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Analysis of foamed concrete properties using artificial aggregates composed of fly ash and epoxy resin as partial sand replacement

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ABSTRACT

Indonesia is one of the most seismically active countries, requiring advanced construction technologies to anticipate earthquake damage and risks. This research focuses on enhancing foamed concrete by substituting normal fine aggregates with artificial aggregates using fly ash as a byproduct of coal combustion and epoxy resin, because both materials have lower density. The mix proportions were determined based on the American Concrete Institute (ACI) guideline Guide for Cellular Concretes Above 50 lb/ft³ (800 kg/m³), resulting in five different mix designs: a control mix (normal foamed concrete, NFC) and four variations incorporating artificial aggregates (AAFC). Cylindrical specimens measuring 10 × 20 cm (diameter × height) were prepared to assess the influence of variations in the water–cement ratio (W/C), superplasticizer dosage, and material composition on slump flow, density, and compressive strength. Results show that the highest slump flow was 58.0 cm, obtained in the mix with a W/C ratio of 0.45 and 1% of superplasticizer dosage. Most AAFC mixes met the lightweight concrete density requirement specified in ASTM C330/C330M (below 1850 kg/m³). The highest value of compressive strength test was 16.71 MPa with a W/C ratio of 0.45 and 1% superplasticizer. However, this result is still below the targeted structural concrete. This study shows the feasibility of using artificial aggregates from fly ash and epoxy resin in foamed concrete and emphasizes the need for further experimentation to improve structural performance.

Keywords: Artificial Aggregate, Fly-Ash, Resin Epoxy, Lightweight Concrete, Foamed concrete

1. INTRODUCTION

Foamed concrete is a type of lightweight concrete made from a mixture of cement paste and foam, resulting in a concrete that is lighter than conventional concrete. This type of concrete has many advantages in construction, that are high workability and a low dead load capacity for structures, making it suitable for a variety of construction applications (Othman et al., 2021). Foamed concrete has properties, including excellent flowability, reduced weight, thermal insulation, and density, with a 400 to 1850 kg/m³ depending on the foam volume used. Its adoption in construction, ranging from non-structural to semi-structural applications, continues to grow due to cost-effectiveness and efficiency (Falliano et al., 2018; Shah et al., 2021).

The first use of foamed concrete dates back to advances in the early 20th century, when Scandinavian countries pioneered the production of high-air-content cementitious materials. This innovation led to the first patent for foamed concrete as an insulating material in 1923 (Bindiganavile and Hoseini, 2019; Raj et al., 2019). his material is globally recognized for its low density, which helps reduce structural dead loads, transportation costs, and energy consumption in construction while improving thermal insulation and sound absorption properties (Amran et al., 2015).

Research has shown that increasing the foam agent content enhances flowability but has a negative impact on compressive strength. For example, a study of foamed concrete that uses expanded clay aggregate reported that increasing the foam agent content from 0% to 20% decreased compressive strength from 24.75 MPa to 12.05 MPa. On the other hand, using silica fume (SF) can improve the quality of foamed concrete by increasing compressive strength and thermal conductivity, but it can reduce water absorption (Ahmad and Chen, 2019). Past research has shown that the use of fly ash and other additives, for example clay or vermiculite, can affect the properties of foamed concrete, such as its strength and thermal properties (Mohamad Ibrahim et al., 2020; Zhang et al., 2022).

The composition of foamed concrete is similar to that of normal concrete, using Portland cement, sand, water, a foaming agent, and reinforcing fibers, that can be considered. Foamed concrete has increased mechanical properties and is often modified with various types of cement or admixtures. Research showed that foamed concrete using magnesium phosphate cement (MPC) showed a higher early strength than foamed concrete using ordinary Portland cement (OPC) (Li et al., 2019). Research shown that combining silica fume with polycarboxylate superplasticizers tends to make concrete stronger and less permeable, and improve internal pore structure (Al-Shwaiter et al., 2023; Gökçe et al., 2019).

In addition to the main cement component, the aggregates used in foamed concrete typically consist of fine particles with a maximum size of approximately 10 mm to prevent foam segregation. Several studies have shown that the use of alternative aggregates can improve some of the mechanical properties of foam concrete, such as rice husk ash, recycled glass powder, and rubber powder (Hadipramana et al., 2012; Khan et al., 2019; Mehrani et al., 2019). A review of many past studies showed that the use of fly ash and other industrial waste in artificial aggregates offers positive environmental benefits by reducing reliance on natural aggregates, while potentially maintaining or improving the overall performance of foamed concrete. This is due to variations in production methods, ranging from forming to hardening of the aggregate through the drying process (Almadani et al., 2022).

Despite valuable findings from previous studies, there are still gaps in understanding the effects of artificial aggregates using fly ash and epoxy resin in foamed concrete. This study investigated foamed concrete using an artificial aggregate made of fly ash and epoxy resin in a 50%:50% ratio as a partial replacement for natural aggregate, to evaluate its potential as an alternative to foamed concrete. The mixing and testing processes were carried out following standard procedures.

The artificial aggregate in this test has a lower specific gravity but a higher compressive strength compared with conventional aggregates and fly ash–based alternative aggregates. According to ACI standards, the specific gravity of fine and coarse aggregates is 2.60–2.65 and 2.60–2.70, respectively. However, lightweight aggregates that were made from sintered fly ash and cold-bonded aggregates have lower specific gravity and lower crushing strength. According to a review by Nadesan & Dinakar (2017), data from previous studies showed that these aggregates have specific gravities between 1.46 and 2.35, with a maximum compressive strength of 23.1 MPa. By contrast, the artificial aggregate used in this study, the same as that in Firda et al., (2023), showed a specific gravity of 1.451 and a much higher crush strength of 85.33 MPa at 28 days for a 50:50 PLA mixture. These physical properties are more advantageous than those of other fly ash–based aggregates.

2. MATERIALS AND METHODS

Materials

Portland Composite Cement is used as the cement material for foamed concrete in this study, which meets the requirements of the Indonesian Standard, SNI 2049:2015. This cement is used because it is a common type of cement widely used in construction for the public. Fine aggregates are natural sand taken from Tanjung Raja, South Sumatra. First, the sand is washed to remove silt and organic matter. Several tests are performed, including bulk density, specific gravity, water absorption, particle size distribution (gradation), silt content, water content, and organic matter content, in accordance with SNI and ASTM standards.

Specific gravity testing is conducted to determine the specific gravity of fine aggregates in accordance with SNI 1970:2016, utilizing the formulas specified in the standard. Water absorption testing was also conducted using the same standards to determine the water absorption rate. Aggregate gradation was determined using ASTM C136/C136M-19. Silt and organic content were measured using ASTM C117-17 and SNI 2816:2014, respectively.

The artificial aggregate in the manufacturing process uses F-type fly ash, a byproduct of coal combustion, known for its pozzolanic properties. Additionally, epoxy resin serves as a binding agent in the manufacture of artificial aggregate. The manufacturing process involves removing water content from fly ash at a temperature of 110 °C for 24 hours, sieving it through a No. 200 sieve, and mixing it with epoxy resin and hardener at a 50:50 weight ratio. In this experiment, the ratio of epoxy resin and fly ash was taken based on previous research with consideration of low specific gravity and high aggregate compressive strength (Firda et al., 2023).

Figure 1. Artificial aggregates made from a mixture of fly ash and epoxy resin

The mixing process began with blending epoxy resin and hardener using a mixer at medium speed for ±3 minutes. Then followed by simple mixing with fly ash for about five minutes to ensure uniform distribution. The resulting mixture was then molded into a layer with a thickness of 1 cm and left to harden for six hours. Once hardened, the material was crushed using a hammer to obtain aggregate sizes ranging from 3/8" (9.5 mm) to No. 4 (4.75 mm), based on the coarse aggregate sieve standard. The artificial aggregates produced were subsequently tested for specific gravity in accordance with SNI 1969:2016 to obtain essential data for the concrete mix design. Figure 1 shows the artificial aggregate form used in this study.

Other materials used in the foamed concrete mixture included clean, uncontaminated water; foam agents with a water-to-agent volume ratio of 1:40, introduced through a foam generator; and Sika Fume brand SF, which was incorporated to enhance the concrete's compressive strength. Previous studies by Gökçe et al., (2019) have shown that SF can increase compressive strength by up to 4.4 times. Additionally, superplasticizer was utilized to improve the workability of the concrete while maintaining a low water-cement (W/C) ratio.

The artificial aggregate production process followed the methodology outlined in (Firda et al., 2023). The procedure involved oven-drying the fly ash, sieving it, and weighing it to maintain a 50% proportion relative to the epoxy resin and hardener. The epoxy resin and hardener were first mixed, then combined with fly ash, molded, and allowed to harden. Once fully cured, the hardened aggregates were crushed to the required size using sieves. The final artificial aggregates underwent specific gravity testing before being incorporated into the mix design for the foamed concrete.

Mix Design

The foamed concrete used in this study uses the ACI 523.3R-14 (2014) standard. This guideline provides comprehensive concrete manufacturing steps, with reference to the target density and design compressive strength. This standard also shows methods to calculate material proportions and mix design. In this study, the target density was set at 1760 kg/m³, with a desired compressive strength of 17.5 MPa or above to meet the structural compressive strength of concrete. The mix design calculations followed the equations based on ACI by determining the sand-cement ratio, oven-dry density, cement quantity, fine aggregate, water, and foam volume. The material requirements were computed using the following formulas:

- Calculate the sand-to-cement ratio (s/c)

$$ {}^{s}/_{c} = \frac{\gamma_f - 673}{345} $$

- Calculate the oven-dry density (D)

$$ D = \gamma_f - 122 $$

- Calculate the cement material required for 1 m³

$$ C = \frac{\gamma_f}{(1 + {}^{W}/_{c} + {}^{S}/_{c})} $$

- Calculate the fine aggregate material required for 1 m³

$$ S = C \times {}^{S}/_{c} $$

- Calculate the amount of water to be mixed

$$ W = C \times {}^{W}/_{c} $$

- Calculate the absolute volume of solids (cement, water, and aggregates) per unit volume of concrete

$$ Va = \frac{C}{Gc \times \gamma_w} + \frac{W}{\gamma_w} + \frac{S}{Gs \times \gamma_w} $$

- Calculate the air volume needed per unit volume of concrete

$$ Av = 1 - Va $$

- Calculate foam volume (Vf)

$$ Vf = \frac{Av}{Fa} $$

- Calculate foam weight (equal to the weight of water in the foam)

$$ Wf = Vf \times rf $$

- Percentage of water contained in the sand (%Ws)

$$ \%Ws = 1{,}34\% $$

- Corrected water requirements:

$$ Wc = W - Wf - Ws $$

- Corrected fine aggregate requirements:

$$ Sc = S + Ws $$

Notations:

fc'	=	Target compressive strength of foamed concrete	Mpa
${}^{s}/_{c}$	=	Sand-to-cement ratio	
γ_f	=	Target fresh concrete density	(kg/m3)
D	=	Target oven-dry concrete density	(kg/m3)
C	=	Cement material required per unit volume of concrete	(kg/m3)
${}^{w}/_{c}$	=	Water-to-cement ratio	
${}^{s}/_{c}$	=	Water-to-sand ratio	
S	=	Fine aggregate material required per unit volume of concrete	(kg/m3)
W	=	Water required per unit volume of concrete	(kg/m3)
Va	=	Absolute volume of solids (cement, water, and aggregates) per unit volume of	(m3)

		concrete	
Gc	=	Cement specific gravity	(m3)
γ_w	=	Water density	(1000 kg/m3)
Gs	=	Sand specific gravity	
Av	=	Air volume per unit volume of concrete	(m3)
Vf	=	Foam volume	
Wf	=	Foam weight	(kg/m3)
Wc	=	Corrected water weight per unit volume of concrete	(kg/m3)
Ws	=	Water weight contained in sand/fine aggregate	(kg/m3)
Sc	=	Corrected sand weight per unit volume of concrete	(kg/m3)

The next phase is the application of artificial aggregate to foamed concrete, which will be referred to as Artificial Aggregate Foamed Concrete (AAFC). The mixture proportions are determined as follows:

- 10% of the PCC cement weight was replaced with SF to increase the compressive strength of AAFC.
- The foam volumes used were 0%, 10%, 20%, and 30% of the fresh concrete volume.
- The volume ratio of fine aggregate to artificial aggregate was 1:1 for AAFC.
- The volume ratio of foam agent and water was 1:40 for all concrete mixes to ensure stable foam production.
- The SP dosage is limited to a maximum value of 1% of the total binder weight in all mixtures to improve the workability of fresh foamed concrete. This value is taken from Al-Shwaiter et al., (2023) and technical data sheets on the product.

Based on the mixture proportions, the final mix design results have been determined for foamed concrete using a mixture of fly ash and epoxy resin as artificial aggregate. This mix design incorporates a formula that considers the various compositions of materials, including cement, water, sand, artificial aggregate, and foam. Foam is made as an admixture in fresh concrete by mixing water and foaming agent with a volume ratio of 1:40. The foam is mixed with proportions of 0%, 10%, 20%, and 30% of the AAFC volume. Then, a maximum superplasticizer with a dose of 1% is mixed into the entire concrete mixture. Tables 1 to 3 show the detailed mix proportions for each concrete type. Type-1 involved testing foam volumes from 0% to 30% and SP dosages from 1% down to 0.25% to evaluate their effects on density and compressive strength. Type-2 used a lower W/C ratio of 0.33 to investigate its effect on overall concrete performance.

Table 1. T1 - foamed concrete Mix design

NO	Code	Cement (kg)	Water (kg)	Sand (kg)	Artificial aggregate (kg)	Foam (% Cement vol.)	SF (kg)	Super plasticizer (kg)	W/C
1	AAFC-F0%-0.45-SF-SP1% (T1)	402.02	201.05	544.97	313.29	---	44.67	4.02	0.45
2	AAFC-F10%-0.45-SF-SP0.75% (T1)	402.03	201.05	544.97	313.29	10.00	44.67	3.02	0.45
3	AAFC-F20%-0.45-SF-SP0.5% (T1)	402.04	201.06	544.99	313.30	20.00	44.67	2.01	0.45
4	AAFC-F30%-0.45-SF-SP0.25% (T1)	402.03	201.06	544.98	313.30	30.00	44.67	1.01	0.45

Table 2. T2 - foamed concrete Mix design

NO	Code	Cement (kg)	Water (kg)	Sand (kg)	Artificial aggregate (kg)	Foam (% Cement vol.)	SF (kg)	Super plasticizer (kg)	W/C
5	AAFC-F20%-0.33-SF-SP1% (T2)	386.77	128.38	1218.61	---	20.00	---	3.87	0.33
6	AAFC-F20%-0.33-SF-SP1% (T2)	348.08	128.38	609.28	355.09	20.00	38.67	3.87	0.33

Table 3. T3 - foamed concrete Mix design

NO	Code	Cement (kg)	Water (kg)	Sand (kg)	Artificial aggregate (kg)	Foam (% Cement vol.)	SF (kg)	Super plasticizer (kg)	W/C
7	NFC-F20%-0,38-SP1% (T3)	382.99	145.18	1206.69	---	20.00	---	3.83	0.379
8	AAFC-F0%-0,38-SF-SP1% (T3)	344.68	145.18	603.33	351.62	---	38.29	3.83	0.379
9	AAFC-F10%-0,38-SF-SP1% (T3)	344.68	145.18	603.33	351.63	10.00	38.30	3.83	0.379
10	AAFC-F20%-0,38-SF-SP1% (T3)	344.67	145.17	603.31	351.61	20.00	38.30	3.83	0.379

Figure 2. Fresh foamed concrete mixing process

Foam concrete mixing guidelines refer to the standard ACI 523.3R-14 (2014). First, the fine aggregate and artificial aggregate are placed in the mixer, followed by the addition of PCC cement and SF. These materials are mixed until homogeneous. Water containing a superplasticizer is slowly added. Foam produced by a foam generator is then incorporated into the mixture during mixing until a consistent composition is achieved. Figure 2 shows the mixing of foamed concrete. After mixing is complete, slump flow and spreadability tests are performed on the fresh concrete. The slump flow test is used to determine the workability and flow characteristics of fresh mixes in accordance with ASTM C1611/C1611M-18, which is commonly employed for self-compacting concrete

(SCC). This method uses a slump cone to measure the distribution diameters (d1, d2, d3), and the average distribution is then calculated. The test evaluates the workability of foamed concrete. Figure 3 shows the process of measuring the diameter of foamed concrete.

For mechanical properties, compressive strength tests were performed on specimens after 28 days of curing in accordance with ASTM C39-14 to determine the load-bearing capacity at failure. Figure 4 shows the hardened foamed concrete specimens to be tested at 28 days using Universal Testing Machine (Figure 5). The results obtained indicate the effectiveness of the concrete mix design and the material composition in achieving the desired structural strength.

Figure 3. Measuring Diameter of Slump Flow

Figure 4. Foamed concrete specimens after 28 days of curing

Figure 5. Universal Testing Machine to conduct compressive strength test

3. RESULT AND DISCUSSION

Slump Flow

Effect of Artificial Aggregate on Slump Flow with W/C = 0.38

The test specimens used in this study were Mixture 7 (NFC) and Mixture 10 (AAFC), both with W/C of 0.38, but differing in their material composition. Mixture 7 (NFC) used only fine aggregate as the filler material, whereas Mixture 10 (AAFC) replaced 50% of the fine aggregate volume with artificial aggregate. The results presented in Figure 6 indicate that the inclusion of artificial aggregate substantially affected slump flow, with measured spread values of 44.67 cm for Mixture 7 and 58.33 cm for Mixture 10. The difference in slump values is due to the use of artificial aggregate in the AAFC specimen rather than fine aggregate in the NFC specimen, which has a lower specific gravity (1471 kg/m³) compared to fine aggregate (2524 kg/m³).

The effect of aggregate specific gravity is discussed by Kim et al., (2010) who analyzed SCC concrete with lightweight aggregates with lower specific gravity but higher slump flow. In this study, two aggregates with specific gravity of 1.58 g/cm³ and 2.07 g/cm³ produced slump flows of approximately 667 mm and 608 mm, respectively. This study demonstrates the impact of aggregate type on the slump flow of SCC. This study shows that lighter, more porous aggregates tend to lift in the cement paste, reducing its resistance to segregation. Although the use of artificial aggregates with higher specific gravity will improve the workability of concrete, detailed control of mix composition and viscosity is still needed to minimize the risk of segregation in high-workability mixes.

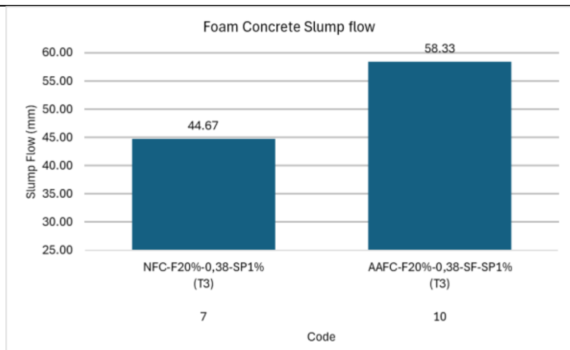

Figure 6. Average Slump Flow of Mixtures 7 (NFC) and 10 (AAFC)

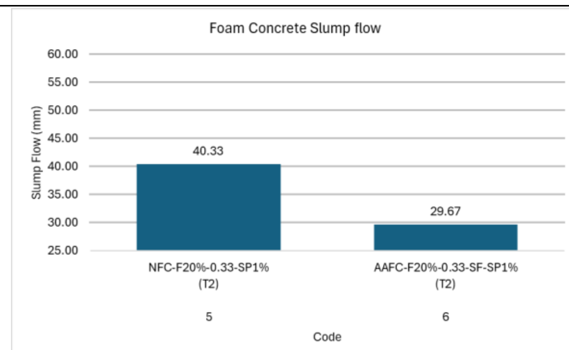

Figure 7. Average Slump Flow of Mixtures 5 (NFC) and 6 (AAFC)

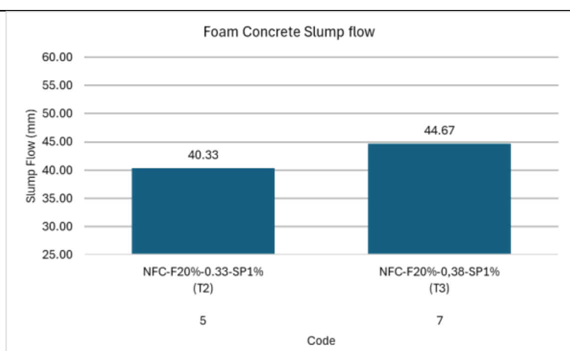

Figure 8. Average Slump Flow of NFC Mixtures 5 and 7

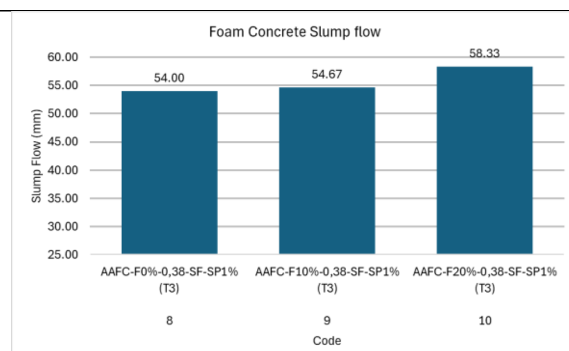

Figure 9. Average Slump Flow of AAFC Mixtures 8, 9, and 10

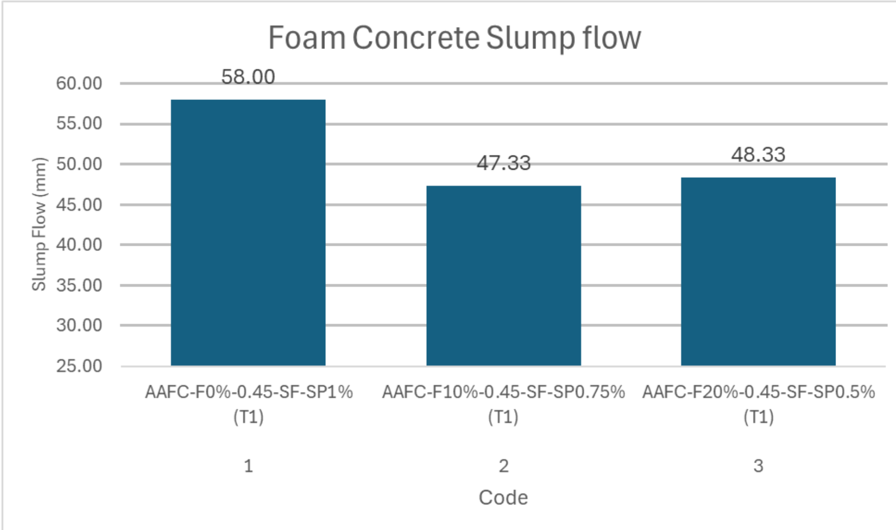

Figure 10. Average Slump Flow of AAFC Mixtures 1, 2, and 3

Effect of Artificial Aggregate on Slump Flow with W/C = 0.33

The specimens used were Mixture 5 (NFC) and Mixture 6 (AAFC). Both were prepared with a W/C ratio of 0.33 and different material compositions, with AA as a fine aggregate substitute at 50% in mixture 6. Figure 7 shows that the use of artificial aggregate results in slump flow values of 40.33 cm for the NFC specimen and 29.67 cm for the AAFC specimen. This result is because, during the test, a "stuck" or "blockage" phenomenon occurred when lifting the slump cone. This occurrence is attributed to the combination of a very low W/C ratio and the larger particle size of the artificial aggregate relative to the fine aggregate, both of which adversely affect flowability. Consequently, optimizing the W/C ratio is essential to improve the workability of foamed concrete containing artificial aggregate.

Effect of W/C on Slump Flow of Foamed concrete

The specimens used were Mixture 5 (NFC) with a W/C ratio of 0.33 and Mixture 7 (NFC) with a ratio of 0.38 for comparison. Figure 8 shows the results, with the average slump flow values of 40.33 cm for Mixture 5 and 44.67 cm for Mixture 7. The test results show that increasing the W/C ratio improves concrete flowability. Previous research conducted by Pour et al., (2024), showed the effect of increasing the W/C ratio value from 0.30 to 0.40-0.45 increases the slump flow value by 10-20%, with a slump flow value of ± 72 - 87 mm in the same mixture. This explanation shows that by reducing the viscosity of the paste and reducing the friction between material particles, the increase in the slump flow results. The authors also emphasized that excessive water content causes paste dilution and water-filled concrete pores. This can reduce cohesion and segregation resistance in highly flowable mixes.

Effect of Foam Content on Slump Flow

The test used three AAFC mixtures, No. 8, 9, and 10, with a W/C ratio of 0.38, with foam values of 0%, 10%, and 20%, respectively. The test results shown in Figure 9 show the slump size results with values of 54.00 cm, 54.67 cm, and 58.33 cm, respectively. Foam has a small water content; the more foam, the more water is given to the concrete. This effect is identical to the difference in W/C ratios explained previously. The results showed that increasing the foam content from 1% to 12% caused an increase in the flow value from 98% to 140%. The authors attributed this behavior to the reduction in mixture stiffness and the increased volume of entrained air associated with higher foam contents. Although the magnitude of flow enhancement observed in the present study is lower, the consistent trend confirms that foam content plays a significant role in governing the workability of fresh foamed concrete systems.

Effect of Superplasticizer on Slump Flow

The tested specimens were Mix No. 1, Mix No. 2, and Mix No. 3 with a W/C value of 0.45. These mixes used SF as a cementitious material replacement at 10% by weight and different SP dosages of 1%, 0.75%, and 0.5%. Figure 10 shows that the highest spread was 58.00 cm for the mix with 1% SP. The spread value decreased to 47.33 and 48.33 cm when the SP amount was reduced to 0.75% and 0.5%. Although reduced, the slump flow for the lower SP dosages remained in the 47–48 cm range.

Al-Shwaiter et al., (2023) reported in the study by using 1% SP as an effective dosage for improving the slump flow spreadability of foamed concrete by increasing particle dispersion and reducing mixture viscosity. Their research results showed that the desired slump size of 23 ± 2 cm can be achieved through the addition of SP and a controlled reduction in W/C, particularly at SP dosages ranging from approximately 1.10% to 1.35%. According to this explanation, SP influences the workability of freshly foamed concrete. The authors also set limits on the amount of SP content to prevent excessive SP content, which could negatively impact foam stability.

Density of Foamed concrete

Effect of Artificial Aggregate on Density of Foamed concrete

Density testing was conducted on Mixture 7 (NFC) and Mixture 10 (AAFC), both of which used a W/C ratio of 0.38. The test results show that the density of Type 3 foamed concrete, as shown in Figure 11 for NFC, is 1732.05 kg/m³, while AAFC has a lower specific gravity of 1619.23 kg/m³. This decrease in numbers is due to the use of artificial aggregate (1471 kg/m³) as a partial replacement for fine aggregate (2524 kg/m³), which can affect the specific gravity of foamed concrete. If this material can be applied to building materials, it will reduce the dead load that the building structure should support.

The second test used samples from mixtures No. 5 (NFC) and No. 6 (AAFC), which both had a W/C of 0.33. The test results, as shown in Figure 12, showed a decrease in the specific gravity of the AAFC sample, with the NFC sample being 1678.46 kg/m³ and the AAFC being 1612.29 kg/m³, caused by the use of Artificial aggregate. The incorporation of artificial aggregate in AAFC significantly affects the physical properties of foamed concrete, supporting its potential as an alternative material for density modification.

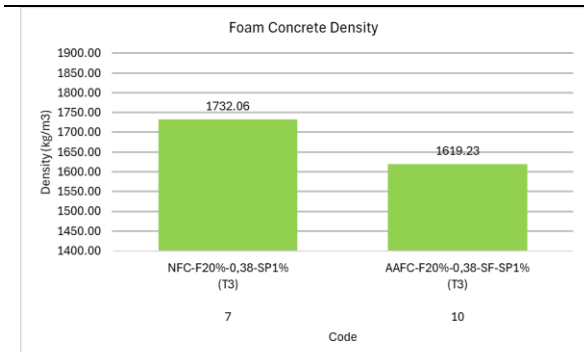

Figure 11. Average Density of Mixtures 7 (NFC) and 10 (AAFC)

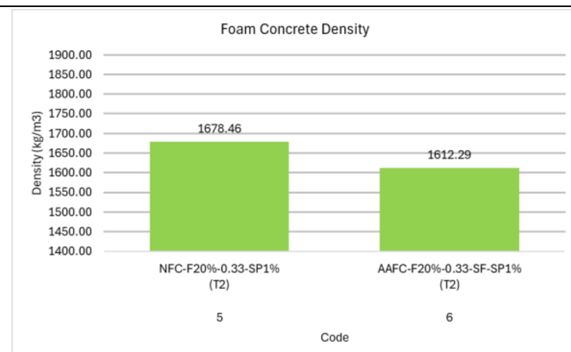

Figure 12. Average Density of Mixtures 5 (NFC) and 6 (AAFC)

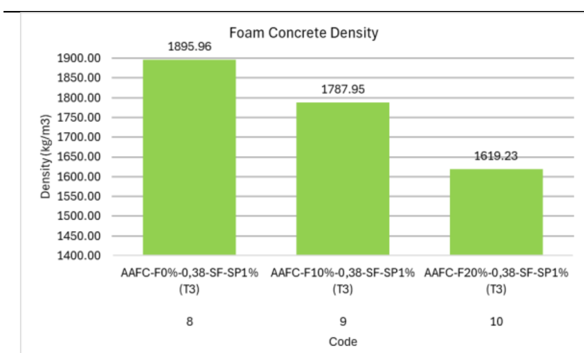

Figure 13. Average Density of AAFC Mixtures 8, 9, and 10

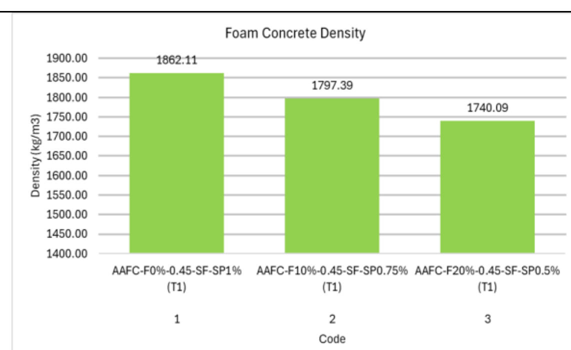

Figure 14. Average Density of AAFC Mixtures 1, 2, and 3

Effect of Foam Content on Density of Foamed concrete

The specimens used in this test are two types of mixtures: Type-3, which contains Mixture 8, 9, and 10 with a W/C ratio of 0.38, and Type-3, which contains Mixture 8, 9, and 10 with a W/C ratio of 0.45. Both types are AAFC with variations in foam content of 0%, 10%, and 20% of the total concrete volume. The test results in the plots in Figures 13 and 14 show that an identical decrease occurs when increasing foam content causes a decrease in the density of foamed concrete in both types of foamed concrete. In Mixture 8, 9, and 10, with an average density of 1865.98 kg/m³, 1787.94 kg/m³, and 1619.22 kg/m³, while in Mixture 1, 2, and 3, with an average density of

1862.11 kg/m³, 1797.39 kg/m³, and 1740.09 kg/m³. Of these two types, 10% foam content is the optimal value to achieve a balance between density and compressive strength. The ASTM C330/C330 M standard states that foamed concrete has a maximum density of less than 1850 kg/m³. This finding is also consistent with research by Sai Krishna et al., (2021), which examined the impact of foam content on the density and properties of fly ash-based foamed concrete.

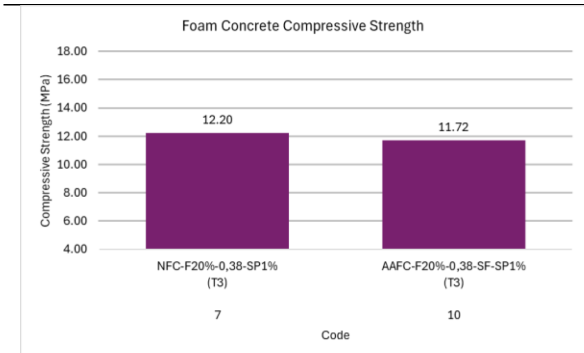

Figure 15. Average Compressive Strength of NFC Mixtures 7 (NFC) and 10 (AAFC)

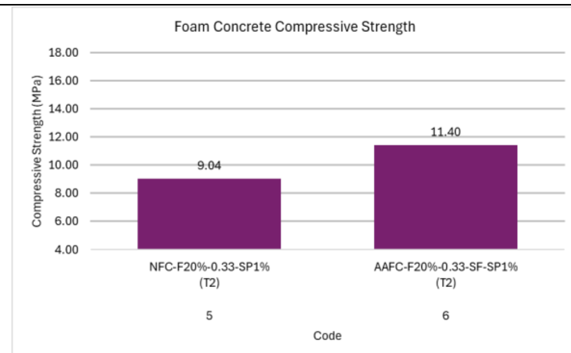

Figure 16. Average Compressive Strength of Mixtures 5 (NFC) and 6 (AAFC)

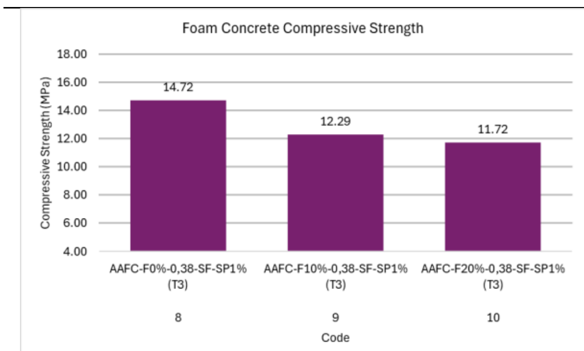

Figure 17. Average Compressive Strength of AAFC Mixtures 8, 9, and 10

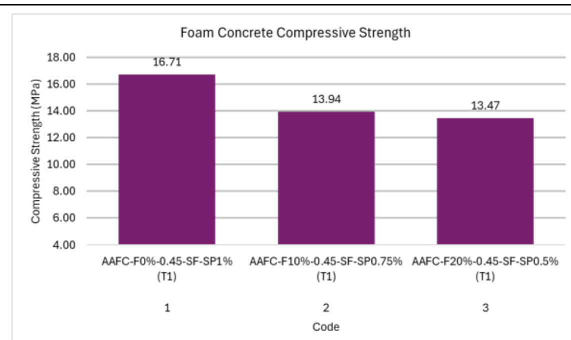

Figure 18. Average Compressive Strength of AAFC Mixtures 1, 2, and 3

Compressive Strength of Foamed concrete

Effect of Artificial Aggregate on Compressive Strength of Foamed concrete

The specimens used in this test were Mixture 7 (NFC) and Mixture 10 (AAFC), both with a W/C ratio of 0.38. The effect of AA on the compressive strength of foam concrete is shown in Figure 15. The NFC and AAFC samples showed average compressive strengths of 12.20 MPa and 11.72 MPa, respectively, representing a small difference of 0.48 MPa. This decrease is due to the mechanical performance being limited by the stress transfer capacity at the aggregate-mortar interface.

This mechanism was also discussed by He et al., (2014), who showed that concrete compressive strength is influenced not only by the strength of the aggregate material but also by the characteristics of the interfacial bond. According to their findings, variations in the contact area, interlocking structure, and interfacial bonding conditions between aggregate and mortar significantly affect crack propagation and overall compressive strength. Therefore, the slight decrease observed in this study is due to suboptimal interfacial bonding between the artificial aggregate and the cement matrix, rather than to insufficient aggregate strength, resulting in a moderate but measurable decrease in compressive performance.

Effect of SF on Compressive Strength of Foamed concrete

The specimens used in this test were Mixture 5 (NFC) and Mixture 6 (AAFC), both of which have a W/C ratio of 0.33. However, AAFC, which only uses SF additives as a substitute for cement weight, differs from NFC. Figure 16 shows positive results for materials using SF on concrete compressive strength. The NFC specimen has a compressive strength value of 9.04, while the AAFC specimen shows an increase in results of 11.40 MPa. According to research conducted by Gökçe et al., (2019), the increase in concrete compressive strength in this test is due to the nature of SF which undergoes a chemical reaction with calcium hydroxide ($Ca(OH)_2$), which is a byproduct of cement hydration. This reaction creates additional calcium silicate hydrate (C–S–H), which increases the concrete's compressive strength.

Effect of Foam Content on Compressive Strength of Foamed concrete

In testing concrete specimens for Type-3, Mixtures 8, 9, and 10, which are AAFC specimens with a W/C ratio of 0.38, were used with foam content ratios of 0%, 10%, and 20% of the total concrete volume, respectively. Figure 17 illustrates that as the foam content increases; the compressive strength decreases. Mixture 8 has the highest compressive strength value of 14.72 MPa, while Mixtures 9 and 10 have compressive strengths of 12.29 MPa and 11.72 MPa, respectively.

In the second test, the Type-1 test specimens, namely Mixture 1, 2 (AAFC), and 3, all of which are AAFC, with foam contents of 0%, 10%, and 20%, respectively, and a W/C ratio of 0.45, gave similar results. Figure 18 also follows the same trend, the compressive strength decreases as the foam content increases, with mixture 1 having the highest compressive strength of 16.71 MPa. However, mixtures 2 and 3 show lower compressive strengths of 13.94 MPa and 13.47 MPa, respectively. These results agree with the earlier tests on Type-3 foamed concrete and further confirm the inverse relationship between compressive strength and foam content.

In a study conducted by Othman et al., (2021), which tested foam concrete with foam values of 20%, 25%, 30%, and 35%, the results showed that the strength of the concrete was affected by 8.8, 7.5, 4.2, and 3.0 MPa, respectively. This clearly shows that increasing the foam dosage can rapidly reduce the concrete strength due to increased porosity and reduced specific gravity. Therefore, the strength reduction observed in the present study can be attributed to the increased volume of entrained air disrupting the continuity of the cementitious matrix, which limits effective stress transfer under compressive loading.

4. CONCLUSION

Based on the experimental results, it can be concluded that concrete mixtures containing AA have a lower mass than those without AA at equivalent foam volume, due to the lower density of AA compared with fine aggregate. AA affects the slump flow of fresh concrete due to its lower density than sand. AAFC mixes showed higher slump flow values, yet achieving effective slump flow still requires the correct water–cement (W/C) ratio and appropriate superplasticizer dosage. A slight reduction in compressive strength observed in AAFC samples is attributed to a suboptimal interfacial bond between the aggregate and mortar rather than to weak aggregate compressive strength, making interfacial bonding a key factor influencing concrete strength. The optimal foam volume determined in this study was 10% of the concrete volume, which provides the best balance between density and compressive strength for the lightweight concrete category. Incorporation of artificial aggregate based on fly ash and epoxy resin into foamed concrete produces a lower-density material that meets the classification for lightweight concrete according to ASTM C330/330M, and the addition of SF improves compressive strength; however, further optimization is still required to achieve the structural strength target of 17.5 MPa.

5. RECOMMENDATION FOR FUTURE RESEARCH

Further research for AAFC, the authors have the following recommendations:

- Detailed microstructural characterization investigations, including SEM, EDS, and ITZ analysis of epoxy-based aggregates and cement pastes, are required to measure their effects on mechanical properties.
- Optimization of the fly ash-epoxy resin ratio is required to improve mechanical bonding and matrix compatibility to achieve structural compressive strength.
- Investigate the optimal W/C ratio and foam content for AAFC to ensure stable flow at the specified density.
- Investigate life-cycle assessment (LCA) and cost-performance analysis to evaluate the feasibility of large-scale use, particularly for weight-critical and earthquake-resistant structures.
- Long-term durability studies, such as water absorption, chloride penetration, sulfate resistance, and shrinkage testing, are required to assess the long-term performance of AAFC

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Author Contributions

Muhammad Farhan designed and conducted the experiments, performed data analysis, and wrote the manuscript. Saloma and Siti Aisyah Nurjannah provided supervision for the manuscript preparation and contributed to data computation and interpretation. Arie Putra Usman supervised the research process and assisted in data analysis and verification.

Ethical issues

Not applicable. This study does not involve any experiments on humans or animals. Hence, ethical approval was not required.

Informed consent

Not applicable.

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Conflict of Interest

The authors declare that they have no conflicts of interest, competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data and materials availability

Data that support the findings of this study are embedded within the manuscript.

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