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Exploratory Analysis on the Physical and Microstructural Properties of Aluminum/Fly-Ash Composite

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ABSTRACT

Metal Matrix Composite (MMC) is an innovative material that has the ability to address demands in a number of industries, including mining, automotive, and aerospace. Stir casting is a well-known technique for making MMC. With weight fractions of 10%, 20%, 30%, and 40%, this study aims to analyze the impact of fly ash addition on the physical properties of aluminum (matrix) - FA (reinforcing phase) composites. The test for water absorbent was carried for each samples at 25°C immersed in water at different time interval of 24hrs, 48hrs, 72hrs, and 96hrs. The density test was carried out on the AL/FA composite samples. The water absorption test results showed that at 20wt% of fly ash composite, the optimum water absorption (0.4%) result was obtained at 24hrs, and also at 48hrs for 10wt%. The density of the composites increased with increasing amount of fly ash, and attained optimum of 4.08g/cm³ at 30wt%. The surface morphology of the samples was observed using digital metallurgical microscope. The scope of this study is to determine the physical and morphological properties of Al/FA reinforced composites.

INTRODUCTION

Generally, in the field of engineering and materials research, the quest for novel and advanced composite materials continues to drive research endeavors. Aluminum being one of the most often utilized metals, is also one of the most commonly discovered compounds in the crust of the earth. Owing to these features, aluminum is widely regarded as a harmless substance. (Lenntech, 2019). An aluminum-matrix composite, like other composites, is a family of materials whose stiffness, strength, density, and electrical and thermal properties may all be customized. Notwithstanding these differences, aluminum composites have the following benefits: they are non-flammable, have low fuel and solvent attack, high shear strength, excellent abrasion resistance, high temperature operation, and can be formed and treated using non-traditional equipment. (Gopalakrishnan & Vishnu Raj, 2023). Fly ash, a byproduct of coal combustion, possesses intriguing properties, and when strategically combined with aluminum, offers a unique avenue for material innovation. It is widely available in thermal power plants and is both low-cost and low-density, it has the potential to be used in discontinuous dispersions in MMCs. In addition to improving hardness, wear resistance, stiffness, damping characteristics, and density reduction in AL alloys, the inclusion of fly ash particles as reinforcement offers numerous advantages for achieving high structural homogeneity in aluminum composites. The economic feasibility of using FA as a waste material and its creative application have made it an appropriate reinforcement material for Al alloys. Additionally, the small particle size (45µm) of FA contributes significantly to the characteristics of AMCs. (Basheer, 2021). Several production techniques, including stir casting, powder

metallurgy, and the infiltration method, are used to fabricate MMCs. Nonetheless, because of its ease of use, affordability, and capacity to create intricate shapes, stir casting has been the method of choice for most academics. Because it is more economically feasible and has greater potential for integration into the current casting process for the creation of Metal Matrix composites, this method is utilized more frequently than powder metallurgy (Aluminum composite). It is introducing a discontinuous phase of reinforcement (fly ash) into a liquid continuous phase of the metal matrix (aluminum). The molten metal can be formed into many molds of the required shape by using traditional casting. Fly ash must be optically incorporated into the aluminum matrix in order to improve the characteristics of aluminum composites. (Emekwisia, *et al.*, 2024). This study therefore aims at exploring the physical and microstructural properties of Aluminum/Fly-Ash composite, to understand the the response of fly-ash on Aluminum composite.

LITERATURE REVIEW

Numerous methods for fabricating composites have been documented by (Morsi, 2023). He pointed out that tight contact between the fly ash and the aluminum is necessary to achieve interfacial bonding between the reinforcing phase and the matrix. The matrix frequently exhibits a strong propensity to flow in the direction of the reinforcement during the composite's developing stage; this behavior is comparable to that of a liquid flow. Wettability is one of the main ideas in the touch. When sufficient wetting of the aluminum on the fly ash particles results in the formation of an intimate contact between the aluminum and the fly ash, bonding takes place. (Basheer, 2021). Rao *et al.*, (2016) conducted an investigation

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into the mechanical characteristics and water-absorbing behavior of a hybrid epoxy thermoset composite that was made by cold pressing and mercerized using coir and sisal reinforcement. The degree of reinforcement in the composite varied between 10% and 50%. For matrix preparation, epoxy resin AW 106 and hardener HV 953 were utilized. It was discovered that as the fiber content rose, so did the amount of water absorbed. The greatest values for tensile strength and flexural strength for 40% Sisal/Coir composite were 48.2 MPa and 76.68 MPa, respectively. In order to manufacture composites by hand layup technique, Thawait *et al.* (2016) used AW 106/HV 953 resin in combination with *Musa acuminata*, also known locally as banana fiber. After drying and cutting the fibers into lengths of 10, 15, and 20 mm, they were formed into a mold and compressed for 24 hours by 50 kg of weight. The findings demonstrated an increase in the maximum water absorption, tension property, and impact energy at 15% and 20% of mass, respectively. Shanmugasundaram, *et al.*, 2011 conducted research on the use of fly ash in combination with pure aluminum to create composites through a two-phase stir casting process. They demonstrated that when the amount of fly ash reinforcement increased, the density of the aluminum composites decreased. An increase in the fly ash content of these composites led to a rise in their mechanical characteristics, including micro hardness. Hybrid aluminum copper alloy composites with varying weights of fly ash and Sic particles were created by (Mahendra & Radhakrishna, 2007). Fluidity, hardness, density, impact strength, and other mechanical characteristics of the hybrid composite were examined. The findings indicate that as particle content increases, so do hardness, impact strength, and other mechanical parameters. On the other hand, when fly ash and Sic content rise, the density falls. Kesavulu, *et al.* (2014) conducted an investigation into the characteristics of aluminum fly ash metal matrix composite. The mechanical and physical properties of the MMC were examined at different amounts of fly ash addition, and aluminum clad and fly ash chemical analyses were performed both before and after mixing and forming as particulate metal matrix composite. Singh, *et al.* (2022) investigated the physical properties of aluminum composites reinforced with varying percentages of fly ash. It revealed that as the fly ash content increased, the composite's density decreased due to the lower density of fly ash compared to the aluminum matrix. This property is advantageous for applications requiring lightweight materials. Also, the hardness of the aluminum composite improved with the addition of fly ash, attributed to the hard nature of fly ash particles, which contribute to the composite's resistance to deformation. Sharma and Gupta (2021) explored the wear resistance of aluminum/fly-ash composites. The study concluded that the incorporation of fly ash particles significantly enhanced the wear resistance of the aluminum matrix. This improvement was due to the hard particles of fly ash creating a wear-resistant surface, which reduced material loss during

wear testing. Patel *et al.* (2023), in their study, investigated the microstructure of aluminum composites reinforced with fly ash using scanning electron microscopy (SEM). The micrographs showed a homogeneous distribution of fly ash particles throughout the aluminum matrix, which is essential for ensuring uniform mechanical properties across the composite. The study also noted strong interfacial bonding between the aluminum matrix and fly ash particles, which is crucial for effective load transfer and enhanced mechanical properties. The grain refinement effect of fly ash in aluminum matrices was analyzed by Kumar and Rao (2022). Their research demonstrated that the introduction of fly ash particles led to a finer grain structure within the aluminum matrix. This refinement occurs because fly ash particles act as nucleation sites during the solidification process, resulting in a more refined and uniform grain structure. This finer grain size enhances the strength and hardness of the composite through the grain boundary strengthening mechanism. Razzak *et al.* (2017) used aluminum fly ash (FA) particle reinforced composites (AA6063-FA) in the automotive and aircraft industries because to its low density and excellent mechanical properties. Three different weight fractions of FA—2%, 4%, and 6%—were added to the AA6063 alloy using the compo casting method. FA particles significantly improved the microstructure and compressive strength of AA6063-FA composites. Micrographs taken with a Field Emission Scanning Electron Microscope (FESEM) showed that the FA particles in the AA6063 alloy were evenly distributed. As the amount of FA is added, the density of AA6063-FA composites falls. Through systematic experimental investigations, this research aims to unravel the intricacies of the Al/fly-ash composite. The study will involve the analysis of the material's physical and microstructural properties. Such a multifaceted approach is essential for gaining a holistic understanding of the composite's capabilities and limitations. This holds a practical implications for various industries as the findings may have applications in fields ranging from construction and aerospace to energy and environmental remediation (Hijazi *et al.*, 2024).

MATERIALS AND METHODS

The materials and equipment used includes; Aluminum alloy, which was gotten from scraps of aluminum window frames and later supplemented with ingots of Aluminum AA6061, Aluminum foils, Fly Ash, Silica sand, Calcium carbonate powder, Water, Gloves, Sand crucible, furnace, draw spikes, clamps, rammer, shovel, brush, trowel, Stirring rod, Crucible, Ladle, Engine oil, Ingots, Airtight container, Weighing balance, Vernier-caliper, Ruler, Weighing balance. Microstructural observation were conducted with these materials: 2.5ml Nitric acid (HNO₃), 1.5ml Hydrochloric acid (HCL), 1ml Hydrogen fluoride (HF), 95ml distilled water, the beaker, the Applicator or brush, the gloves and the eye goggles.

Preparation of the mold

Silica sand and Calcium Carbonate (CaCO_3), used as binding agent, was mixed together with water, to strengthen the sand and enable plasticity which make the aggregate suitable for molding. Sand molding are relatively inexpensive and give accuracy.

Steps in mold making

1. Place a pattern in the drag, then fill up with sand and compact together, using a Rammer.
2. Fill the cope with sand and compact together with the aid of a Rammer.
3. Add sand and the pattern to a gating system.
4. Withdraw the Pattern.
5. Melted metal should be poured into the mold cavity once the cope and drag are clamped.
6. The metal was permitted to cool and harden.
7. The metal cast was extracted and the sand mold was split into individual forms.

Setting up of the furnace for melting.

1. Gathering the Aluminum: The aluminum scraps were gathered and the impurities removed from the body by peeling them off.
2. Setting up the Furnace: The furnace were set up by putting charcoal under it and set it lit after heating it up to a suitable temperature.
3. Preheating: The crucible were put inside the furnace, with other apparatus used for the melting, in order to preheat.
4. Setting up the Blower: The blower was set beside the furnace to blow hot air and condemn oil through the ducts into the furnace.
5. Melting and pouring of the Aluminum Mold: The aluminum sheets were poured inside the furnace, and allowed to heat up to 700°C and then scooped from the furnace with a ladle and poured inside the mold through the runner and it came out from the riser.

Heat treatment process

Prior to casting, the aluminum sheets were subjected to heat treatment for grain refinement, and optimizing the properties for composite fabrication. Fly-Ash as bolster (reinforcement) underwent a thermal treatment process to reduce carbon content and enhance its pozzolanic reactivity. Mechanical milling was employed to achieve a consistent particle size distribution, promoting uniform dispersion in the aluminum matrix.

Stir casting process

Using mechanical stirring, the fly ash was combined with the molten metal matrix in this process. Through this procedure, it is possible to produce large-sized composites at a very low cost. The distribution of the reinforcing material, wettability, porosity of the cast composites, and the chemical reaction between the matrix and the reinforcement material are some of the important process characteristics during this procedure.

Using a stirring rod in a crucible that was still soaking at around 700°C , a mixture of 10%, 20%, 30%, and 40% weight fraction of fly ash were combined to create MMC using this technique. Aluminum was used as a matrix in this process.

Water absorption test

The purpose of this test was to ascertain how susceptible aluminum composite was to water penetration. When only one surface of the specimen is exposed to water, the increase in mass that results from water absorption is measured as a function of time. The initial weight value of the aluminum composite samples was determined by weighing them. After that, it was submerged in room temperature (25°C) water for 24 hours, and it was taken out at regular intervals (every 24 hours) for a total of 120 hours, during which time the samples had reached saturation. The samples were weighed on an automated weighing balance and dried with a lint-free cloth at each

$$\%W.A] = \frac{\text{Wet weight}-\text{Dry weight}}{\text{Dry weight}} \times 100 \quad (1)$$

removal point. The weight of the water absorbed was measured using this weighing scale. Using the expression below, the percentage water absorption (% W.A.) was calculated. (Emekwisia *et al.*, 2019);

$$\rho_c = \rho_{fa} + \rho_m = \frac{M_{fa}}{V_{fa}} + \frac{M_m}{V_m} \quad (2)$$

Density Test

This test was done for substance identification and understanding behavior in relationship to other objects. This expression was utilized to ascertain the density of the composite (ρ_c). (Emekwisia *et al.*, 2020); Using an electronic weighing balance, the masses of the FA (M_{fa}) and the Aluminum matrix (M_m) or control sample were first determined. It is also possible to calculate the mass of the aluminum matrix by subtracting the mass of FA from the aluminum reinforced composites (i.e. $M_c - M_{fa}$). Secondly, the volume of FA (V_{fa}) was determined with the aid of Graduating Cylinder. The cylinder was placed in a weighing balance at 0g, and the fly ash was weighed to give 3g (10%), 6g (20%), 9g (30%), and 12g (40%) respectively, and the volume of each gram of the fly ash was recorded, as $1\text{gm} = 1\text{cm}^3$. The volume of aluminum matrix (V_m) was determined by calculating the diameter (the length, breadth and height) of the composite. The values were entered into the expression for the composite density, and the density of the composite was calculated.

Mass Fraction Expression

The mass fraction is calculated by dividing the mass of one ingredient by the mass of the combination as a whole. It can also be stated as a percentage by mass with a denominator of 100. (Commonly referred to as percentage by weight, or wt%) in commercial contexts. Mass fraction (wt %) was determined with this expression;

$$Wt\% = \frac{m}{m_{total}} \times 100 \quad (3)$$

$$\text{For } 3g(W_1) \rightarrow Wt\% = \frac{W_1}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (4)$$

$$\text{For } 6g(W_1) \rightarrow Wt\% = \frac{W_2}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (5)$$

$$\text{For } 9g(W_1) \rightarrow Wt\% = \frac{W_3}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (6)$$

$$\text{For } 12g(W_1) \rightarrow Wt\% = \frac{W_4}{W_1 + W_2 + W_3 + W_4} \times 100 \quad (7)$$

Microstructure Observation

During microstructural experiment, the composite samples were cut into small sections with dimensions of 3mm using a low-speed angle grinder. After cutting, an intermediate and fine grinding was applied, which was carried out using emery papers of grades 220, 500, 800, 1200, and 2200 (from coarse to fine). After grinding, the samples were polished with aluminum oxide, which was placed on a lint cloth and each samples was rubbed on the paste (aluminum oxide mixed with little water). After polishing, the samples were rinsed in water and dried. The process of etching involved immersing the surface for around 20 seconds in the Keller's reagent (2.5ml (HNO₃), 1.5ml HCL, 1ml HF, 95ml of distilled water) and then dried. After which the samples were viewed using a metallurgical microscope at different magnifications. The photographs were taken with digital camera as shown in figures 4 - 8. materials and equipment used includes; Aluminum alloy, which was gotten from scraps of aluminum window frames and later supplemented with ingots of Aluminum AA6061, Aluminum foils, Fly Ash, Silica sand, Calcium carbonate powder, Water, Gloves, Furnace, Shovel, Brush, Trowel, Rammer, Riddle, Draw spikes, Clamps, Stirring rod, Crucible, Ladle, Engine oil, Ingots, Airtight container, Weighing balance, Vernier-caliper, Ruler, Weighing balance. The following items were used for microstructural observation: 2.5ml Nitric acid (HNO₃), 1.5 ml of Hydrochloric acid (HCL), 1 ml of hydrogen fluoride (HF), 95 ml of distilled water, the beaker, the applicator or brush, gloves, and eye goggles.

RESULTS AND DISCUSSION

Determination of mass fraction (%) of fly-ash composites.

$$\text{For } 3g(W_1) \rightarrow Wt\% = \frac{3}{3+6+9+12} \times 100 = 10\%$$

$$\text{For } 6g(W_1) \rightarrow Wt\% = \frac{6}{3+6+9+12} \times 100 = 20\%$$

$$\text{For } 9g(W_1) \rightarrow Wt\% = \frac{9}{3+6+9+12} \times 100 = 30\%$$

$$\text{For } 12g(W_1) \rightarrow Wt\% = \frac{12}{3+6+9+12} \times 100 = 40\%$$

Table 1: Mass Fraction of Each Al-FA Composite

Aluminum- Fly Ash Composites In (g)	Mass Fraction of AL-FA Composites (%)
3g	10%
6g	20%
9g	30%
12g	40%

Water Absorption Test Results

Table 2: Parameters for Percentage Water Absorption Determination (in gram)

Samples of Al-FA Composites (%)	Wet Weight Meno Mass (g)	Wet Weight (g) for 24 hours.	Wet Weight (g) for 48 hours.	Wet Weight (g) for 72 hours.	Wet Weight (g) for 96 hours.
10%	162.67	163.10	163.40	163.06	163.20
20%	163.96	164.59	164.07	164.30	164.30
30%	173.92	174.20	174.30	174.30	174.40
40%	162.30	162.63	162.53	162.60	162.70
0%	162.82	163.23	163.30	163.60	163.30

Table 3: Percentage Water Absorption of Al-FA Composites.

Samples of Al-FA Composites (%)	Wet Weight for 24 hours Mean mass(g)	Wet Weight for 48 hours Mean mass (g)	Wet Weight for 72 hours Mean mass(g)	Wet Weight for 96 hours Mean mass(g)
10%	0.3%	0.4%	0.2%	0.3%
20%	0.4%	0.1%	0.2%	0.2%
30%	0.2%	0.2%	0.2%	0.3%
40%	0.2%	0.1%	0.2%	0.3%
0%	0.3%	0.3%	0.5%	0.3%



Figure 1: Graph of Percentage Water Absorption of Al-FA Composites

The water absorption experiment was done with the goal of determining how much water was absorbed by each sample while using various grams of fly ash in the aluminum composite samples. Room temperature was utilized for this test. Figure 1 displayed the rate of water uptake for each aluminum composite sample. The mass fluctuations of each sample were monitored during the conduct of this experiment. This is accomplished by recording the mass variations of the sample every hour beginning with its immersion in water and continuing until the sample's mass remains constant.

The results demonstrate that the aluminum composite containing 20% and 10% fly ash exhibited a significant degree of water uptake at 24 and 48 hours, respectively. The samples containing 20% and 40% fly ash absorbed the least water after 48 hours, with a percentage of 0.1%

for each sample relative to the total mass absorbed. The sample containing pure aluminum absorbed the most water after 72 hours, or 0.5%. The samples containing 10%, 20%, and the pure aluminum control at 96 hours all absorbed the same amount of water, or 0.3%. These results go counter to the original ideas, which predicted that larger fly ash levels would result in greater water reduction. This demonstrates that the rate of water absorption is not significantly impacted by the presence of fly ash. However, because there is very little difference in the percentage of water absorbed between each sample with a varied proportion of water, the result is regarded as inconsequential. In theory, samples containing a greater fly ash content should absorb less water.

Density Test Results

Table 4: Density of Composite.

Mass of Fly Ash (g)	Volume of Fly Ash (cm ³)	Density of Fly Ash(g/cm ³)	Density of Al matrix (control). g/cm ³	Density of the Composite (g/cm ³)
(g)	Ash (cm ³)	Ash (g/cm ³)	(control). g/cm ³ x (control). g/cm ³	Density of the Composite (g/cm ³)
3g(10%)	2.5	1.2	2.48	3.68
6g(20%)	4.0	1.5	2.48	3.99
9g(30%)	5.5	1.6	2.48	4.08
12g (40%)	8.0	1.5	2.48	3.99

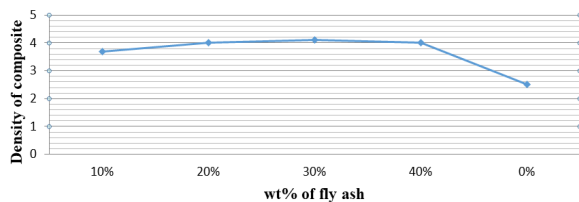


Figure 2: Variations of Density among the AL-FA Composites.

The density investigation examined several Al/Fly-Ash composite compositions. The densities of all the composites increased. As the weight of the fly ash particles grew, so did the density of the composites. At 30 wt% fly ash, the optimal density (4.08g/cm³) was attained; at 0wt% fly ash, it declined. This demonstrated that the fly ash particles had a notably better impact on the aluminum composite as a whole.

Result of Microstructural Analysis

Using an L2003A metallurgical optical microscope, the composite's microstructural investigation was carried out; the results are shown in Figs. 3–7. The composite samples' photo-micrographic components were examined and analyzed. The distribution and

morphology of the aluminum matrix within the fly-ash particles, as well as the composite's structural properties, particle size distribution, and interfacial bonding, were all disclosed by the microstructure of the composites. In the process of strengthening it with the solution, the primary reinforcement (FA) partially dissolved in the aluminum solution and partially created inter-metallic phases with aluminum. The microstructure displayed extremely homogenous tiny grain. It is composed of precipitates of inter-metallic phases crystallizing mostly as eutectic dispersed in inter-dendritic regions and dendrites of Al solid solution. Al solid solution strengthened the major reinforcement FA, which partially dissolved in it and partially formed inter-metallic phases with aluminum.

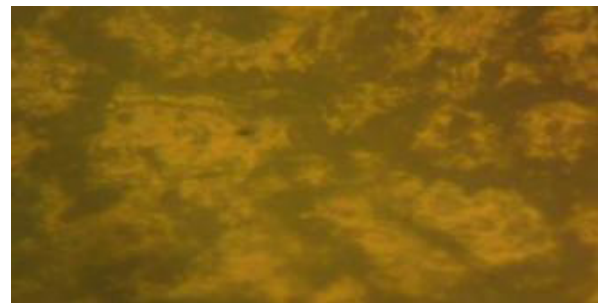


Figure 3: Al - 0%wt of fly-ash

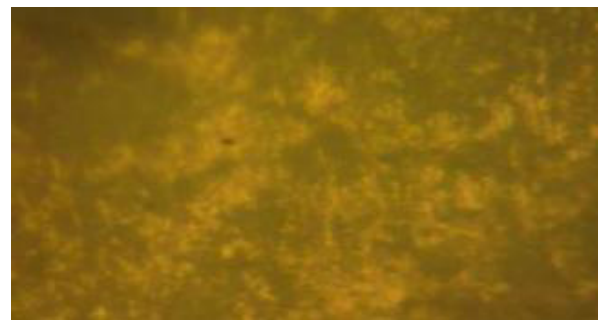


Figure 4: Al - 0%wt of fly-ash

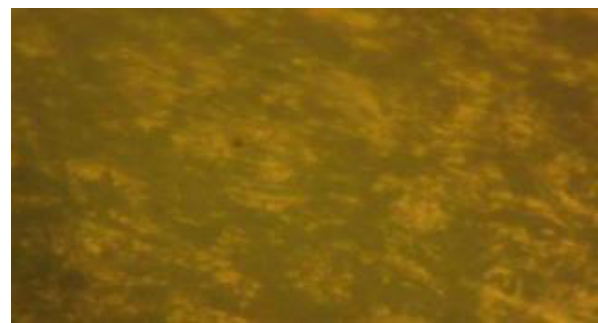


Figure 5: Al - 0%wt of fly-ash

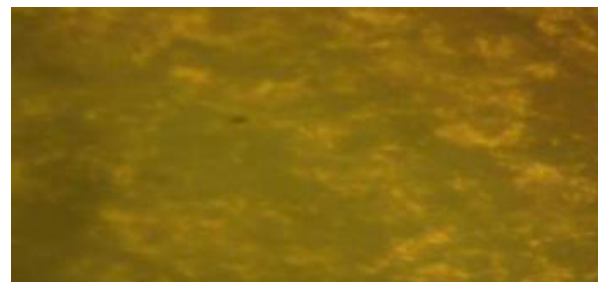


Figure 6: Al - 0%wt of fly-ash



Figure 7: Al - 0%wt of fly-ash

CONCLUSIONS

This study delved into the behavior of Al/Fly-Ash composites, providing a deeper understanding of their capabilities. By utilizing the stir casting approach, various Al-fly ash composites were successfully produced. Impressively, up to 40 weight percent of fly ash was incorporated into the Al matrix, showcasing a strong bond between the reinforcements and a uniform distribution of fly ash particles within the matrix. The water absorbency test yielded favorable results, with the best performance seen at 24 hours for the 20 weight percent composite and at 48 hours for the 10 weight percent. Interestingly, the control sample had the highest water uptake after 72 hours, while the 20wt% and 40wt% composites showed the lowest uptake after 48 hours. As fly ash content increased, so did the density of the composites, reaching an optimal level of 4.08g/cm³ at 30wt%. These findings align with previous research, highlighting the positive impact of incorporating organic reinforcement, specifically industrial waste like fly ash, on the physical properties of aluminum composites. This was further supported by the results of the microstructural study. Overall, this study emphasizes the potential of utilizing fly ash industrial waste to create lightweight composites, such as Al-FA composites, with wide-ranging applications in general engineering, automotive, defense, and military industries.

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