High-Performance Concrete Incorporating Almond Leave Ash as Supplementary Cementing Material

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Abstract:

High-Performance Concrete (HPC) offers greater strength and resilience compared to conventional concrete. Almond leaves frequently clog areas where they are planted and have no recognized commercial value. In this research, Almond Leaf Ash (ALA) was included in HPC in percentages ranging from 0, 5, 10, 15, 20% as a cement additive. Concrete specimens, engineered to possess a minimum strength of 50 N/mm², were poured and underwent water curing for up to 56 days. The workability of the newly mixed concrete was evaluated by analyzing its compacting factor and slump. Furthermore, evaluations were conducted on the density, compressive and split tensile strengths, as well as the internal microstructure of the cured concrete. The workability tests revealed that the concrete stiffened as the proportion of ALA increased. Adding 5% ALA to HPC led to achieving a strength of 56.56 N/mm^2 after 56 days of curing, surpassing the expected strength. Meanwhile, incorporating 10% ALA attained the targeted minimum strength of 50 N/mm^2. 15% and 20% of the ALA, however, fell short of the minimum strength. The HPC's split tensile strength followed the same pattern. The results were corroborated by examining the microstructure of the HPC, revealing that substituting 5% ALA for cement yielded the highest strength.

Keywords: Almond Leaf Ash, Compressive strength, High-performance concrete, Split tensile strength.

I. Introduction

High-Performance Concrete (HPC) is a specialized form of concrete designed to meet specific demands for properties and consistency, often challenging to achieve through conventional raw materials and traditional mixing, pouring, and curing methods [1]. The advancement of HPC materials, notably ultra-high-performance concrete, will lead to the availability of superior materials for specific civil engineering endeavours. The use of HPC materials has increased more in civil engineering because they have superior mechanical qualities and endurance compared to regular concrete [2]. Numerous researchers are focusing on the development of HPC while also working on the mechanism research for specific features, preparation technologies, testing methodologies, modelling, and applications of various high-performance building materials [3], [4]. To obtain HPC, there are numerous options. In most cases, HPC can be created by mixing specific aggregates, binders, and mixes with conventional concrete. For instance, a variety of non-conventional aggregates, chemical admixtures, mineral admixtures, and diverse fibres can be used to produce HPC. Besides cement, supplementary materials like ground blast furnace slag, fly ash, or silica fume are employed in the production of HPC to fulfill its requirements. Depending on the desired outcome, the ingredients are combined in varied ratios with Portland cement [5]. Ramos *et al.* [6] observed that worldwide, the annual per capita production of concrete exceeds one cubic meter, primarily utilizing Portland cement, thus posing considerable environmental challenges. Currently, around 3 billion tons of cement are utilized worldwide, leading to the emission of 400 kilograms of carbon dioxide (CO_2) gas for every 600 kilograms of cement produced. In response to growing environmental apprehensions and shifts towards renewable energy sources in conventional energy production methods, supplementary cement materials (SCMs) are increasingly employed as alternatives to traditional cement [7].

Almond trees (Terminalia catappa Linn) are plentifully distributed across major cities, towns, and villages in the southern region of Nigeria. They are frequently cultivated for their shade and the consumption of their edible nuts [8]. Nevertheless, the foliage produced due to the deciduous characteristics of almond trees poses an environmental issue. Furthermore, attempting to discard these leaves via open incineration results in environmental pollution [8]. Hence, Almond leave ash (ALA) which is obtained through the burning of almond leaves was used as SCMs in HPC. Evidence indicated that utilizing ashes significantly decreased the life-cycle expenses, carbon emissions, and energy consumption throughout the lifespan of HPC [9], [10].

Magudeaswaran & Eswaramoorthi [11] explored the mechanical properties of Silica Fume (SF) and Fly Ash (FA) as partial replacements for cement. The study revealed that the highest compressive strengths, reaching 61.33 N/mm^2 at 28 days, were attained by combining 5% SF and 10% FA, compared to 54 N/mm^2 for the control mix. Optimal replacement levels were observed with 15% SF combined with 7.5% FA (3.60 N/mm^2) and 5% SF blended with 2.5% FA (9.91 N/mm^2) for split and flexural strengths, respectively. As a result, HPC made from a combination of FA and SF reached a sufficient strength level for structural usage.

Kumar *et al*. [12] stated that a perfect combination of 15% fly ash (FA), 12% silica fume (SF), and a 1% addition of steel fibres resulted in a rise of 5.89% in compressive strength, along with enhanced workability. Ghazy, Abd Elaty, and Zalhaf [13] examined the impact of SCM on HPC compressive, tensile, and flexural strengths after exposure to various temperatures. The study examined various factors such as the type of SCM, including fly ash (FA) and ground granulated blast furnace slag (GGBFS), as well as the presence of steel fibre (SF), polypropylene fibre (PP), and hybrid fibres. The findings indicated that FA and GGBFS, SF, and hybrid fibres notably enhanced the residual mechanical properties of high-performance concrete (HPC). In contrast, PP fibre had a detrimental impact on these properties.

Mustapha *et al*. [14] discovered that the blend of 40% cement, 50% FA, and 10% SF had achieved a maximum strength of 87.06 MPa after 28 days of curing, which was 5% higher than the control specimen.

Using ultra-fine FA and nano-silica, Sujay *et al*. [15] examined the strength characteristics of HPC. The split tensile test recorded a value of 5.51 N/mm^2, while the flexural strength test yielded 82.36 N/mm^2, and the optimal compressive strength test also resulted in 82.36 N/mm^2. These tests were conducted using a mixture containing 4.5% Nano-silica admixtures and 10% ultrafine fly ash. In comparison to standard concrete, this formulation resulted in a material with superior strength properties.

The execution of SCM on high-strength concrete mixes containing FA, metakaolin, SF, and mixtures of the ashes was examined by Megat *et al*. [16]. The FA and SF mixture's compressive strength implementation outperformed the control. Odeyemi *et al*. [17] investigated the properties of HPC incorporating bamboo leaf ash (BLA) as an additive. The research indicated that after a 56-day curing period, the effective strength was achieved with 5% replacement. Microscopic analysis revealed enhanced interlocking of concrete grains with 5% BLA incorporation. Consequently, it was determined that 5% BLA could effectively substitute for cement in HPC. Wu *et al*. [18] conveyed that using Sugar cane bagasse ash (SCBA) retains compressive strength, enhances workability, and reduces autogenous shrinkage, with a substitution rate of 40% showing satisfactory results.

A review of existing literature revealed no prior studies on the utilization of almond leaf ash (ALA) in HPC formulation as of 2022. This investigation assessed the oxide compositions, consistency, setting time, fresh properties (such as slump and compacting factor), compressive and split tensile strengths, internal microstructure, as well as consistency and setting time of ALA.

II. MATERIALS AND METHODS

In this study, Portland limestone Cement (PLC) Grade 42.5R with a specific gravity of 3.13, potable water with a pH of 7.0, natural sand that passes through a 4.75 mm sieve, and crushed stone with a maximum diameter of 12.5 mm, adhering to BS 882 [19] specifications were employed. The almond leaves collected from Offa, Kwara, Nigeria, were incinerated at 650°C in a furnace at the Department of Science, Federal Polytechnic Offa to produce Almond Leaf Ash (ALA). The ashes were then finely ground with a milling machine and sifted through a 75 µm sieve. Additionally, Conplast Superplasticizer (HYDROPLAST-200), which complies with ASTM C494 [20], was used to disperse fine particles in the mix, thereby improving workability.

The initial and final setting times of the ALA blended cement paste were determined as specified by BS EN 196-3 [21]. The consistency of ALA blended cement was measured according to BS EN 197-1 [22]. The workability of fresh concrete was done using BS EN 12350-1 [23].

The attributes of the materials utilized are detailed in Table 1.

Table 1: Physical properties of materials

Test	**Materials**			
	PLC	ALA	Fine Aggregates	Coarse Aggregates
Fineness (%)	3	8.5		
Fineness Modulus (%)			2.9	4.2
Specific Gravity	3.11	2.73	2.61	2.63

Almond Leaf Ash (ALA) was integrated into the cement mixture at levels ranging from 0, 5, 10, 15, and 20%. Furthermore, to improve concrete strength and decrease water content, 1% Superplasticizer (SP) by weight of cement was introduced. The concrete mix proportions for both cubes and cylinders are detailed in Tables 2 and 3. These proportions adhere to the guidelines established by the Council for the Regulation of Engineering in Nigeria [24], aiming for a characteristic strength of 50 N/mm².

Table 2: Mix Proportions for Concrete Cube

W/C	Cement (kg)	ALA (kg)	SP (g)	Aggregates	
				Fine (kg)	Coarse (kg)
0.31	24.60	0	246	19.35	35.85
0.31	23.37	1.23	246	19.35	35.85
0.31	22.14	2.46	246	19.35	35.85
0.31	20.91	3.69	246	19.35	35.85
0.31	19.68	4.92	246	19.35	35.85

Table 3: Mix Proportions for Concrete cylinders

W/C	Cement (kg)	ALA (kg)	SP (g)	Aggregates	
				Fine (kg)	Coarse (kg)
0.31	25.80	0	258	20.22	37.50
0.31	24.51	1.29	258	20.22	37.50
0.31	23.22	2.58	258	20.22	37.50
0.31	22.00	3.87	258	20.22	37.50
0.31	20.64	5.15	258	20.22	37.50

Forty-five concrete cubes and thirty cylindrical concrete samples were produced. After being cured for 7, 28, and 56 days in water, the density of the cubes was gauged, and assessments were carried out to evaluate the compressive strength of the cubes and split tensile strength for the cylindrical samples. These evaluations were conducted utilizing a Universal Testing Machine (UTM) with a capacity of 1000 kN, adhering to standards BS EN 12390-3 [25] for compressive strength and BS EN 12390-6 [26] for split tensile strength. The experiments were conducted at the Materials and Structures Laboratory within the Department of Civil Engineering at Federal Polytechnic Offa, located in Offa, Nigeria. The oxide content of the ALA was analyzed using a Skyray EDX 3600B Energy Dispersive X-ray Fluorescence (XRF) Spectrometer at ROLAB Nigeria Ltd., situated in Ibadan, Nigeria. Moreover, scanning electron microscopy (SEM) was employed to investigate the internal microstructure of the concrete specimens hardened with ALA.

III. RESULTS AND DISCUSSION

a. Chemical composition of ALA

Table 2 presents the oxide composition of the ALA.

Table 4: Oxides Composition of ALA

Content	Percentage
SiO_2	56
Al_2O_3	7.1
Fe_2O_3	10.1
CaO	7.61
MgO	10
K_2O	9.9
NIO	0.02
SO_3	2.01
Mn	0.08
Zn	0.02
LOI	0.00
CuO	0.02
Sb_2	0.98

According to ASTM C-618 [27], the combined percentage of SiO_2, Al_2O_3, and Fe_2O_3 in ALA should not fall below 70%. The combined percentage of SiO_2, Al_2O_3, and Fe_2O_3 found in the tested ALA is 73.2%, exceeding the percentage reported by Eme & Ohwerhi [8] and the 70% requirement specified by ASTM C-618 [27]. However, the analysis indicates that silicon dioxide (SiO_2) constitutes the highest proportion of oxide composition, as expected for a SCM.

b. Consistency and setting time of PLC-ALA

Figures 1 and 2 depict the findings regarding the consistency and setting time of the PLC-ALA blend. The information depicted in Figure 1 reveals that the lowest consistency occurs in the absence of ALA (0%), whereas the highest consistency was attained when 20% ALA is incorporated based on the weight of PLC (signifying that more volume of water would be required to produce a workable paste). Obviously, the consistency increases with higher percentages of PLC replacement. The increase in consistency with higher percentages of almond leaf ash in cement is due to the pozzolanic reactions, fineness, and microfiller effect [28].

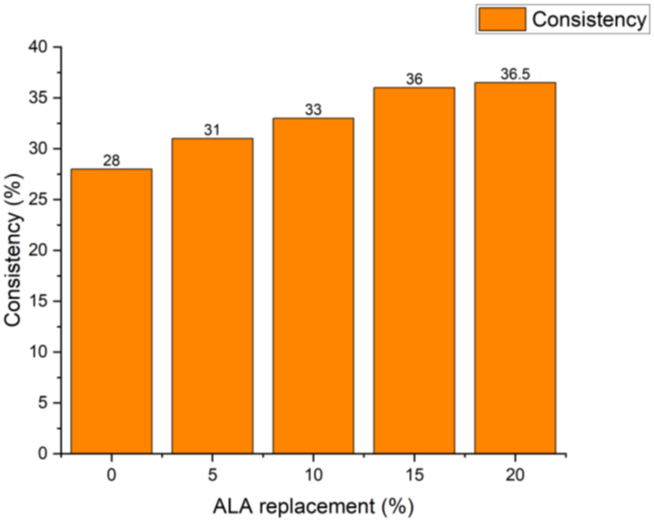


Fig. 1. Consistency against PLC Blended ALA

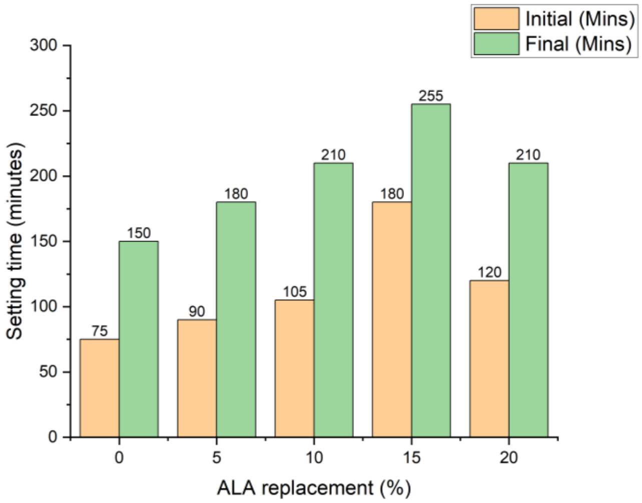


Fig. 2. Setting Time against PLC Blended ALA

While BS EN 197-1 [29] specifies a minimum initial setting time of 60 minutes for 42.5R PLC, ASTM C150 [30] recommends a minimum of 45 minutes for the initial setting time and a maximum of 375 minutes for the final setting time. The setting time findings (Figure 2) indicate that each percentage replacement (PLC/ALA) met the minimum initial time and maximum final time requirements outlined by ASTM C150 [30].

c. Workability of fresh concrete

The results of the initial HPC slump test and compacting factor test are shown in Figures 3 and 4. Figure 3 illustrates that slump height decreases as the percentage of ALA relative to cement weight increases, indicating reduced workability with higher ALA content. Similarly, the compacting factor value follows the same trend as the slump behavior. This is likely due to the porous nature of almond leaf ash particles, consistent with findings by Gabrijel, Rukavina, and Štirmer (2021), as well as Haambozi [31]'s research on the effects of wood fly ash and rice husk ash on concrete workability.

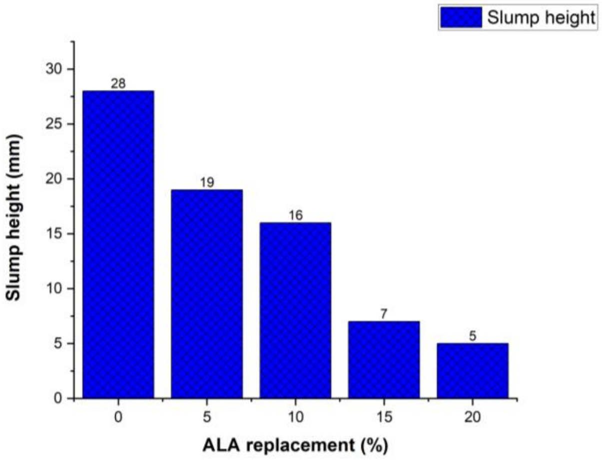


Fig 3. Slump Height against PLC/ALA

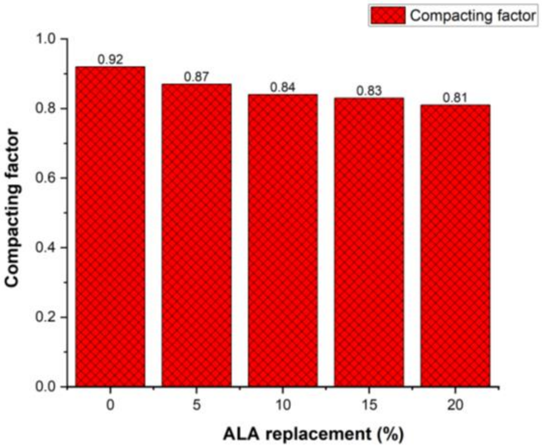


Fig 4. Compacting Factor against PLC/ALA

d. Density, strength properties and micrographs

i. Density of fresh concrete

Table 3 displays the average densities of the ALA-HPC cubes.

Table 5: Summary of Mean Density of Concrete Cubes

Replacement	Mean Density (kg/m^3)		
	7 Days	28 Days	56 Days
0% ALA	2460	2520	2586
5% ALA	2475	2570	2571
10% ALA	2451	2455	2500
15% ALA	2385	2391	2442
20% ALA	2310	2363	2390

The densities of the HPC-ALA cubes fall between 2310 and 2586 kg/m^3. These fall within the required density stipulated for structural concrete by BS EN 12390-7 [32]. As the proportion of ALA increased, the densities of the concrete declined.

ii. Strength properties

Figure 5 illustrates the ALA-HPC values for compressive strength measured at 7, 28, and 56 days. On the seventh day, the compressive strength assessments reveal that both the control and 5% ALA mixtures surpass the minimum threshold of 36 N/mm² for concrete grade 50. However, the strength of mixtures containing 10%, 15%, and 20% ALA falls below this requirement stated by BS 8110-2 [33]. Similarly, at the 28th day of curing age, the control and 5%ALA compressive strengths fulfil the least requirement of 50 N/mm^2 for concrete grade 50 as prescribed by BS 8110-2 [33], however, the strengths of 10, 15, and 20% ALA fall short of the necessary strength.

By the 56th day of curing, both the control and 5% ALA specimens exhibit compressive strengths surpassing the desired target mean strength of 56.56 N/mm². In contrast, the compressive strength of the 10% ALA specimen meets the target characteristic strength of 50 N/mm². However, the compressive strengths of the 15% and 20% ALA specimens fall short of both the target mean strength and characteristic strength. The findings demonstrate that concrete's compressive strength increases with curing age, with the 5% ALA blended concrete achieving the maximum strength at 56.82 N/mm². At 5%, the ALA likely provides the ideal amount of silica and other pozzolanic materials, which react with calcium hydroxide in the cement paste to form additional calcium silicate hydrate (C-S-H), thereby enhancing strength. These results corroborate earlier research indicating that there is an optimal percentage for pozzolanic material addition to maximize concrete strength [34].

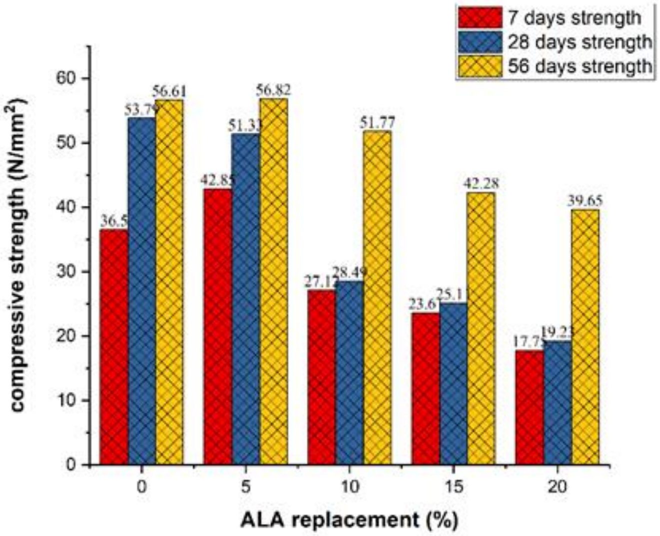


Fig 5. Compressive Strength against ALA-HPC

Figure 6 presents the split tensile strength results for GCHA-HPC following 7, 28, and 56 days of curing. In line with the observation regarding compressive strength, the results depicted in Figure 6 indicate a positive correlation between split tensile strength and curing duration. Furthermore, it is noted that following 56 days of curing, a 5% ALA concentration resulted in the highest splitting strength. Nevertheless, while the splitting strength demonstrates an increase with the ALA percentage up to 5% after 56 days of curing, it subsequently diminishes with further increments in ALA concentration.

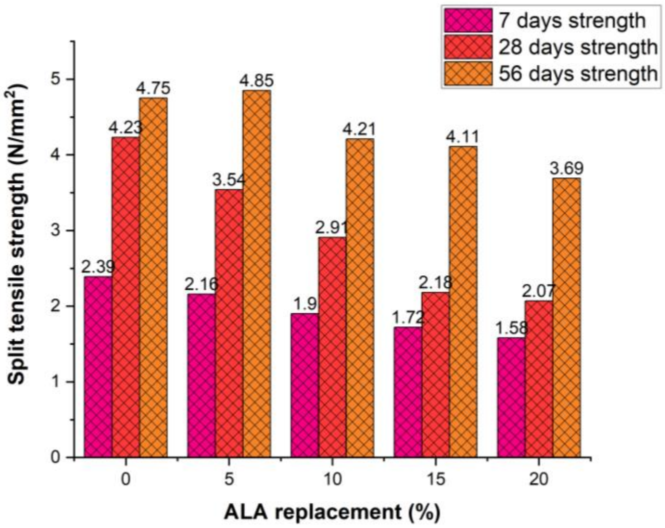
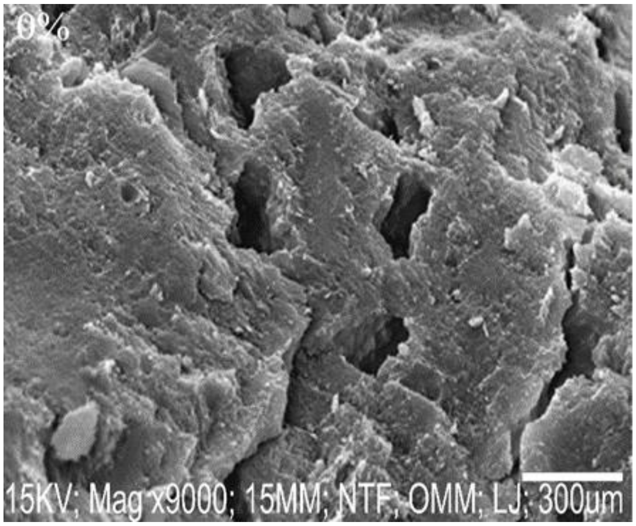


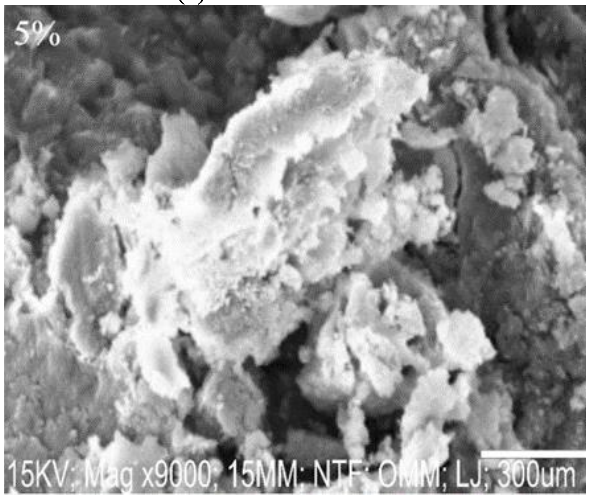
Fig 6. Split Tensile Strength against ALA-HPC

iii. Microstructure of HPC

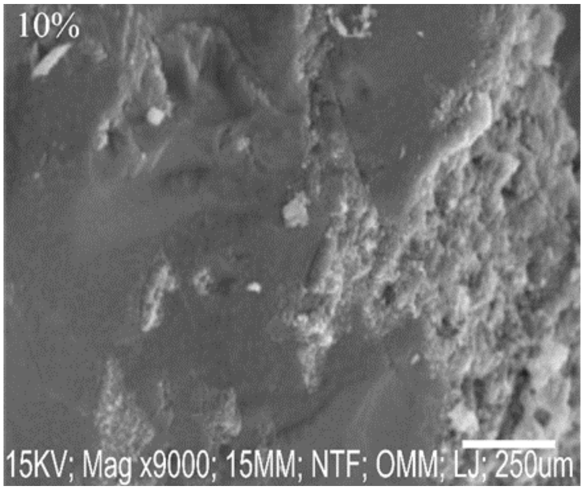
The SEM images were assessed and displayed in Figures 7a-e.



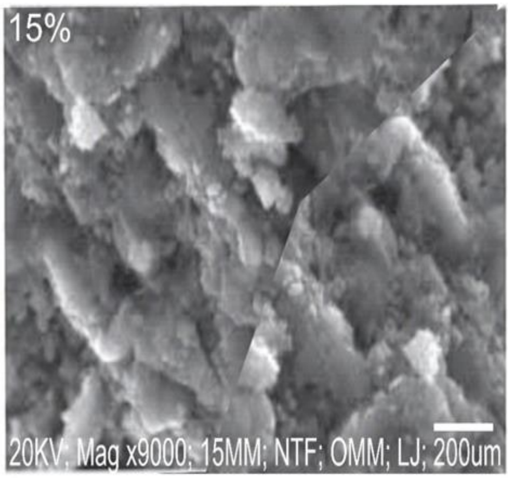
(a) 0% ALA Inclusion



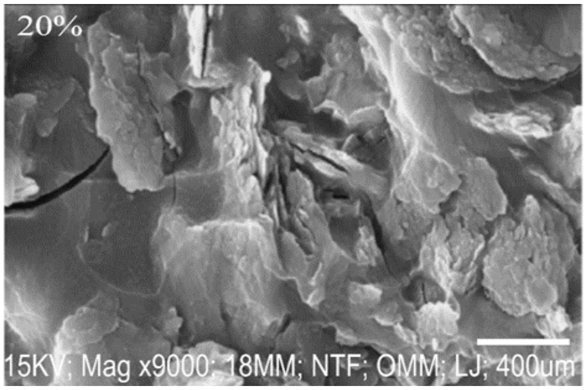
(b) 5% ALA Inclusion



(c) 10% ALA Inclusion



(d) 15% ALA Inclusion



(e) 20% ALA Inclusion

Fig 7. SEM Images of PLC-ALA HPC

Based on the SEM images displayed in Figure 7, it is observed that the addition of 10% ALA resulted in the most uniform dispersion of fillers. However, when the ALA content exceeds this level, the resulting composite exhibits numerous distinct grains and occasionally exhibits weak interfaces. These weak interfaces could potentially compromise the overall mechanical properties of the composite due to inadequate bonding. Therefore, it is expected that the inclusion of ALA will influence the mechanical properties of the composite, with optimal outcomes achieved at a 10% ALA content after 56 days of curing. The enhanced qualities observed at this ALA content level may be attributed to the crack deflection or hindrance provided by ALA fillers. Consequently, the SEM findings align with the outcomes of compressive, flexural, and split tensile strength tests, indicating that the optimum performance of PLC-ALA HPC occurs when ALA is utilized as a substitute for PLC up to 10%.

IV. CONCLUSIONS

The research findings can be summarized as follows:

i. The silicon dioxide (SiO_2) content of the ALA is highest among the oxides present, aligning with expectations for supplementary cementing materials. Results for specific gravity, fineness modulus, fineness, standard consistency, and setting time of the materials adhere to standards set by ASTM C150/C150M (2021), ASTM C 618 (2014), and ASTM C494 (2019).

ii. Increasing the percentage of ALA in fresh concrete leads to decreased workability, making it stiffer and less usable.

iii. Concrete strength at 10%, 15%, and 20% ALA content falls below the required levels. However, on the 28th day, the compressive strength of the control and 5% ALA mix meet the minimum requirement of $50N/mm^2$ for concrete grade 50. Furthermore, their compressive strength surpasses the target mean strength of $56.56\ N/mm^2$ by day 56. The compressive strength of the 10% ALA mix reaches the intended target of $50N/mm^2$ for characteristics strength. Conversely, the strength of mixes containing 15% and 20% ALA falls short of the intended target.

iv. For the production of HPC, replacing 5% of Ordinary Portland Cement with ALA by weight is optimal.

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