Cement Substitution with Palm Oil Fuel Ash (POFA) on the Compressive Strength of Concrete

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Abstract

Concrete uses cement as its main component; however, cement production generates high CO_2 emissions and depletes limestone reserves. Palm Oil Fuel Ash (POFA), a palm oil waste rich in silica, can serve as a partial alternative to cement. POFA primarily contains silicon dioxide (SiO_2) at 89.91%. Palm shell ash is a biomass material with significant silica (SiO_2) content that has potential for utilization. This study aims to investigate the effect of palm oil fuel ash substitution on the compressive strength of concrete. An experimental method was used in this research. The test specimens were cylindrical in shape (10 x 20 cm), with a target strength of fc' 30 MPa. The variations of palm oil fuel ash added were 5%, 10%, 15%, 20%, and 25% by weight of cement. The test results showed that the compressive strength increased up to the 10% variation, reaching 31.916 MPa at 28 days of age. At 15%, 20%, and 25% variations, the compressive strength decreased to 30.647 MPa, 29.459 MPa, and 28.975 MPa, respectively. The highest compressive strength was obtained at 10% POFA substitution, with an increase of 5.81%. Further research is needed with smaller increment variations above 10% POFA substitution in concrete.

Keywords: Substitution, palm oil fuel ash, cement, concrete compressive strength

1. INTRODUCTION

Concrete is the primary material in the construction industry, consisting of a mixture of cement, fine aggregate, coarse aggregate, water, and other additives. However, cement production as the main component of concrete contributes significantly to CO_2 emissions due to the calcination process, accounting for 6–8% of total anthropogenic CO_2 emissions (Muttaqien, 2023). In addition, the exploitation of limestone as a non-renewable raw material for cement production causes environmental problems and damages the limestone ecosystem (Sulasmi et al., 2022). To address this issue, alternative materials with pozzolanic properties and high silica content are required, one of which is Palm Oil Fuel Ash (POFA). POFA is derived from palm oil solid waste such as fibers, shells, and empty fruit bunches, and has the potential to reduce cement consumption while also minimizing the accumulation of palm oil industry waste (Ting et al., 2020).

The use of POFA as a cement substitute can influence the compressive strength of concrete, as it functions as a filler and generates additional C–S–H (Hasan, 2023). POFA can also reduce the heat of hydration, improve the durability of concrete, and contains a high amount of silicon dioxide (SiO_2) of about 89.91% (Dandi et al., 2022). Previous studies have shown that the addition of POFA in certain variations can increase the compressive strength of concrete, although it has not fully reached the target strength. Therefore, this research was conducted to analyze the effect of cement substitution with POFA on the compressive strength of concrete and to determine the optimal POFA mix proportion to produce high-quality and environmentally friendly concrete.

2. METHOD

The method used in this study is the experimental method. The purpose of this experiment is to determine the effect of POFA substitution on the compressive strength of concrete. The test specimens used in this experiment are cylindrical in shape, measuring 10 x 20 cm, with a target compressive strength of f'c = 30 MPa.

2.1. Research Sample

This study used 54 samples for compressive strength testing. The samples were made by substituting POFA for the weight of cement, using the following variation levels: 0%, 5%, 10%, 15%, 20%, and 25%.

Table 1: Number of Samples for Compressive Strength Test

Sample Name	Concrete Age (Days)			Number of Samples
	7	14	28	
BSPOFA 0%	3	3	3	9
BSPOFA 5%	3	3	3	9
BSPOFA 10%	3	3	3	9
BSPOFA 15%	3	3	3	9
BSPOFA 20%	3	3	3	9
BSPOFA 25%	3	3	3	9
Amount	18	18	18	54

2.2 Material

This study used the main materials commonly used in concrete production, namely cement, fine aggregate, coarse aggregate, water, and POFA as a substitute material. The cement used was Type I Portland cement of the Tiga Roda brand, which meets the specifications for normal concrete. The fine aggregate used was sand sourced from the Galunggung area, known for its good quality, while the coarse aggregate was crushed stone with a maximum size of 20 mm.

The Palm Oil Fuel Ash (POFA) used in this study was obtained from PTPN VIII (Persero), Kertajaya Palm Oil Mill, and was sieved using a No. 200 sieve. The POFA has a specific gravity of 2.13. This value meets the specific gravity criteria for industrial pozzolanic materials such as fly ash, silica fume, and rice husk ash, which typically range between 2.0 and 2.4 (Nugraha & Antoni, 2007).

Fig. 1. POFA

2.3 Design of Concrete Mix f'c 30 MPa

The stages of this research begin with the quality inspection of the materials used, such as cement, fine aggregate, coarse aggregate, and granite powder. The inspection is carried out to ensure that all materials meet the technical requirements in accordance with SNI standards.

Table 2: Final Composition for Design of 30 Mpa Normal Concrete

FINAL COMPOSITION FOR CONCRETE PLANNING /M3

No	Information	Amount	Unit
1	Cement	554,054	kg/m3
2	Water	205,000	
3	Fine Aggregate	600,650	
4	Coarse Aggregate	834,942	

After that, the concrete mix design was carried out using the SNI 7656:2012 method to obtain a composition that meets the target strength of f'c = 30 MPa. Then, the concrete was mixed and poured into cylindrical molds measuring 10 cm × 20 cm. After 24 hours, the specimens were removed from the molds and immersed in water for curing until they reached the designated testing age.

3. Results and Discussion

3.1 Research Result Data

3.1.1 Slump test

The Slump Test is conducted to measure the consistency or workability of fresh concrete, specifically to determine whether it is easy to handle during casting.

Table 3. Summary of Slump Test Results

Code	Slump Value (mm)	Standard SNI 7656:2012 (mm)	Information
BSPOFA 0%	70	25-100	Fulfil
BSPOFA 5%	55		Fulfil
BSPOFA 10%	45		Fulfil
BSPOFA 15%	25		Fulfil
BSPOFA 20%	15		Does not meet the
BSPOFA 25%	10		Does not meet the

3.1.2 Specific Gravity Test Results

The concrete density test is carried out by comparing the mass of the specimen to its volume.

Table 4. Concrete Specific Gravity Results

Persentase POFA	Average Specific Gravity of Concrete (kg/m3)			
	7 Days	14 Days	28 Days	Average
0%	2264.67	2289.28	2248.97	2267.64
5%	2254.27	2241.96	2304.78	2267.00
10%	2266.15	2214.38	2309.66	2263.40
15%	2247.48	2264.03	2257.88	2256.46
20%	2250.66	2244.93	2263.40	2253.00
25%	2241.33	2264.03	2249.81	2251.72

3.1.3 Concrete Compressive Strength Test Results

The compressive strength test of concrete specimens was conducted at the ages of 7, 14, and 28 days.

Table 5. Results of Concrete Compressive Strength Test at 7 Days of Age

Code	Test Object Weight (Kg)	Cross-sectional area (mm)	Burden (kN)	compressive strength 7 days (MPa)	Average Compressive Strength (Mpa)
BSPOFA 0%	3.625	7853.982	160.8	20.474	21.772
	3.336	7853.982	170.9	21.760	
	3.711	7853.982	181.3	23.084	
BSPOFA 5%	3.558	7853.982	181.3	23.084	22.384
	3.551	7853.982	175.2	22.307	
	3.514	7853.982	170.9	21.760	
BSPOFA 10%	3.595	7853.982	202.2	25.745	23.712
	3.542	7853.982	181.3	23.084	
	3.542	7853.982	175.2	22.307	
BSPOFA 15%	3.535	7853.982	175.2	22.307	22.507
	3.521	7853.982	190.4	24.242	
	3.535	7853.982	164.7	20.970	
BSPOFA 20%	3.508	7853.982	141.4	18.004	21.573
	3.59	7853.982	202.2	25.745	
	3.508	7853.982	164.7	20.970	
BSPOFA 25%	3.542	7853.982	155.5	19.799	21.165
	3.51	7853.982	172.2	21.925	
	3.51	7853.982	171	21.772	

Table 6. Results of Concrete Compressive Strength Test at 14 Days of Age

Code	Test Object Weight (Kg)	Cross-sectional area (mm)	Burden (kN)	compressive strength 7 days (MPa)	Average Compressive Strength (Mpa)
BSPOFA 0%	3.533	7853.982	175.2	22.307	23.364
	3.559	7853.982	184.9	23.542	
	3.696	7853.982	190.4	24.242	
BSPOFA 5%	3.532	7853.982	190.4	24.242	23.623
	3.574	7853.982	184.9	23.542	
	3.459	7853.982	181.3	23.084	
BSPOFA 10%	3.474	7853.982	212.8	27.095	25.185
	3.474	7853.982	195.7	24.917	
	3.487	7853.982	184.9	23.542	
BSPOFA 15%	3.598	7853.982	184.9	23.542	23.924
	3.598	7853.982	207.9	26.471	
	3.473	7853.982	170.9	21.760	
BSPOFA 20%	3.569	7853.982	175.2	22.307	23.084
	3.53	7853.982	207.9	26.471	
	3.48	7853.982	160.8	20.474	
BSPOFA 25%	3.537	7853.982	201.9	25.707	22.655
	3.537	7853.982	169.3	21.556	
	3.595	7853.982	162.6	20.703	

Table 7. Results of Concrete Compressive Strength Test at 28 Days of Age

Code	Test Object Weight (Kg)	Cross-sectional area (mm)	Burden (kN)	compressive strength 7 days (MPa)	Average Compressive Strength (Mpa)
BSPOFA 0%	3.545	7853.982	250.0	31.831	30.163
	3.528	7853.982	216.6	27.578	
	3.525	7853.982	244.1	31.080	
BSPOFA 5%	3.669	7853.982	240.6	30.634	30.537
	3.618	7853.982	244.0	31.067	
	3.574	7853.982	234.9	29.908	
BSPOFA 10%	3.688	7853.982	227.3	28.941	31.916
	3.592	7853.982	284.1	36.173	
	3.604	7853.982	240.6	30.634	
BSPOFA 15%	3.558	7853.982	244.1	31.080	30.647
	3.558	7853.982	222.9	28.381	
	3.524	7853.982	255.1	32.480	
BSPOFA 20%	3.486	7853.982	250.2	31.856	29.459
	3.625	7853.982	216.6	27.578	
	3.555	7853.982	227.3	28.941	
BSPOFA 25%	3.518	7853.982	212.8	27.095	28.975
	3.566	7853.982	219.7	27.973	
	3.518	7853.982	250.2	31.856	

3.2 Discussion Of Research Results

3.2.1 Slump Test

Table 5. Results of Concrete Compressive Strength Test at 7 Days of AgeBased on the slump test data in Table 3, the slump values can be illustrated in a graph, as shown in Figure 2.

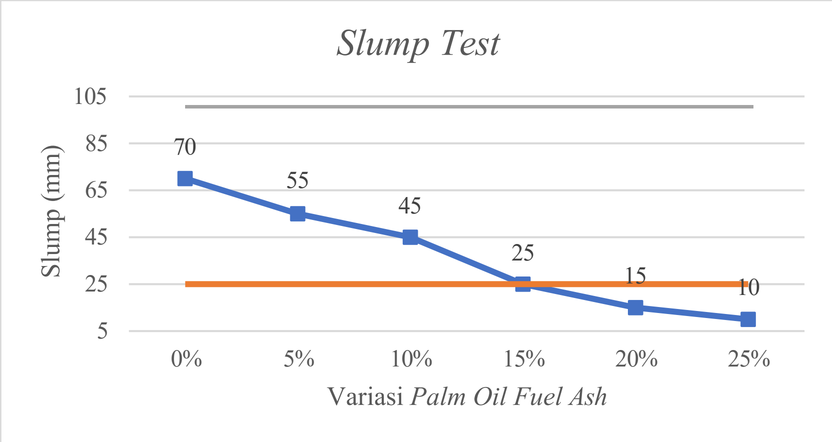

Fig 2. Slump Test Results

Figure 2 shows a decrease in concrete slump values as the percentage of POFA substitution increases, where the slump value reaches 70 mm at 0% variation and gradually decreases to 10 mm at 25% substitution.

3.2.2 Concrete Specific Gravity Test Results

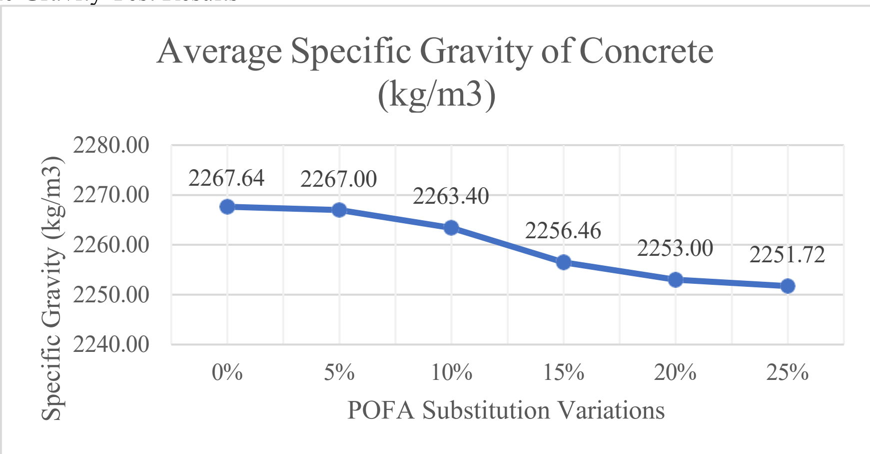

Fig 3. Average Specific Gravity of Concrete

Based on the results of the concrete density tests for each POFA variation, it can be concluded that the average density of concrete at 7, 14, and 28 days decreases as the amount of POFA added to the mix increases. This is due to the partial replacement of cement with POFA, where the specific gravity of cement is higher (3.15 g/cm³) compared to the lower specific gravity of POFA (2.13 g/cm³). As a result, concrete with POFA substitution is lighter than the control concrete.

3.2.3 Concrete Compressive Strength Test Results

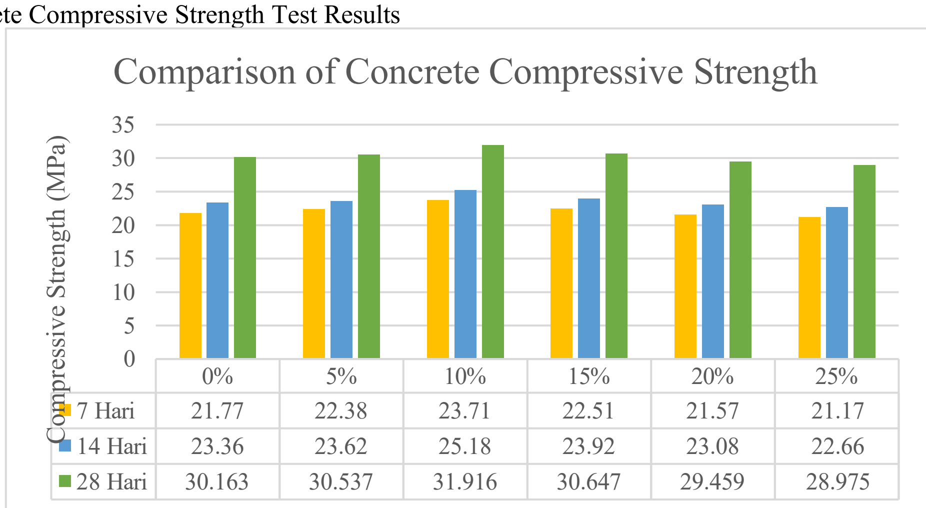

Fig 4. Comparison of Concrete Compressive Strength at 7, 14, and 28 Days

The compressive strength of concrete increased with the addition of POFA percentage, reaching its maximum strength at the 10% variation, which is consistent with Vike's (2018) study on the improvement of concrete compressive strength using 10% palm shell ash substitution. However, the compressive strength began to decline starting from the 15% variation, and this trend consistently occurred at 7, 14, and 28 days of concrete age.

The increase in concrete compressive strength at 7, 14, and 28 days is caused by two main factors. First, the finer particle size of POFA compared to cement allows it to act as a filler material, enabling it to fill the voids within the concrete. As the voids decrease, the concrete requires greater pressure to crack, thus increasing its strength in line with the desired quality. This is consistent with Hasan (2023), who stated that POFA functions as a filler and produces additional C–S–H to enhance the bonding capacity of concrete when added. Second, POFA also enhances the cement hydration process through chemical reactions.

Portland cement consists of several main compounds, including Tricalcium Silicate (C_3S), Dicalcium Silicate (C_2S), Tricalcium Aluminate (C_3A), and Tetracalcium Aluminoferrite (C_4AF). Among them, C_3S and C_2S contribute the most to concrete strength. Calcium hydroxide ($Ca(OH)_2$) produced from the hydration of cement with water reacts with the silica content (SiO_2) in POFA to form calcium silicate hydrate (C–S–H gel) of higher quality, which contributes to the increase in compressive strength of the concrete. Conversely, a decrease in compressive strength may occur if the mixture lacks sufficient cement, since POFA does not have the binding ability of cement and cannot form optimal bonds on its own. This is in line with the study by Ray (n.d.), which stated that the morphology and nanostructure of C–S–H(II) formed from the reaction between nanosilica and $Ca(OH)_2$ may differ from C–S–H(I), which is formed solely through the hydration of C_3S.

4. Conclusions

Based on the results of the research and analysis in the previous chapter, the following conclusions were obtained:

1. The substitution of Palm Oil Fuel Ash (POFA) as a replacement for cement at 5%, 10%, and 15% was able to increase the compressive strength of concrete. The compressive strength achieved was 30.537 MPa, 31.916 MPa, and 30.647 MPa, representing an increase of 1.24%, 5.81%, and 1.60% at 28 days of age compared to normal concrete. At 20% and 25% POFA substitution, the compressive strength values of 29.459 MPa and 28.975 MPa showed a decrease compared to the control concrete.
2. The maximum compressive strength of concrete was obtained with 10% POFA substitution, reaching a value of 31.916 MPa, which represents an increase of 5.81% compared to normal concrete.

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