $Ca(OH)_2$ serves as a pivotal pointer in pozzolanic reactions. An increase in fineness content leads to a decrease in $Ca(OH)_2$ content, thereby enhancing the durability of concrete [47–53].

4. CONCLUSIONS

The significant results obtained from the experimental investigations of this study can be summarized as follows:

- Including POFA in concrete mixes led to decreased workability, evident in lower slump values compared to the control mix.
- Mix PFA-12 emerged as the optimal mix, exhibiting a compressive strength increase of 13.95% compared to the control mix. However, higher POFA replacement adversely affected the strength at 28 days.
- Mix PFA-12 confirmed notable improvements in flexural and split tensile strengths, showing increases of 16.4% and 21% respectively over the control mix at 28 days.
- POFA enhanced the resistance of concrete mixes against chloride attacks, limiting the ingress of damaging particles into the concrete matrix, especially in chloride solutions.
- Examination of concrete specimens highlighted changes in hydration product nature, with POFA-incorporated specimens exhibiting a crystalline structure. This structure exhibited superior resistance to chemical attacks, resulting in enhanced strength compared to OPC mixes.
- The utilization of POFA shows possibilities in maintaining the integrity of concrete matrices in aggressive environments. Additionally, it contributes to waste material conservation, aligning with sustainability goals.

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