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Experimental study of artificial lightweight aggregates using coal fly ash and epoxy resin

Ani Firda[a], Anis Saggaff[b], Hanafiah[b] and Saloma[a*]

[a]Engineering Science Doctoral Program, Faculty of Engineering, Sriwijaya University, Indonesia
[b]Department of Civil Engineering, Faculty of Engineering, Sriwijaya University, Indralaya, Indonesia

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A B S T R A C T

A lack of natural aggregates in the future is unavoidable, which generates issues for building development. For many industries, natural resources constitute a significant source of revenue. As a result, light artificial aggregate is produced to anticipate the decreasing source of natural aggregate. Production of artificial geopolymer aggregates, fly ash from the burning of coal has been proposed. This paper investigates the optimal proportion of epoxy resin and coal fly ash-based synthetic aggregates. The artificial aggregates are produced following specific gravity and compressive strength standards that may be used as a component of lightweight structural concrete (LWC). The production polymer lightweight aggregate (PLA) comes from a combination of coal fly ash and epoxy resin. The results show that PLA 50:50 to PLA 74:26 can be used for 6 hours to make structural concrete with a strength of more than 17 MPa. PLA 80:20 could achieve compressive strength with the range of 7-17 MPa. PLA 84:16 achieves a compressive strength range of 0.35 to 7 MPa and is utilized as a non-structural element. However, the flexural strength values in concrete LWC 70:30 and LWC 80:20 are higher, at 46.1% and 7.63%, respectively.

1. Introduction

In 2020, the demand for aggregate in the worldwide construction market was about 55 billion tons. If the current consumption rates continue, the amount will double in the next ten years. Natural aggregates are in low supply due to the increasing demand, which causes problems for the development of building construction. Also, a lot of the original green environment were moved to the cities and modified due to the rapid growing of urbanization (Shang et al., 2022).

Materials like aggregate are widely used in many different sectors. Natural resources are a major source of income for many industries. As a result, the production of light artificial aggregate is to substitute the utilization of natural aggregate. Reducing and recycling industrial waste is currently one of the main concerns that must be addressed (Nor et al., 2016).

Various solid wastes have been transformed into artificial aggregates in recent years, an idea motivated by sustainability issues. Lightweight aggregate (LWA) is benefited from its low density, thermal insulation, and affordability. Two types of lightweight aggregate (LWA) can be distinguished: natural and artificial LWA. Natural LWA is often produced by the well-sintered process of a porous microstructure as molten lava from a low volcano temperature. In contrast, artificial LWA is produced through artificial sintering and made from three different types of waste such as natural resources, waste from household activity, and hazardous waste from industrial activity (Balapour et al., 2021; Balapour et al., 2022; Arriagada et al., 2019; Zhao et al., 2018; Franus et al., 2016).

* Corresponding author.
E-mail addresses: salomaunsri@gmail.com (Saloma)

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Concrete technology offers solutions for efficiently converting industrial waste, even if it is harmful. Numerous studies have been done, but significant gaps exist in applying a cementitious material to replace the cement. However, academics and experts have begun considering the waste material from the industry in producing artificial lightweight aggregates as a potential strategy for increased usage (Vali & Murugan, 2022).

The replacement of natural aggregate is necessary due to decreasing natural aggregate supply due to the advancement of technology. Geopolymer artificial aggregate is produced by fly ash from industrial waste. Fly ash and alkaline activator can be combined to create artificial aggregates. The alkaline activator such as NaOH and Na_2SiO_3 has an important role in binding the fly ash material, thus it produced artificial aggregates (Balapour et al., 2022; Adhitya et al., 2023; Fu et al., 2020; Xu et al., 2021; Risdanareni et al., 2020; Shivaprasad & Das, 2017; Saloma et al., 2016; Tomthong et al., 2021; Yomthong et al., 2021). Artificial aggregates can be produced using the crushing method or the pelletization method. Some variables affect the granulator pan in the pelletization method: the slope of the granulator pan, rotational speed, stirring time, and water content. These variables are changed to produce different artificial aggregates. While the granulator is mixing the constituent material, the alkaline activator is sprayed. Finally, various curing techniques are used to complete the curing process (Adhitya et al., 2023; Xu et al., 2021; Karyawan et al., 2019).

Nevertheless, this technology results in significant energy use, a long production process, and significant pollutants (Nor et al., 2016). Hence, an eco-friendly production process is required for creating artificial aggregates, especially when employing waste products like recovered solid waste and excess powder or ash (Shang et al., 2022; Shi et al., 2019). Polymer materials for producing artificial aggregates, like epoxy resin, are utilized as an alternate material. Few prior researchers have employed resin to create artificial aggregates. However, the resin is extensively used as a composite material for automobiles, sports equipment, and electrical components (Sim et al., 2020).

According to a study by Firda et al. (2021), fly ash combined with resin can replace coarse aggregate. Fly ash and resin, in the proportion of 40% resin to 60% fly ash to the total weight, were used as the primary constituents in the lightweight aggregates used as the basis for this research. The sieve analysis results show that the aggregate has a 20 mm maximum in size and the gradation of the proposed aggregate was gravel type. The aggregate also has 1891 kg/m^3 for the specific gravity and the compressive strength was 6.85 MPa.

In other research, epoxy resin and several types of fly ash were employed in producing artificial aggregates (Firda et al., 2023). The proportion of LWA were 70:30, 80:20, and 90:10 for the fly ash and epoxy resin ratio. The 70:30 LWA proportion shows a compressive strength with 18.60 MPa and a specific gravity of less than 1920 kg/m^3 as the lightweight concrete material. This lightweight concrete's specific gravity value satisfies the ASTM C-330 requirements for structural lightweight concrete compressive strength.

Conventional concrete has different amounts of water, aggregates, and cement and is thought to have lower tensile strength, be less brittle, and be more easily eroded by synthetic materials and faster-moving water. The need for structures that require the least maintenance and are more durable is becoming a persistent problem in today's society (Gagandeep, 2021). Concrete's limitations include low tensile strength, brittleness, and high specific gravity of 2200–2500 kg/m^3. Lightweight concrete has been suggested to have a low specific gravity.
This paper aims to investigate the ideal mix of artificial aggregates by combining epoxy resin and fly ash. The artificial aggregates proposed in this study need to fulfil specifications for specific gravity and compressive strength to be utilized as a component of lightweight structural concrete.

2. Experimental Programs

2.1 Materials

Coal fly ash (CFA) from PT. Pupuk Sriwijaya Tbk Palembang is the source of Polymer Made Lightweight Aggregate (PLA). The epoxy resin used is a grout-type resin with extremely low viscosity (super dilute), high strength, and solvent free. The standard follows the ASTM C 881 - 78 type I standards, Grade 1, Class B + C. The ultra-low viscosity (super diluted) epoxy resin utilized in this investigation consists of epoxy and a hardener (ERh). The CFA in this PLA combination has 2.72% CaO, 91.06% SiO_2, Al_2O_3, and Fe_2O_3 (Table 1). Class F fly ash is included in the CFA content based on the chemical substance that composes the CFA. Suppose the combination of SiO2 + Al2O3 + Fe2O3 exceeds 70% of the total mass and the percentage of limited calcium oxide (CaO) is less than 10%. In that case, fly ash is categorized as class F.

Table 1. Coal Fly-Ash (CFA) XRF Test Results

CHEMICAL ELEMENTS	COMPOSITION (%)	CHEMICAL ELEMENTS	COMPOSITION (%)
SiO_2	55.81	MgO	1.12
Al_2O_3	29.63	TiO_2	0.790
Fe_2O_3	5.62	K_2O	0.735
CaO	2.72	SO_3	0.376
Na_2O	2.55	P_2O_5	0.263

2.2 Production of Polymer Lightweight Aggregate (PLA)

The oven process of CFA is intended to remove the water content, which is the production phases of PLA start. The oven procedure took place at 110°C for 24 hours. After being dewatered, CFA is screened, and those that pass filter No. 200 are used as the raw materials for making PLA. The ratio of CFA to ERh of 50%: 50%, 60%: 40%, 70%: 30%, 74%: 26%, 80%: 20%, 84%: 16%, and 90%: 10% of the total aggregate volume was also taken into consideration when weighing CFA and Erh (Ferdous et al., 2020). The epoxy resin and hardener were mixed in the ERh at a 2:1 ratio and stirred for approximately three minutes.

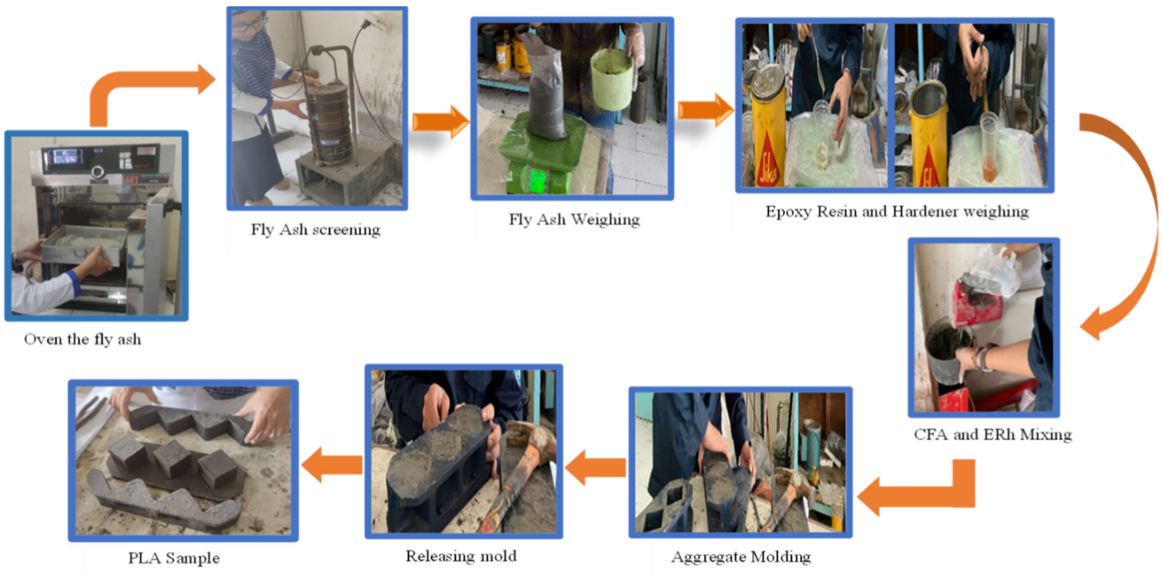

Fig. 1. The Process of Making PLA

2.3 Testing

PLA uses various mixing techniques and hardening time modifications for the best compressive strength. The tests were conducted on microstructure, specific gravity, and compressive strength for various PLA compositions. "PLA with the optimum composition" refers to PLA that satisfies the lightweight aggregate requirement as a structural lightweight concrete component. PLA with the best composition will have the highest compressive strength, lowest specific gravity, highest elemental content, strongest bonding between PLA constituent particles, and fastest setting time (Purnert et al., 2017).

3. Results and Discussion

3.1 Specific Gravity Results of PLA

The results informed that the proposed composition affects the specific gravity of PLA. However, the testing age shows no effect on the specific gravity of PLA. Fig. 2 shows the specific gravity test results of the PLA. PLA_50:50 has a specific gravity of 1451 kg/m^3.

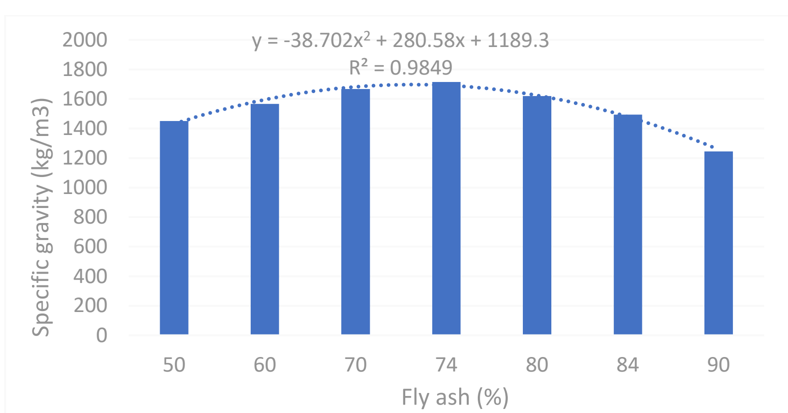

Fig. 2. The Relationship Between the Composition of Coal Fly-Ash and the Specific Gravity of PLA

When the number of CFA rises in the PLA, it also increases the specific gravity of PLA until it reaches PLA_74:26, which has a specific gravity of 1716 kg/m^3. In addition, the specific gravity of PLA decreases when the number of CFA in the PLA mixture rises, starting at PLA_80:20, which is 1621 kg/m^3, and keeps decreasing until it reaches PLA_90:10, which is 1245 kg/m^3.

There are three categories of concrete based on ASTM 621: low-density concrete, medium-strength concrete, and construction concrete. The specific gravity estimation and the classification of lightweight concrete aggregates are also shown in the following standard. The specific gravity results of PLA ranged from 1245 kg/m^3 to 1728 kg/m^3. According to Table 2, PLA_50:50 - PLA_86:14 satisfies the requirements for construction-grade concrete, although PLA_90:10 only satisfies those for medium-strength concrete.

Table 2. Classification of Test Results for Specific Gravity of Polymer Lightweight Aggregate (PLA)

Aggregate Code	Specific Gravity (kg/m^3)	Information
PLA_50:50	1451	Meets Standards For Construction Concrete
PLA_60:40	1568	Meets Standards For Construction Concrete
PLA_70:30	1668	Meets Standards For Construction Concrete
PLA_74:26	1716	Meets Standards For Construction Concrete
PLA_80:20	1621	Meets Standards For Construction Concrete
PLA_84:16	1494	Meets Standards For Construction Concrete
PLA_90:10	1245	Meets Concrete Standards With Medium Strength

3.2 Compressive Strength Results of PLA

The compressive strength test of PLA used a cube-shaped aggregate sample 50x50x50 mm in size. It has 15 compositions with CFA:ERh ratios of 50%:50%, 60%:40%, 70%:30%, 74%:26%, 80%:20%, 84%:16%, and 90%:10% of the total aggregate volume. According to ASTM guidelines, tests were performed using compressive strength testing equipment with a 1000kV capability. The compressive strength test was conducted when the aggregate was older than one day (24 hours), specifically when it was older than six, twelve, and 24 hours. Additional tests were also conducted when the aggregate was older than three, seven, fourteen, twenty-one, and thirty days as the age of tests conducted on concrete.

Fig. 3 illustrates how the PLA mixture's composition and the PLA test's age affect the PLA's compressive strength. With a test age of 28 days, PLA_50:50 achieved the maximum compressive strength value of 85.33 MPa. Whereas PLA_90:10, with a test life of 6 hours, achieved the lowest compressive strength result, which is 0.00 MPa. A compressive strength test at PLA_90:10 with a test age of 6 hours was not practicable because, at 6 hours, the aggregate had not fully hardened. When the test was conducted, the PLA aggregate had already been segregated. The results show that the compressive strength of PLA will decrease as the CFA concentration in the PLA mixture increases.

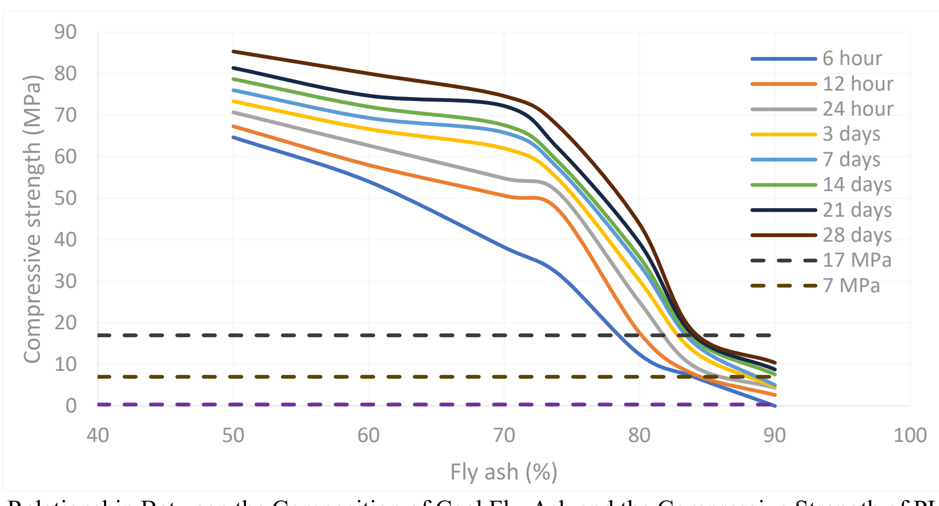

Fig. 3. The Relationship Between the Composition of Coal Fly-Ash and the Compressive Strength of PLA For Each Hardening Time

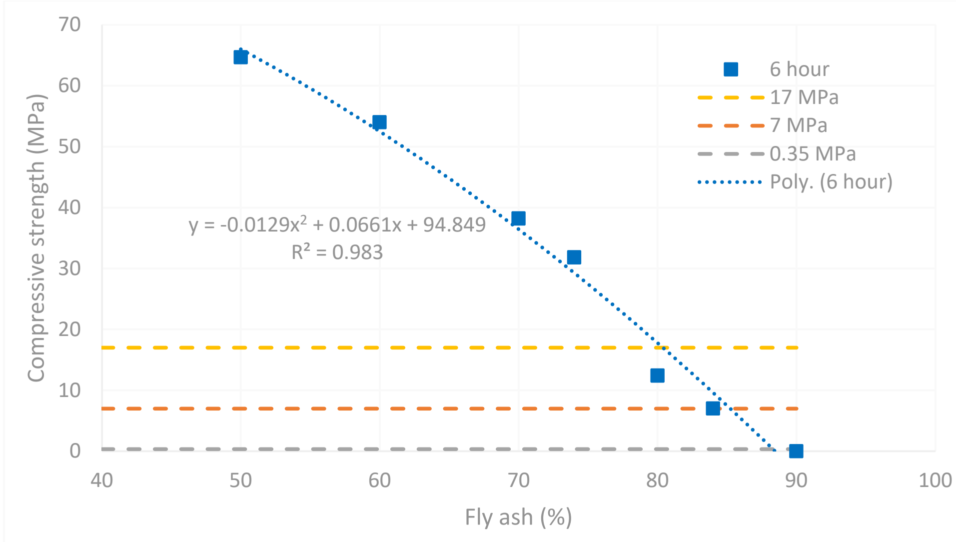

Fig. 4. The Compressive Strength Test Results of PLA After 6 Hours of Hardening Time

Fig. 4 shows that the PLA samples with the highest average compressive strength test results at 6 hours of testing were PLA_50:50 with 64.67 MPa, while the PLA samples with the lowest were PLA_90:10, which measured 0 MPa. According to the test results, PLA_50:50 to PLA_74:26 may be utilized as aggregate for structural concrete in the 6-hour age test. Both PLA_84:16 and PLA_80:20 can be used as aggregates in lightweight non-structural concrete. PLA_80:20 can be utilized as an aggregate in lightweight structural concrete. PLA_90:10, on the other hand, falls short of the requirements for usage as a lightweight aggregate.

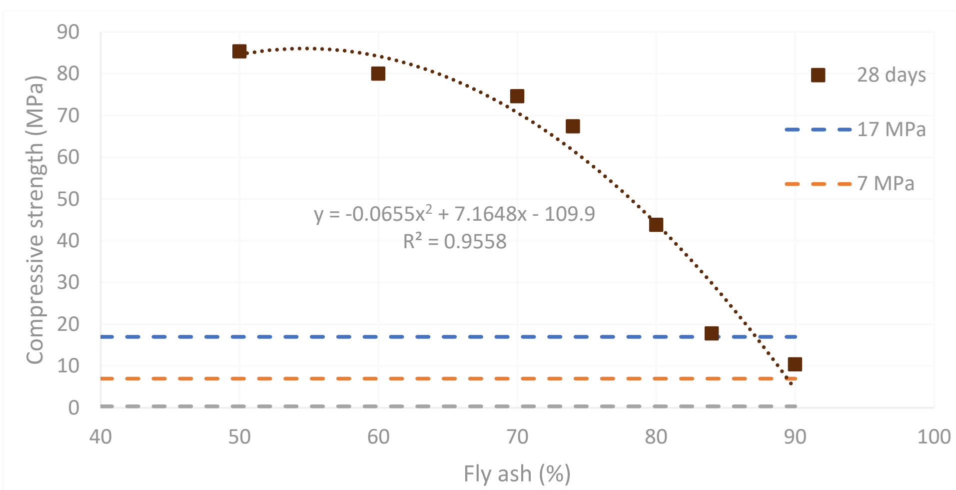

Fig. 5. The Compressive Strength Test Results of PLA After 28 Days of Hardening Time

Fig. 5 shows that at 28 days, PLA_50:50 achieved the greatest average compressive strength test result, 85.33 MPa, and PLA_90:10 obtained the lowest, 10.40 MPa. According to the test findings, PLA_50:50 to PLA_84:16 may be used as an aggregate for structural concrete, whereas PLA_90:10 can be used as an aggregate for lightweight concrete constructions.

3.3 Determination of the Optimum Composition of PLA

In general, the grouping of aggregates based on the designation of PLA in the usage of lightweight concrete may be formed based on the results of testing the specific gravity and compressive strength of PLA on various compositions and ages of testing, namely:

1) For non-structural uses, often used for separating walls or isolation walls; specific gravity ranges from 240 kg/m^3 to 800 kg/m^3, and compressive strength ranges from 0.35 to 7 MPa.

2) For lightweight buildings, they are often used for walls that also transport loads, with specific gravities of 800 kg/m3 to 1400 kg/m^3 and compressive strengths of 7 to 17 MPa.
3) It is also utilized as normal concrete for constructions with specific gravities between 1400 and 1800 kg/m^3 and compressive strengths of more than 17 MPa.

Based on Table 3, it is shown that PLA_50:50, PLA_60:40, PLA_70:30, and PLA_74:26 have specific gravities between 1400 and 1800 kg/m^3 and compressive strengths greater than 17 MPa at each test age ranging from 6 hours to 28 days. It shows that the specimen is suitable for a mixture of concrete structural applications with normal concrete in general. At 6 hours of testing, PLA_84:16 had 1400–1800 kg/m^3 for its specific gravity and compressive strength of 0.36–7 MPa. At 12 hours of the test, the concrete's compressive strength continued to rise until 21 days, when it reached 7–17 MPa in compressive strength. At 28 days of testing, the compressive strength exceeded 17 MPa.

It is visible from the compressive strength test results that PLA_84:16 may be utilized as a combination for structural concrete, lightweight structural concrete, and non-structural concrete. A compressive strength test cannot be performed on PLA_90:10 since it does not have a firm texture after 6 hours of testing and has a specific gravity of 800 to 1400 kg/m^3. The concrete compressive strength continues to rise until 28 days. The compressive strength of PLA_90:10 ranges from 7 to 17 MPa in the 24-hour, and in 7 days, it ranges from 0.36 to 7 MPa. According to the compressive strength test results, PLA_90:10 may be used to make non-structural concrete. However, it cannot be utilized to make structural concrete.

Table 3. Determination of OptimumLevels of PLA

Sample of PLA	Specific Gravity (kg/m3)	Compressive Strength (MPa)							
		6 hour	12 hour	24 hour	3 days	7 days	14 days	21 days	28 days
PLA_50:50	1451	64.67	67.33	70.67	73.33	76.00	78.67	81.33	85.33
PLA_60:40	1568	54.00	58.00	62.67	66.67	69.33	72.00	74.67	80.00
PLA_70:30	1668	38.20	50.60	54.80	62.00	65.80	67.60	72.20	74.60
PLA_74:26	1716	31.80	47.20	51.40	54.60	57.20	58.80	62.00	67.40
PLA_80:20	1621	12.40	17.60	25.00	30.20	34.00	35.80	39.20	43.80
PLA_84:16	1494	7.00	7.68	9.60	13.20	15.20	16.20	17.00	17.80
PLA_90:10	1245	0.00	2.60	4.40	4.60	5.00	7.60	8.80	10.40

Note:

- Specific Gravity of PLA between 1400 - 1800 kg/m^3 for construction
- Specific Gravity of PLA between 800 - 1400 kg/m^3 for medium strength concrete
- Compressive Strength of PLA > 17 MPa for structural concrete
- Compressive Strength of PLA between 7 – 17 MPa for structural ligthweigth concrete
- Compressive Strength of PLA between 0.35 – 7 MPa for non structural concrete
- Compressive Strength of PLA < 0.35 MPa not for lightweight concrete mix

3.4 *PLA Microstructure Testing*

Scanning Electron Microscope (SEM) testing examined the PLA's microstructure. The results from SEM showed that the CFA particles remained whole and spherical according to the PLA_50:50 aggregate, indicating no chemical interaction between CFA and Erh. The ERh, both massive and microscopic particles, cover nearly every surface of the CFA particles, causing the CFA particles to connect.

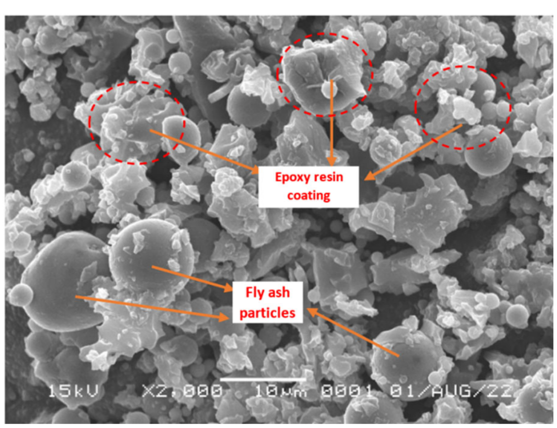

Fig. 6. PLA_50:50 SEM Test Results (2000x Magnification)

According to SEM results on PLA 60:40, CFA particles of different sizes all remained fully spherical and had not undergone any shape changes. It shows that CFA and ERh did not engage in a chemical reaction; instead, Erh envelops the CFA particles to enable them to attach. While the big CFA particles were only partially covered by Erh, preventing them from being totally bonded, the small-sized CFA particles were entirely covered by ERh, forming new, dense, massive particles.

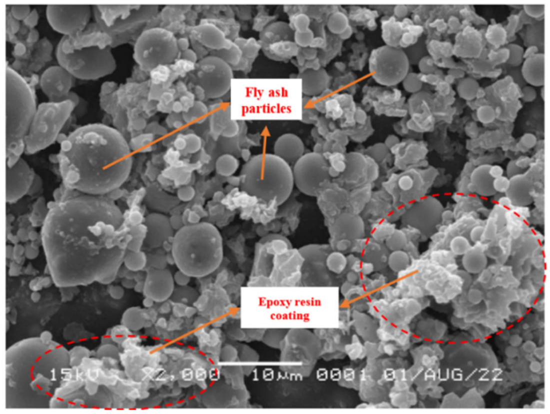

Fig. 7. PLA_60:40 SEM Test Results (2000x Magnification)

The SEM result of PLA 70:30 revealed that the ERh-coated CFA particles did not chemically react. The Erh solely covered the CFA particles so they could bind with one another. While the big CFA particles were only partially covered by ERh, preventing them from being totally bound, the small-sized CFA particles were entirely covered by ERh, forming new, dense, massive particles.

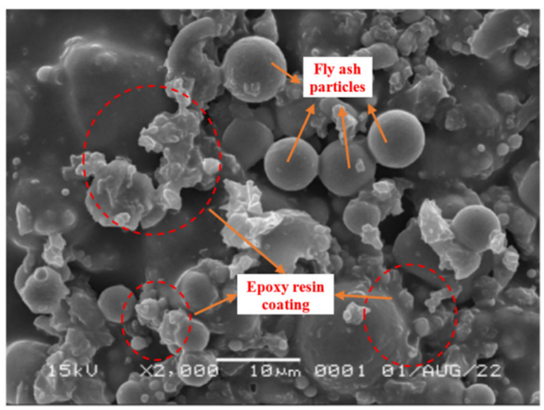

Fig. 8. PLA 70:30 SEM Test Results (2000x Magnification)

The massive and micro CFA particles are only partially covered by ERh in the PLA 80:20 SEM test findings, leaving some CFA particles that are not connected. According to the SEM results of PLA 80:20, the ERh does not chemically react with the CFA. It just covers the CFA, so it connects with other CFA particles.

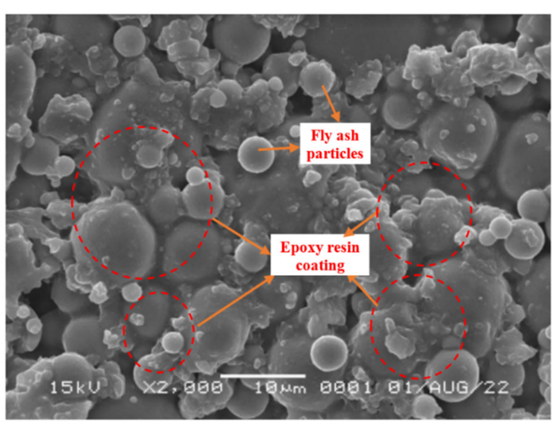

Fig. 9. PLA 80:20 SEM Test Results (2000x Magnification)

From the SEM test results, it was discovered that the ERh coating on CFA only occurred in small particles with modest quantities for aggregate microstructure morphology 90:10 (Fig. 10). Large fly ash particles are invisible, while ERh covers make them morphologically comparable to pure CFA's microstructure. This aggregate thus becomes fragile and susceptible to weathering.

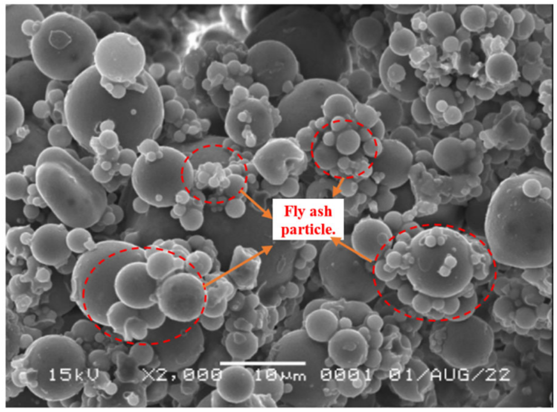

Fig. 10. PLA 90:10 SEM Test Results (2000x Magnification)

Table 4. XRF Test Results on Artificial Aggregate

Chemical Elements	Fly Ash	Artificial Aggregate				
		PLA_50:50	PLA_60:40	PLA_70:30	PLA_80:20	PLA_90:10
Al_2O_3	29.63%	18.00%	20.00%	20.00%	20.00%	23.00%
SiO_2	55.81%	44.40%	45.70%	48.70%	46.00%	50.70%
Fe_2O_3	5.62%	18.30%	17.00%	16.90%	15.30%	14.80%
CaO	2.72%	7.27%	7.76%	7.22%	11.80%	6.59%
TiO_2	0.790%	2.08%	2.24%	2.28%	2.21%	2.15%
K_2O	0.735%	1.36%	1.45%	1.82%	1.28%	1.31%
P_2O_5	0.263%	-	0.98%	1.20%	-	-
SO_3	0.376%	1.90%	2.10%	-	1.50%	-

Due to the majority of this PLA being constructed by CFA, which contains a lot of SiO_2, Table 4 displays the results of the XRF test for each sample of artificial aggregate, with SiO_2 being the significant chemical element. Table 4 shows that the proportion of content for the number of these elements has changed, indicating that the usage of ERh can alter the chemical composition of CFA. As the ERh composition increased, the Al_2O_3 chemical content fell while the Fe_2O_3 chemical content rose. This rise in Fe_2O_3 suggests that PLA's flexural strength may increase (Gerasimova, 2016).

3.5 Lightweight Concrete (LWC) Mechanical Properties

Concrete with a design quality of 20 MPa and aggregates of PLA 70:30 (LWC 70:30) and PLA 80:20 (LWC 80:20) were used to evaluate the mechanical properties, which are compressive and flexural strength of LWC. Cylindrical molds were used to evaluate the compressive strength with 15x30 cm in size at 3, 7, 14, 21, and 28 days. The outcomes of producing the LWC sample are shown in Fig. 11 and Fig. 12.

Fig. 11. LWC 70:30 Specimens

Fig. 12. LWC 80:20 Specimens

Fig. 13 shows the compressive strength results at ages 3, 7, 14, 21, and 28 days by comparing normal concrete (NC) with LWC, where NC employs natural aggregates and LWC uses PLA. The compressive strength of LWC is lower than NC, with a decrease of 24.25% for LWC 70:30 and 43.79% for LCW 80:20, which is shown in Fig. 13. The compressive strength of LWC 70:30 and LWC 80:20 was obtained at 18.3 MPa and 13.58 MPa, less than 20 MPa, respectively. In 28 days, it shows that LWC does not meet the quality of the designed concrete.

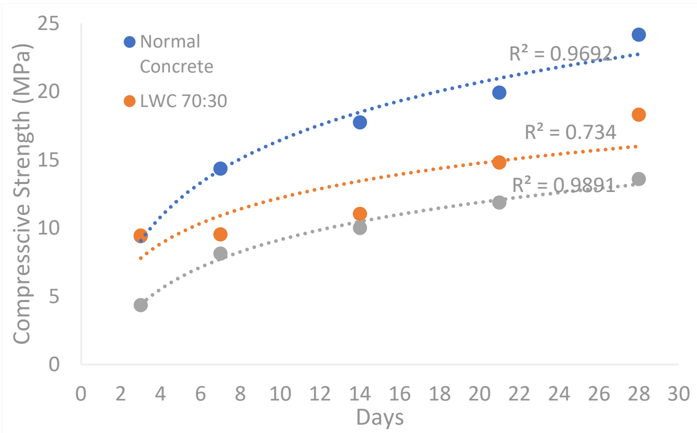

Fig. 13. Comparison of The Compressive Strength of Lightweight Concrete (LWC) Against Normal Concrete (NC)

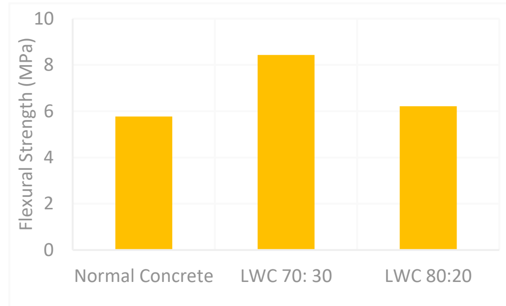

Fig. 14. Comparison of The Flexural Strength of Lightweight Concrete (LWC) Against Normal Concrete (NC)

Fig. 14 shows the flexural strength test results. It shows that LWC has a higher flexural strength value than NC. NC had a flexural strength of 5.77 MPa after 28 days, while LWC 70:30 and LWC 80:20 had values of 8.43 MPa and 6.21 MPa, respectively. Due to the flexibility and hardness of epoxy resin as an adhesive, this increase in flexural strength is evident (Septriansyah et al., 2021). Moreover, adding Epoxy resin to PLA raises the amount of Fe_2O_3. It hardens the mixture and increases lightweight concrete's flexural strength (Gerasimova, 2016).

4. Conclusion

Several research phases have been completed on producing artificial aggregates utilizing epoxy resin and coal fly ash. The following conclusions may be drawn from the research:

1. The composition of CFA and Erh influences the PLA specific gravity with a maximum value at 1716 kg/m^3 on PLA_74:26 before decreasing to 1245 kg/m^3. PLA_50:50 meets the specifications for construction-grade concrete to PLA_86:14, which is based on ASTM 621.

2. PLA_50:50 obtained the maximum compressive strength value with a test age of 28 days, equivalent to 85.33 MPa. The coal fly ash and epoxy resin mixture affect an aggregate's compressive strength value. In the 28-day age test, PLA_50:50 - PLA_84:16 may be used as an aggregate for structural concrete, whereas PLA_90:10 can be used as an aggregate for lightweight concrete constructions, according to the test results.

3. It was discovered that PLA_50:50 to PLA_74:26 can be used for 6 hours to build structural concrete with a strength of more than 17 MPa, while PLA_80:20 can create lightweight concrete with a 7–17 MPa strength range. Since PLA_84:16 has a strength range of 0.35 to 7 MPa, it may be utilized as a non-structural concrete material.

4. From the SEM result, the strength of the LWC was influenced by the size of the ERh composition. The ERh covers the CFA to create a solid binding structure. According to the XRF test findings, it was discovered that as ERh was applied, Fe_2O_3 chemical composition increased.

5. The flexural strength of LWC 70:30 and LWC 80:20 is increasing compared to the flexural strength of NC, with values of 46.1% and 7.63%, respectively. The compressive strength of LWC are lower than NC's, with a decrease reaching 24.25% for LWC 70:30 and 43.79% for LCW 80:20.

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