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Research Paper

Sustainable Cement Development Using Palm Oil Boiler Ash: Mechanical and Microstructural Evaluation

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Abstract

The cement industry significantly contributes to CO_2 emissions, releasing approximately 1 ton of CO_2 for every ton of cement produced, which accounts for up to 40% of total global industrial emissions. This study aims to mitigate these emissions by utilizing Palm Oil Boiler Ash (POBA) as a clinker substitute, creating POBA Cement with substitution levels ranging from 10% to 30%. The POBA was sourced from the Cikasungka Palm Oil Plantation in Bogor, Indonesia and underwent analysis using X-Ray Fluorescence (XRF) and Scanning Electron Microscopy (SEM) to assess its chemical properties and microstructure. The findings revealed a decrease in compressive strength with increased POBA substitution levels; however, it maintained a pozzolanic effect that supported the crystallization process, albeit with a longer setting time compared to Ordinary Portland Cement (OPC). Notably, the addition of 1% nano-silica was found to enhance compressive strength more effectively than 3%. This research underscores the potential of POBA as an environmentally friendly clinker substitute for sustainable cement production.

Keywords

Nano-Silica, POBA, Compressive Strength, Durability, Green-Concrete, Eco-Friendly

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1. INTRODUCTION

Cement serves as the primary constituent in construction materials, with the production of one ton of cement releasing an equivalent ton of CO_2 into the atmosphere. Consequently, the cement industry is estimated to be responsible for approximately 40% of global CO_2 emissions, with an annual increase of 10-15% (Anderson et al., 2016; Junaid et al., 2022). This alarming figure has prompted researchers worldwide to explore strategies aimed at reducing cement usage or substituting it with alternative materials. According to Scrivener et al. (2018), innovations in cement chemistry and the adoption of supplementary cementitious materials (SCMs) can significantly lower the carbon footprint of concrete production.

Efforts to mitigate this dependence on cement include the utilization of recycled materials and industrial waste, thereby minimizing both the consumption of natural resources and environmental pollution (Abbas et al., 2018; Yashwanth et al., 2019; Thomas et al., 2020). One promising avenue involves the use of Supplementary Cementitious Materials (SCM), which, when employed in significant proportions, may foster the development of environmentally friendly cement options that effectively reduce CO_2 emissions. Commonly used SCMs include fly ash derived from coal combustion, which is rich in aluminum and silica (Al-Si) (Long et al., 2021; Mohammadi et al., 2023).

Recent advancements in cement technology have introduced Limestone Calcined Clay Cement (LC3), a green cement alternative that enhances sustainability by partially replacing clinker with calcined clay and limestone (Karkhaneh et al., 2023). Numerous studies have demonstrated that concrete incorporating up to 20% calcined limestone exhibits compressive strength that is either superior to or comparable with that of Ordinary Portland Cement (OPC) concrete (Shah et al., 2020). Furthermore, the use of LC3 as a partial substitute for cement can substantially decrease carbon emissions and energy consumption, with studies indicating reductions of 26-42% in cement content (Huang et al., 2023). Notably, LC3 concrete with a 50% cement substitution has shown a 3% increase in compressive strength, achieving 33.13 MPa at 28 days, compared to 32.15 MPa for the control specimen (Seralathan et al., 2023).

An additional candidate for cement substitution is Palm Oil Boiler Ash (POBA), which is generated from the combustion of biomass originating from palm oil shells and fine fibers. According to the Malaysian Palm Oil Board, in 2020, Malaysia had 15 million hectares devoted to palm oil cultivation, with over 5% of the biomass produced being converted to ash and typically disposed of in open fields (Hamada et al., 2021). Indonesia is the world's largest producer of crude palm oil (CPO), with a total production exceeding 48.3 million tons in 2023. As reported in the 2021–2023 National Plantation Statistics, the country's oil palm plantation area reached 16.83 million hectares, comprising smallholder, state-owned, and private plantations (Yusuf et al., 2025).

Building upon prior research regarding environmentally friendly cement and the utilization of POBA, this study specifically investigates the use of POBA as a cement clinker substitute in concrete. The percentage of clinker substitution ranges from 10% to 30%, thereby denoting the resulting material as POBA Cement. The POBA utilized in this study is sourced from the Cikasungka Palm Oil Plantation in Bogor, Indonesia. Comprehensive analyses of the chemical properties of the material are conducted using X-Ray fluorescence (XRF) to determine its chemical composition, and Scanning Electron Microscopy (SEM) to evaluate the bonding and microstructural characteristics. Additionally, nano-silica is incorporated at 1% and 3% to enhance the pozzolanic reactivity and mechanical performance of POBA-based cement. The application of POBA cement involves the preparation of cement paste and mortar samples, which are analyzed for their compressive strength to assess their construction suitability. The novelty of this study lies in the synergistic combination of POBA and nano-silica to optimize both the mechanical and microstructural performance of sustainable cement composites approach that has been scarcely explored in prior literature. The outcomes of this research have the potential to contribute significantly to the development of alternative cementitious materials for green construction.

2. EXPERIMENTAL SECTION

2.1 Materials

2.1.1 Ordinary Portland Cement (OPC)

The cement used in this study is Ordinary Portland Cement (OPC). The cement was obtained from PT Indocement Tunggal Perkasa. The cement meets the requirements set by ASTM C-150, namely type 1 cement.

2.1.2 Sand

River sand obtained from Tayan, West Kalimantan was used in this study. Its fineness modulus and specific gravity were recorded as 2.42 and 2.67, respectively. The sand was dried to a consistent mass.

2.1.3 Palm Oil Boiler Ash (POBA)

Palm Oil Boiler Ash (POBA) used in this study was obtained from the Cikasungka Palm Oil Mill (PKS) located in Bogor Regency, Indonesia. POBA is a solid waste generated from the combustion of palm oil biomass in the mill's boiler system shown in figure 1. The ash was produced using a furnace operating at temperatures between 400–600°C. Samples were collected manually by taking the remaining ash directly from the boiler discharge area after the combustion process had completed and the ash had sufficiently cooled. The collected ash was stored in sealed containers to prevent contamination and moisture absorption prior to testing. The POBA material used in this study was utilized directly without any additional treatment, such as re-drying, sieving, or chemical activation.

Figure 1. (a) Palm Oil Mill (PKS) Cikasungka (b) Shell and Fine Fiber (c) Combustion Process, (d) Oil Palm Boiler Ash (POBA)

2.1.4 Polycarboxylate Superplasticizer (PCE)

Polycarboxylate superplasticizer (PCE) used from CV John Hi-Contrindo. PCE is a water reducer commonly used in cement mixtures because it can significantly increase the fluidity of concrete and improve overall construction performance because the water-to-cement ratio is reduced (Gamboa Idrogo et al., 2024; Xie et al., 2023).

2.1.5 Nano Silica ($nSiO_2$)

Nano silica used from Wacker Chemicals. ltd with SiO_2 content of 99.8% and particle size of 20 nm. Nano silica in this study has a density of 2.2 g/cm^3. Figure 2 presents the nano silica utilized in this study

2.2 Methods

2.2.1 Sample Preparation

Ordinary Portland Cement (OPC), nano silica, and Palm Oil Boiler Ash (POBA) were first mixed in a dry state using a mechanical mixer for 1 minute. Subsequently, water mixed

Figure 2. (a) Ordinary Portland Cement (OPC), (b) Nano Silica ($nSiO_2$), (c) Palm Oil Boiler Ash (POBA), (d) Polycarboxylate Superplasticizer (PCE)

with a Polycarboxylate Superplasticizer (PCE) was added, and the mixture was further blended for 5 minutes. The mixing procedure followed the guidelines specified in ASTM C305 for mechanical mixing of hydraulic cement pastes and mortars. In this study, cube specimens measuring 5 × 5 × 5 cm were prepared in the form of both cement paste and mortar. The samples were cured at a constant temperature of 25°C, and compressive strength tests were conducted at the ages of 3, 14, 28, and 56 days to evaluate the strength development over time (ASTM International, 2020).

2.2.2 Mixture Proposition

Initial stage experiments were conducted to determine the optimum w/b, starting with using w/b 0.3-0.5 and obtaining the most optimum w/b of 0.43, targeting a cement paste with a control strength at 28 days of 30 MPa (Kim et al., 2024). The mix design is based on the absolute volume method for cement paste. In this study, OPC was substituted with POBA with a percentage of 10-30, because based on research conducted by Sata et al. (2007), substituting cement with POBA by 10 to 40% and obtaining maximum compressive strength at 20% substitution. Therefore, this study will substitute cement 10, 15, 20, 25, and 30% to determine the phenomena that occur between the compressive strengths as seen in Table 1 percentage of cement paste mixture.

The composition of mortar is listed in Table 2, the initial preparation of the composite involves the dry mixing of POBA, cement, nano silica (NS), and sand to ensure uniform distribution of the constituents. Following the dry mixing process, water is incorporated and stirred for a duration of 5 minutes to achieve a homogeneous mixture conducive to optimal performance in subsequent applications.

To increase the pozzolan reaction in the cement paste, variations were also added by substituting POBA with nano silica of 1 and 3%. The addition of nano-silica can increase the percentage of SiO_2 content in POBA cement and produce secondary calcium silicate hydrate (CSHs) which is expected to increase the compressive strength along with the increasing age of the specimen. So there are 16 variations of the mixture including the control specimen that will be carried out in this study.

Table 1. Percentage of Cement Paste Mixture

Sample	OPC	POBA	NS	PCE	W/B
Control	100%	0%	0%	0.5%	0.43
CP10	90%	10%	0%	0.5%	0.43
CP15	85%	15%	0%	0.5%	0.43
CP20	80%	20%	0%	0.5%	0.43
CP25	75%	25%	0%	0.5%	0.43
CP30	70%	30%	0%	0.5%	0.43

Because the hygroscopic POBA and nanosilica materials can increase the water requirements in the mixture, a Polycarboxylate Superplasticizer (PCE) of 0.5% of the mixture is used to reduce the water-cement ratio.

Table 3 shows the percentage composition of cement paste mixtures with the addition of 1% and 3% nano silica. Table 4 presents the mortar mixtures with the addition of 1% and 3% nano silica for six cube specimens measuring 5×5×5 cm

2.2.3 Compressive Strength

The paste samples will be tested for compressive strength at the ages of 3, 14, 28, and 56 days at the University Indonesia Civil Engineering Structure and Materials Laboratory. The purpose of the compressive strength test on cement paste is to measure the ability of cement paste to withstand compressive loads until collapse occurs. This test is carried out to evaluate the quality of cement material, the effect of additional materials, and the characteristics of the mixture.

2.2.4 X-Ray Fluorescence (XRF) Analysis

X-Ray fluorescence (XRF) testing was conducted using a PANalytical Epsilon 1 instrument with a 50 kV Ag radiation source, manufactured by Malvern Panalytical. This test aims to determine the chemical composition of OPC and POBA materials.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength of Cement Paste and Mortar

Compressive strength testing was conducted on cement paste samples to evaluate the mechanical properties of cement paste

Table 2. The Mortar Compositions for 6 Specimens Based ASTM C 109

Sample	OPC (g)	POBA (g)	NS (g)	PCE (ml)	Water (ml)	Sand (g)	W/B
Control	500	0	0	6	240	1375	0.48
CP10	450	50	0	6	240	1375	0.48
CP15	425	75	0	6	240	1375	0.48
CP20	400	100	0	6	240	1375	0.48
CP25	375	125	0	6	240	1375	0.48
CP30	350	150	0	6	240	1375	0.48

OPC: Ordinary Portland Cement; POBA: Palm Oil Boiler Ash; NS: Nano silica; PCE: Polycarboxylate superplasticizer; W/B: Water Binder Ratio

Table 3. Percentage of Cement Paste Mixture with Nano-Silica

Sample	OPC	POBA	NS	PCE	W/B
CP9S1	90%	9%	1%	0.5%	0.43
CP7S3	90%	7%	3%	0.5%	0.43
CP14S1	85%	14%	1%	0.5%	0.43
CP12S3	85%	12%	3%	0.5%	0.43
CP19S1	80%	19%	1%	0.5%	0.43
CP17S3	80%	17%	3%	0.5%	0.43
CP24S1	75%	24%	1%	0.5%	0.43
CP22S3	75%	22%	3%	0.5%	0.43
CP29S1	70%	29%	1%	0.5%	0.43
CP27S3	70%	27%	3%	0.5%	0.43

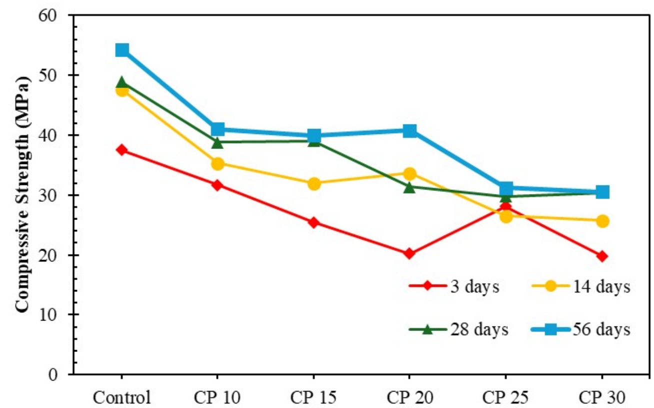

Figure 3. Cement Paste Compressive Strength Test Results

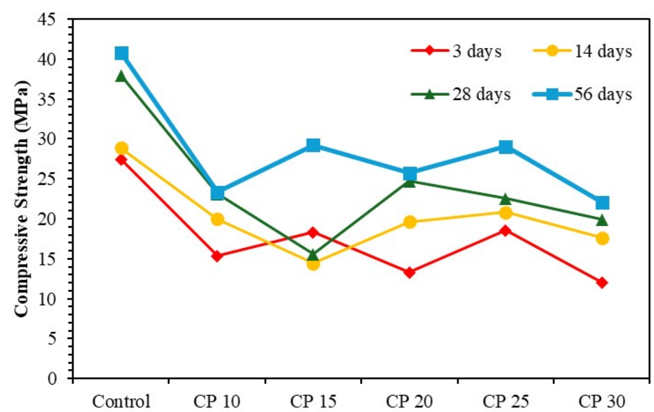

Figure 4. Mortar Compressive Strength Test Results

substituted with POBA, utilizing a fixed water-cement ratio of 0.43 and a PCE dosage of 0.5% of the mixture. The cement substitutions were set at 10%, 15%, 20%, 25%, and 30%. As shown in Figure 3, the compressive strength values at 28 days of age indicated a decline in strength as the level of cement substitution increased. Specifically, the CP10 specimen experienced a 21% reduction in compressive strength, while the CP15 specimen showed a 20% decrease compared to the control specimen. Notably, the CP15 specimen exhibited better compressive strength than the CP10 specimen, a finding that aligns with the research conducted by Sata et al. (2007).

Figure 4 shows that the control specimen exhibits higher compressive strength compared to the other samples. CP 20 and CP 25 demonstrate a more stable increasing trend in compressive strength over time, with CP 25 reaching 29 MPa at 56 days of curing.

3.2 Compressive Strength of Paste and Mortar with Nano Silica

As shown in Figure 5, the incorporation of nano-silica significantly enhances the compressive strength, particularly at the 3-day mark. This improvement is attributed to nano-silica's ability to accelerate the initial hydration process in the cement paste, as noted in research conducted by Kim et al. (2024). Their findings indicate that specimens containing 3% nano-silica exhibit higher compressive strength at 3 days compared to other samples with the same substitution percentage. The effects of adding 1% nano-silica become evident at 28 days, as reflected in the compressive strength test results in Figure 3. The CP19S1 specimen achieved a compressive strength of 37.9 MPa, while the CP17S3 specimen recorded only 32.75 MPa.

The introduction of 1% nano-silica leads to reduced porosity in the cement paste, as the nanomaterial fills the voids. Conversely, the addition of 3% nano-silica results in decreased compressive strength due to the clumping of nanomaterials within the cement paste, which creates weak points.Compressive streng th testing was conducted on cement paste samples to evaluate

Table 4. The Mortar Compositions for 6 Specimens with NanoSilica

Sample	OPC (g)	POBA (g)	NS (g)	PCE (ml)	Water (ml)	Sand (g)	W/B
CP9S1	450	45	5	6	240	1375	0.48
CP7S3	450	35	15	6	240	1375	0.48
CP14S1	425	70	5	6	240	1375	0.48
CP12S3	425	60	15	6	240	1375	0.48
CP19S1	400	95	5	6	240	1375	0.48
CP17S3	400	85	15	6	240	1375	0.48
CP24S1	375	120	5	6	240	1375	0.48
CP22S3	375	110	15	6	240	1375	0.48
CP29S1	350	145	5	6	240	1375	0.48
CP27S3	350	135	15	6	240	1375	0.48

OPC: Ordinary Portland Cement; POBA: Palm Oil Boiler Ash; NS: Nano silica;
PCE: Polycarboxylate superplasticizer; W/B: Water Binder Ratio

the mechanical properties of cement paste substituted with POBA, utilizing a fixed water-cement ratio of 0.43 and a PCE dosage of 0.5% of the mixture.

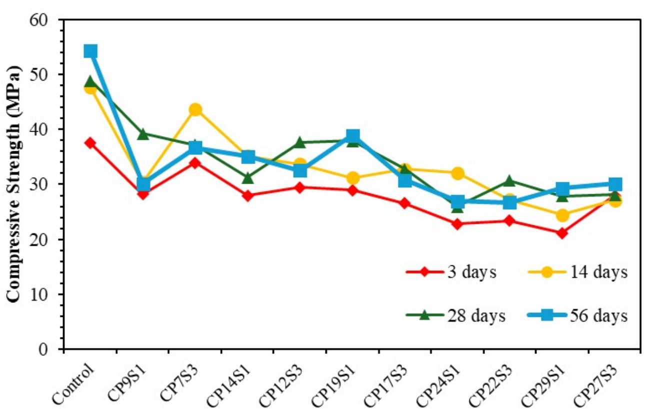

Figure 5. The Results of the Compressive Strength Test of Cement Paste with Nano-Silica

Based on the test results, it is evident that the compressive strength of the paste sample increases with curing age. This is attributed to the formation of calcium silicate hydrates (CSH) and calcium hydroxide ($Ca(OH)_2$) over time. Both CSH and $Ca(OH)_2$ significantly influence the strength of cement paste. The observed decrease in compressive strength with higher percentages of cement replacement using POBA at 3 and 14 days can be attributed to an inadequate amount of CaO in the mixture, which is necessary for generating $Ca(OH)_2$ and CSH.

However, a notable increase in compressive strength is observed at 28 days for the CP9S1 and CP19S1 samples from Figure 1 , attributable to the pozzolanic reaction. The silica dioxide (SiO_2) present in POBA and nano-silica reacts with $Ca(OH)_2$, resulting in the production of additional secondary calcium silicate hydrates (CSH). This finding is corroborated by research conducted by Tasnim et al. (2018), which reported similar results with POBA substitutions.

The compressive strength test results indicate that as the

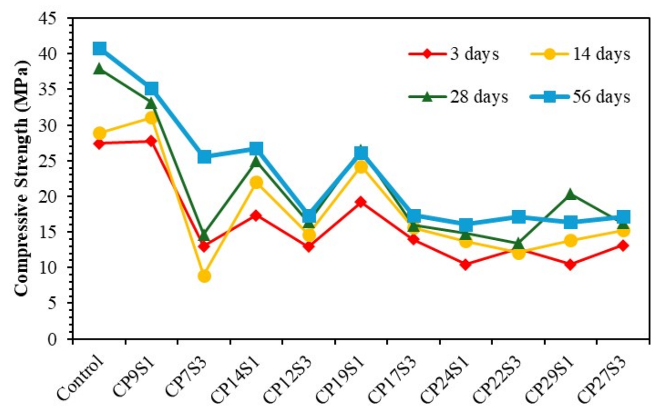

Figure 6. The Results of the Compressive Strength Test of Cement Mortar with Nano-Silica

percentage of cement substituted with POBA increases, the compressive strength decreases. The incorporation of palm oil combustion ash contributes to a lower hydration level at early ages, impacting the development of compressive strength (Al-Mulali et al., 2015). The test results reveal that the lowest compressive strength occurs with a 30% cement substitution.

In summary, the initial compressive strength at 3 and 14 days is reduced due to the insufficient CaO content in the samples containing POBA. Nonetheless, at 28 days, a significant improvement is observed, driven by the SiO_2 content in POBA and nano-silica. Furthermore, the test results suggest that optimal cement replacement lies between 10% and 30%, achieving mechanical capabilities comparable to those of the control paste sample.

3.3 Effect of nano−SiO_2 on Concrete Compressive Strength

Nano-silica significantly reduces porosity and enhances the microstructure of cement paste, while also improving compressive strength and overall mechanical properties due to accelerated hydration and increased C–S–H formation (Septriansyah et al., 2025; Tjahjani et al., 2023; Du et al., 2015), found that the porosity of Lightweight Concrete (LWC) containing 1% nano-silica was decreased, resulting from a denser and more homogeneous microstructure attributed to the filler effect and pozzolanic reaction of the nano-silica particles (Belkowitz et al., 2015), noted that the agglomeration of nano-silica, along with an increasing percentage of its use, can lead to the formation of cavities in the cement paste, ultimately resulting in higher porosity, which negatively affects the mechanical properties of the concrete.

This aligns with research demonstrating that the inclusion of 1% nano-silica is more effective in enhancing the compressive strength of cement paste compared to 3%. For instance, the CP19S1 sample achieved a compressive strength of 37.9 MPa at 28 days, surpassing the strength of CP17S3, which reached only 32.75 MPa.

3.4 Chemical Composition of POBA and OPC

The chemical composition of OPC, POBA, CP9S1, and CP19S1 was determined using X-Ray fluorescence (XRF) analysis, as presented in Table 4. The results indicate that SiO_2 is the predominant component in POBA, accounting for 58.13%, with the combined content of SiO_2, CaO, and Fe_2O_3 reaching 66.74%. These findings are consistent with those reported by Siregar et al. (2024), who observed that the combined concentration of SiO_2, Al_2O_3, and Fe_2O_3 in POBA materials, as determined by XRF analysis, was approximately 50%. However, the Loss of Ignition (LoI) is quite large, which is 13.79%. Loss of Ignition (LoI) is an indication of the percentage of organic matter in the material (Pourakbar et al., 2015). In this study, POBA is classified as a class N pozzolan because of the amount SiO_2, CaO, and Fe_2O_3 are close to 70% and have SO3 below 4% based on ASTM C 618 standard (ASTM C, 2005).

Despite having a higher SiO_2 content than OPC, POBA has a low CaO content is only 7.25%. The high LoI percentage of POBA from the XRF results is due to the percentage of carbon in the POBA sample. Thus, this value is considered because it is included in the LoI range found by previous researchers. In the study conducted b (Chub-uppakarn et al., 2023) y, the loss on ignition (LOI) of POBA material was found to be 11.52%, while in this study, it was measured at 13.79%.

The low percentage of CaO in POBA suggests a slow hydration property, as $CA(OH)_2$ is essential for the pozzolanic reaction. Conversely, the high percentage of SiO_2 indicates that POBA has the potential to exhibit pozzolanic characteristics. From the data, it is evident that POBA has a lower percentage of Fe2O3 compared to OPC and does not contain Al_2O_3.

On the other hand, POBA contains higher percentages of K_2O and MgO than OPC. The elevated K_2O content in POBA can contribute to an increased risk of damaging alkali-silica reactions when reactive aggregates are used (Tasnim et al., 2018). However, the SO_3 content in POBA is significantly lower than that found in cement.

Furthermore, the XRF analysis reveals that the CP9S1 mixture comprises 6.17% Al_2O_3, 2.36% Fe_2O_3, 1.92% MgO, 1.37% K_2O, and 2.27% SO_3. In contrast, the CP19S1 mixture contains 5.53% Al_2O_3, 2.30% Fe_2O_3, 1.87% MgO, 1.77% K_2O, and 2.17% SO_3. Notably, the SO_3 content in both CP9S1 and CP19S1 is lower than that of OPC, while their SiO2 content is higher. Additionally, the K2O levels in both mixtures are lower than those in POBA.

In conclusion, the chemical composition of cement that is substituted with POBA and enhanced with nano-silica reveals a higher SiO_2 content and lower SO_3 levels compared to OPC. The CaO content in both mixtures is also similar to that of OPC, measuring at 50.64% and 47.48%, suggesting that the mixtures still retain pozzolanic properties.

3.5 Scanning Electron Microscopy (SEM) Result

Scanning Electron Microscopy (SEM) is employed to analyze the chemical composition and morphological characteristics of cement paste samples. In this study, SEM tests were conducted to identify the presence of calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (CSH) in the samples labeled CP9S1 and CP19S1, as these mixtures demonstrated optimal performance parameters. As depicted in Figure 7a and 7c, the SEM images at a magnification of 2500x reveal that the CP19S1 sample exhibits a larger cavity when compared to CP9S1. This observation can be attributed to the higher water absorption capacity of the POBA material used in the CP19S1 mixture, resulting in a significant cavity formation post-hydration.

Figure 7b and 7d illustrate the particle size distribution obtained from SEM image segmentation of two material variations, namely CP9S1 and CP19S1. The data were extracted using ImageJ software and visualized in histogram form to capture the spread and frequency of particle sizes.

Based on the graphical results, the CP9S1 variation exhibits a dominant concentration of particles within the 1–2 μm range, with a notably high frequency (>40 particles). In contrast, the CP19S1 variation presents a broader and more evenly distributed particle size range, extending beyond 6 μm, albeit with lower overall frequency.

The narrower distribution observed in CP9S1 indicates a higher degree of uniformity in particle size, suggesting a more homogeneous and dense microstructure, with minimal presence of large voids or pores. Conversely, the wider and less centralized distribution in CP19S1 suggests increased microstructural heterogeneity, which may result from particle agglomeration or the formation of larger voids within the cement paste matrix.

These differences imply that the CP9S1 variation has the potential to produce a denser microstructure, which could contribute positively to mechanical performance, particularly in terms of compressive strength and elastic modulus. On the other hand, the broader particle size distribution in CP19S1 may indicate a reduction in microstructural integrity due to greater heterogeneity.

Figure 8 illustrates the SEM results for both the CP9S1 and CP19S1 samples after 56 days of curing. The obtained images showcase a hexagonal plate morphology characteristic of crystalline calcium hydroxide ($Ca(OH)_2$), alongside a flower-like

Table 5. Chemical Characteristics of OPC, POBA, CP9S1, and CP19S1

Chemical Composition	OPC	POBA	CP9S1	CP19S1	Unit
Magnesium oxide (MgO)	1.92	2.90	1.92	1.87	%
Silicon dioxide (SiO_2)	29.37	58.13	32.13	33.63	%
Phosphorus pentoxide (P_2O_5)	0	7.34	0	0	%
Aluminium oxide (Al_2O_3)	6.56	0	6.17	5.53	%
Sulfur trioxide (SO_3)	2.45	0.69	2.27	2.17	%
Chloride (Cl)	0	0.66	0	0	%
Potassium oxide (K_2O)	1.05	7.88	1.37	1.77	%
Calcium oxide (CaO)	54.55	7.25	50.64	47.48	%
Strontium oxide (SrO)	0.35	0	0.30	0.30	%
Iron oxide (Fe_2O_3)	2.47	1.36	2.36	2.30	%
Loss of Ignition (LoI)	1.28	13.79	2.82	4.94	%
Total	98.72	86.21	97.18	95.06	%

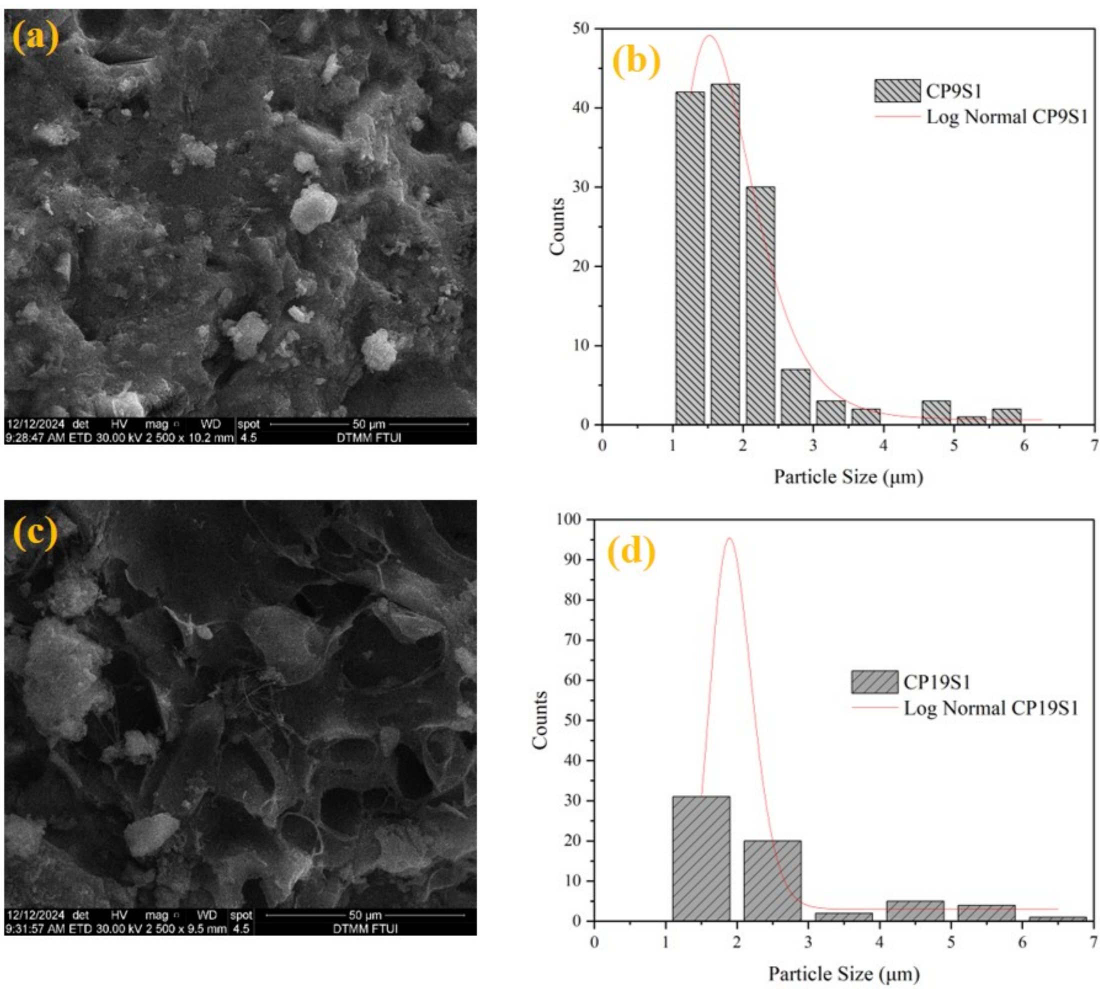

Figure 7. SEM Image Sample cement paste at 56 days with a magnification of 2500x (a) CP9S1 sample, (b) Statical distribution particle size of CP9S1, (c) CP19S1 sample, (d) Statical distribution particle size of CP19S1

morphology indicative of CSH. Both $Ca(OH)_2$ and CSH are critical byproducts of the cement hydration process, influencing the mechanical strength of the cement paste (Tasnim et al., 2018). Additionally, the presence of rod-like crystal structures, known as ettringite, is observed, which typically forms during the early stages of hydration reactions.

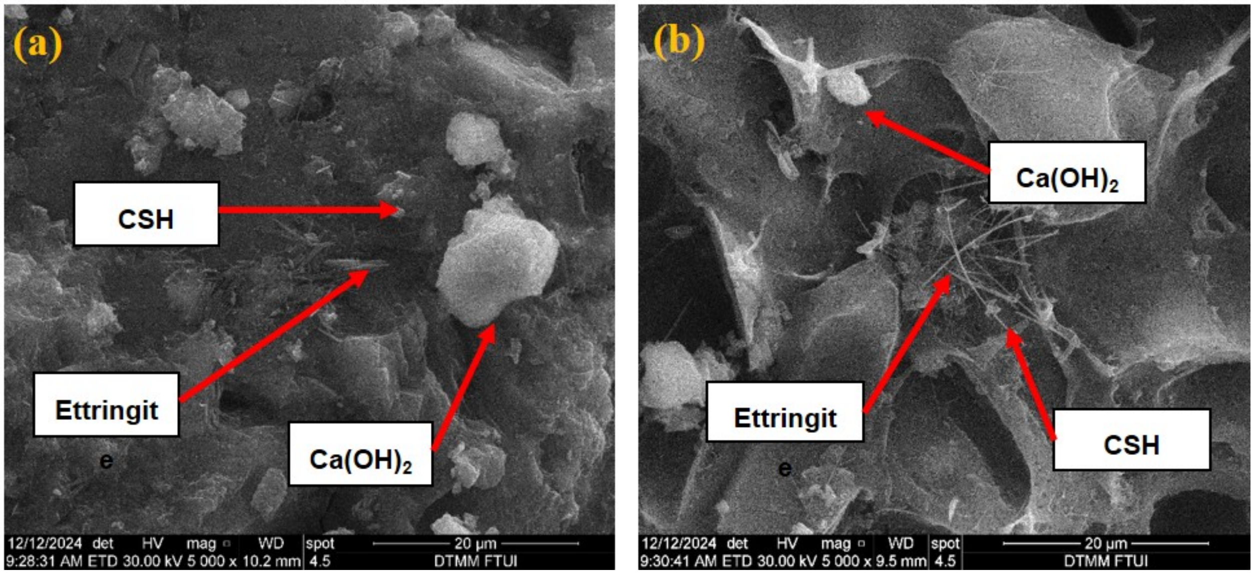

Figure 8. (A) CP9S1, (B) CP19S1 Sample Cement Paste at 56 Days Magnification 5000x. Moreover, Observations Suggest That as the Curing Age Increases, the Overall Quantity of Calcium

Analysis reveals that the quantity of ettringite in the CP9S1 sample is less pronounced than in the CP19S1 sample, suggesting that the mechanical properties of CP19S1 may still be enhanced. The slower hydration kinetics of the CP19S1 sample, attributed to the incorporation of 19% POBA, resulted in a reduced formation of CSH, indicated by the lower CaO content in this mixture.

Calcium silicate hydrate tends to rise. This phenomenon is linked to the generation of secondary calcium silicate hydrate (CSH), which results from the reaction between silica and $Ca(OH)_2$. According to Aprianti (2017), the formation of C–S–Hgel in cement paste is facilitated by the presence of SiO2 from POBA and $Ca(OH)_2$ from cement, leading to the development of the chemical structure $Ca_{1.5}SiO_{3.5}\cdot x\ H_2O$ as a component of the C–S–H gel.

4. CONCLUSIONS

Palm oil boiler ash (POBA) shows potential as a pozzolanic cement additive, contributing to environmental sustainability and reducing cement usage. A significant increase in compressive strength was recorded, which was due to the SiO_2 content in POBA and the addition of nano-silica. Test results indicate that the incorporation of 1% nano-silica is more effective in enhancing the compressive strength of the cement paste compared to 3%. This is evidenced by the CP19S1 sample, which achieved a compressive strength of 37.9 MPa at 28 days, surpassing the 32.75 MPa obtained by CP17S3. Recent scanning electron microscopy (SEM) analyses indicate that the cement paste based on plain old portland cement (POBA) exhibiting a content of 19% generates a rod-like crystalline structure identified as ettringite. These findings suggest that the mechanical properties of the CP19S1 sample have the potential for further enhancement. The use of POBA as a partial cement replacement material can reduce palm oil industry waste while reducing carbon emissions from cement production, supporting the concept of sustainable and environmentally friendly construction.

5. ACKNOWLEDGMENT

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