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RESEARCH ARTICLE

The Influence of Fly Ash Incorporation on the Compressive Strength of Foamed Concrete

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ABSTRACT

Foamed concrete is a lightweight cement-based material with considerable potential for embankment construction on soft soils because its low density can reduce vertical stress on weak subgrades and minimize settlement problems. The use of fly ash as a partial cement replacement also supports material efficiency and the development of more sustainable cementitious composites. However, the incorporation of fly ash in low-density foamed concrete must be carefully evaluated because it may affect both fresh-state performance and early-age strength development. This study investigates the influence of fly ash replacement on the flowability and compressive strength of foamed concrete and identifies the most suitable mixture for lightweight embankment applications. Foamed concrete mixtures were designed using a trial mix approach with a target density of 800 kg/m^3. Fly ash was used to replace cement at 0%, 10%, 20%, and 30% by weight. Flowability was measured to assess workability, while compressive strength tests were conducted at 7 and 14 days to evaluate mechanical performance. The results show that increasing fly ash content consistently reduced flowability and compressive strength due to cement dilution and lower early-age binding capacity. The control mixture achieved the highest 14-day compressive strength of 2.70 MPa, while the 10% fly ash mixture reached 2.25 MPa and still met the performance requirements for lightweight embankment materials. Mixtures with 20% and 30% fly ash showed a substantial reduction in strength and workability. Therefore, 10% fly ash replacement provides the most balanced performance and is recommended as a technically feasible and material-efficient alternative for lightweight embankment construction on soft soils.

Keywords: Foamed Concrete, Fly Ash, Compressive Strength, Flowability, Sustainable materials

INTRODUCTION

Road embankments constructed on soft soils are frequently affected by excessive settlement and instability due to low bearing capacity and high compressibility. The application of conventional high-density fill materials further increases vertical stress on the subgrade, accelerating deformation and reducing long-term performance. These conditions emphasize the need for alternative fill materials reducing self-weight while still maintaining adequate mechanical performance.

Lightweight materials have been widely introduced as a practical solution for embankment construction on weak ground conditions. Among them, foamed concrete, also known as aircrete or lightweight cellular concrete, has gained significant attention due to its low density, high flowability, and self-compacting behavior, which make it suitable for geotechnical and transportation engineering applications. The performance of foamed concrete is highly dependent on mixture proportions, density, and constituent materials. Previous studies have confirmed that its mechanical behavior is strongly governed by mix design parameters and constituent ratios [1, 2]. Recent studies on low-density and ultra-lightweight cellular concrete have also emphasized that pore structure, binder content, foam stability, and curing condition strongly influence the engineering performance of foamed concrete, particularly when the material is intended for geotechnical applications [3, 4].

The use of fly ash as a supplementary cementitious material has been widely reported to improve workability and contribute to sustainability by reducing cement consumption. However, its relatively low early-age reactivity can lead to a reduction in early compressive strength development [1, 2]. In foamed concrete, fly ash may influence both fresh-state and hardened-state properties. Its fine particle size and spherical morphology can improve mixture mobility, whereas its slower pozzolanic reaction may limit early-age strength gain, particularly when the replacement level is high. This behavior becomes more critical in low-density foamed concrete because the high air-void content already reduces the effective solid matrix contributing to strength development [5, 6].

Recent experimental studies have shown that fly ash content significantly affects dry density, compressive strength, and water absorption of foamed concrete, and that the influence of fly ash depends strongly on replacement level, mixture design, and curing age [6]. From an environmental standpoint, fly ash utilization is also important, as improper disposal may cause environmental pollution due to the dispersion of fine particulate matter [7]. Therefore, incorporating fly ash into foamed concrete represents a sustainable approach to industrial by-product utilization and resource efficiency.

Several studies have investigated the influence of fly ash on the mechanical, physical, and thermal behavior of foamed concrete, as well as mix optimization strategies to achieve a balance between strength and density [8-13]. For example, Li et al. examined low-cement foamed concrete incorporating fly ash and waste lime mud for road embankment applications and considered wet densities of 600, 700, 800, and 900 kg/m^3, indicating the relevance of low-density foamed concrete for embankment-related applications [5]. Chaiyaput et al. demonstrated the practical use of a cement–clay–air foam mixture as a lightweight embankment material on soft clay and reported that lightweight embankment construction could reduce settlement compared with traditional embankment systems [14]. However, most of the existing research focuses on medium- to high-density foamed concrete or emphasizes structural and thermal applications. Limited attention has been given to low-density foamed concrete (approximately 800 kg/m^3), particularly for lightweight embankment applications where both compressive strength and flowability must be simultaneously satisfied, especially at early curing ages.

This gap indicates the need for a systematic evaluation of fly ash substitution levels in low-density foamed concrete to ensure both mechanical adequacy and fresh-state workability for field application on soft soils. Therefore, this study investigates the influence of fly ash substitution (0–30%) on the compressive strength and flowability of foamed concrete with a target density of 800 kg/m^3. This study investigates the effect of fly ash as a partial cement replacement on the compressive strength and flowability of foamed concrete, and identifies the optimum mix for lightweight embankment applications. The outcomes of this research are expected to support the development of more sustainable construction materials through the utilization of industrial by-products, while also offering a technically viable alternative for reducing embankment loads and improving infrastructure performance on soft soil foundations.

LITERATURE REVIEW

FOAMED CONCRETE AND ITS CHARACTERISTICS

Foamed concrete is a type of lightweight concrete produced by introducing preformed foam into a cementitious mortar mixture, resulting in a porous structure with uniformly distributed air voids [15]. This structure significantly reduces density while maintaining sufficient mechanical performance for non-structural and geotechnical applications. The typical pore distribution within the cement matrix is illustrated in Figure 1 [16], showing the presence of entrained air voids that govern density and mechanical behavior.

Figure 1. Foamed Concrete [17]

Compared to normal concrete, which typically has a density of 2200–2400 kg/m^3 and compressive strength of 15–40 MPa [18], foamed concrete offers lower self-weight, high flowability, and self-compacting characteristics [17]. The performance of foamed concrete is strongly influenced by its mix composition, density, and curing conditions. Previous studies have shown that parameters such as water–cement ratio, binder composition, and pore structure play a critical role in determining compressive strength and durability [17].

EFFECT OF FLY ASH ON FOAMED CONCRETE

Fly ash, a by-product of coal combustion, is widely used as a supplementary cementitious material due to its environmental and technical benefits [19]. Its spherical particle morphology improves workability by enhancing particle packing and reducing internal friction. In addition, the use of fly ash contributes to sustainability by reducing cement consumption and mitigating environmental pollution associated with improper disposal [9].

However, several studies have reported that high fly ash substitution levels may reduce early-age compressive strength due to cement dilution and delayed pozzolanic reactivity [7, 8]. The extent of this reduction depends on replacement level, curing age, and the proportion of amorphous and crystalline phases. Fly ash with a higher crystalline content tends to exhibit lower reactivity, thereby limiting early formation of calcium silicate hydrate (C–S–H), which is the primary strength-contributing phase in cementitious materials.

Recent studies have investigated the influence of fly ash on the mechanical, physical, and thermal properties of foamed concrete [10-12], as well as optimization strategies to balance strength and density [13, 15, 16]. Nevertheless, most of these studies focus on medium- to high-density foamed concrete, with limited attention given to low-density applications.

FOAMED CONCRETE FOR LIGHTWEIGHT EMBANKMENT APPLICATIONS

In road embankment applications, foamed concrete is used as a lightweight fill material to reduce vertical stress on weak subgrade soils, thereby minimizing settlement and improving stability [18, 20]. The role of pavement structure in distributing loads to the subgrade is illustrated in Figure 2.

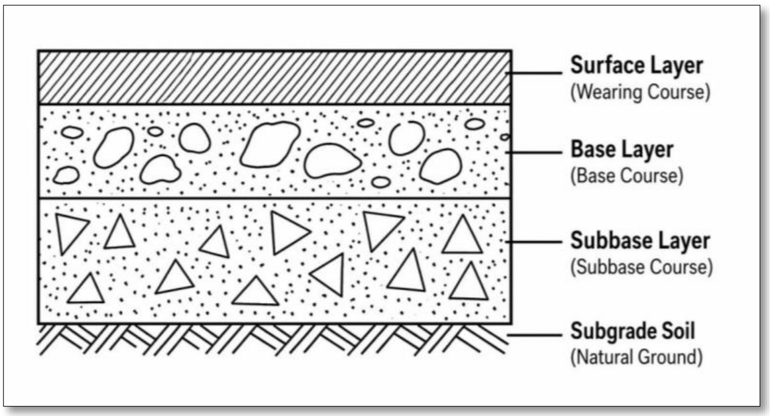

Figure 2. Pavement Layer Structure [21].

For practical implementation, foamed concrete must satisfy several performance criteria, including low density (0.5–1.2 t/m^3), adequate flowability (180 ± 20 mm), and sufficient compressive strength [22, 23]. The design criteria are summarized in Table 1.

Table 1. Design Criteria of Foamed Mortar for Road Construction

Mix Design Formula	Compressive Strength (kPa)	Density (t/m^3)
Lower layer (as embankment fill)	800	0.600
Upper layer (as base course layer)	2000	0.800

These requirements indicate that mixture design must be optimized to balance strength, density, and workability.

Mechanical Properties and Data Evaluation

Compressive strength is a key parameter used to evaluate foamed concrete performance, defined as the maximum load per unit area that a specimen can withstand before failure [11]. It is influenced by mixture composition, pore structure, and hydration processes. Statistical parameters such as mean value, standard deviation, and coefficient of variation are commonly used to assess data consistency and reliability [24].

Research Gap and Significance

Although numerous studies have investigated the incorporation of fly ash in foamed concrete, most have focused on medium- to high-density systems and emphasized structural or thermal performance [10-13, 15, 16]. Limited attention has been given to low-density foamed concrete (approximately 800 kg/m^3), particularly for lightweight embankment applications where both compressive strength and flowability are critical design requirements.

In addition, previous studies generally assess mechanical properties and workability separately, without providing an integrated evaluation of their combined performance under varying fly ash substitution levels. As a result, the interaction between fly ash content, compressive strength development, and flowability in low-density foamed concrete remains insufficiently understood, especially for early-age performance relevant to field applications.

To address this gap, this study evaluates the effect of fly ash substitution (0–30%) on the compressive strength and flowability of foamed concrete with a target density of 800 kg/m^3. The analysis focuses on identifying the optimum replacement level that satisfies both mechanical and workability criteria for lightweight embankment materials. Microstructural analyses such as XRD, FTIR, and SEM–EDS reported in previous studies [25-29] are not employed in this research as primary analytical methods. Instead, they are cited solely as supporting references to reinforce the interpretation of the experimental results. This study focuses on the macroscopic engineering performance of foamed concrete, particularly compressive strength and flowability, rather than detailed chemical or microstructural investigation.

The significance of this research lies in providing a practical and integrated evaluation of low-density foamed concrete performance for embankment applications on soft soils. The findings contribute to optimizing fly ash utilization as a sustainable construction material by reducing cement consumption while maintaining adequate engineering performance. In addition, this study offers a clearer understanding of the relationship between mixture composition and field applicability, which is essential for improving the design of lightweight embankment systems.

Materials and Methods

Materials and Equipment Preparation

The materials used in this study included Portland composite cement (PCC) produced by PT. Semen Padang, conforming to Indonesian National Standards

(SNI) [30], a surfactant-based foam agent, and fly ash obtained from the Nagan Raya power plant (FANR), which was used as a supplementary cementitious material at replacement levels of 0%, 10%, 20%, and 30% by weight [30]. Mixing water sourced from the local water supply (PDAM) was used for all mixtures and met the requirements for concrete production [18].

The selection of materials was intended to represent commonly used constituents in practical foamed concrete applications, particularly for lightweight embankment construction, in line with the engineering performance focus of this study.

Mix Design and Specimen Preparation

The foamed concrete mixtures were designed to achieve a target density of 800 kg/m^3 with a water–cement ratio of 0.5, following the guidelines specified in the Circular Letter of the Ministry of Public Works and Housing No. 44/SE/M/2015. The cementitious slurry was first prepared using a mechanical mixer, followed by the incorporation of preformed foam generated separately using a foam generator and air compressor.

Cylindrical specimens with dimensions of 100 mm in diameter and 200 mm in height were cast. A total of 24 specimens were prepared, consisting of three replicates for each variation of fly ash content (0%, 10%, 20%, and 30%) and curing ages (7 and 14 days). After casting, the specimens were cured under laboratory conditions until the testing age.

The mix design variations were specifically developed to evaluate the combined effect of fly ash substitution on compressive strength and flowability in low-density foamed concrete (800 kg/m^3), as required for lightweight embankment applications.

Testing Procedures

Compressive strength testing was conducted using an unconfined compressive strength (UCS) testing machine, where load was applied continuously until failure [11, 31]. The compressive strength was calculated using equation 1.

$$F'c = \frac{P}{A} \qquad (1)$$

where fc' is the compressive strength (N/mm^2), P is the maximum applied load (N), and A is the cross-sectional area of the specimen (mm^2).

Flowability was evaluated using a flow table test to assess the workability and consistency of the fresh foamed concrete mixtures [9]. These tests were selected to represent key engineering parameters governing the applicability of foamed concrete in field conditions, particularly its load-bearing capacity and ease of placement.

Data Analysis

The compressive strength data were analyzed using statistical parameters to evaluate variability and consistency. The standard deviation was calculated using equation 2, mean compressive strength was determined using equation 3 and coefficient of variation (cv) was calculated using equation 4 and can also be used for data classification [20, 24].

$$S = \sqrt{\frac{\sum_{i=1}^{n}(X_1 - X)^2}{n-1}} \quad (2)$$

$$X = \frac{\sum_{i=1}^{n} X_i}{n} \quad (3)$$

$$Cv = \frac{S}{X}\ x\ 100\% \quad (4)$$

S is the standard deviation, Xi is the compressive strength of each specimen (N/mm^2), is the average compressive strength (N/mm^2), and n is the number of specimens.

The influence of fly ash content on compressive strength and flowability was evaluated based on observed trends, and the performance of each mixture was assessed with reference to the requirements for lightweight embankment materials.

Results and Discussion

Mix Design Results

A total of 24 cylindrical specimens (10 cm × 20 cm) were prepared for each variation of fly ash content (0%, 10%, 20%, and 30%) and curing ages of 7 and 14 days. The mix design was formulated to achieve a target density of 800 kg/m^3 with a water–cement ratio of 0.5, and the detailed composition of each mixture is presented in Table 2. As shown in the table, the proportion of cement decreases with increasing fly ash content, while the water content remains constant across all mixtures. At the same time, the volume of foam is adjusted to ensure that the target density is consistently maintained. This indicates that in low-density foamed concrete, density control is primarily governed by foam volume rather than binder composition, which aligns with the design principle of lightweight embankment materials where reducing unit weight is essential.

Table 2. Mix Design for 1 m^3 with Density = 800 kg/m^3 and w/c = 0.5

Cement (%)	Fly Ash (%)	Cement (kg)	Fly Ash (kg)	Water (kg)	Specific Gravity of Cement	Specific Gravity of Fly Ash	Water (L)	Foam (L)
100	0	533	0	266.50	3.15	0	266.50	564.29
100	10	479.7	53.30	266.50	3.15	1.92	266.50	553.45
100	20	426.40	106.60	266.50	3.15	1.92	266.50	542.61
100	30	373.10	159.90	266.50	3.15	1.92	266.50	531.77

Flow Test Results

The flow test results presented in Table 3 show a clear decreasing trend in flow diameter with increasing fly ash content. The control mixture (0%) exhibits the highest flow value of 180 mm, followed by 10% (170 mm), 20% (150 mm), and 30% (140 mm). This demonstrates that increasing fly ash content reduces the workability of the foamed concrete mixture.

This behavior can be attributed to the finer particle size and higher specific surface area of fly ash, which increases water demand and reduces mixture mobility. In addition, previous studies suggest that fly ash with dominant crystalline phases and lower amorphous content exhibits reduced reactivity, which contributes to increased internal friction and viscosity within the mixture [**Error! Bookmark not defined.**, **Error! Bookmark not defined.**]. As a result, only mixtures containing up to 10% fly ash meet the target flow requirement of 180 ± 20 mm, while higher substitution levels fall outside the acceptable range.

Table 3. Flow Test Results of Foamed Concrete

Mix	Fly Ash Content (%)	Flow Diameter (mm)	Target Flow (mm)
1	0	180	180 ± 20
2	10	170	180 ± 20
3	20	150	180 ± 20
4	30	140	180 ± 20

This finding indicates that workability becomes a limiting factor in the use of higher fly ash content, particularly for field applications requiring adequate flowability and self-compaction. The trend is further illustrated in Figure 3, which shows a consistent decrease in flow diameter with increasing fly ash content.

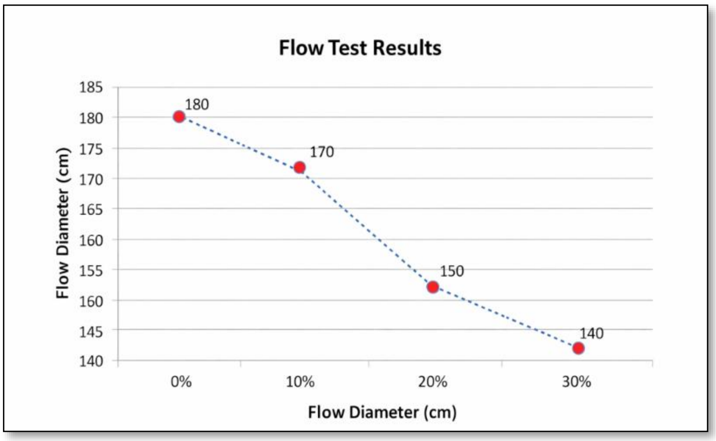

Figure 3. Flow Test Results

Compressive Strength of Foamed Concrete

The compressive strength results at 7 days, as presented in Table 4, show a consistent decrease with increasing fly ash content. The control mixture (0%) achieved the highest average compressive strength of 2.53 MPa, while the 10%, 20%, and 30% mixtures exhibit progressively lower values. This reduction is primarily associated with the cement dilution effect, where part of the reactive cement is replaced by fly ash, resulting in reduced formation of hydration products at early ages. The binding capacity of the matrix decreases, leading to lower compressive strength. However, the 10% fly ash mixture still provides acceptable performance for lightweight embankment applications, indicating that limited substitution does not significantly compromise early strength.

Table 4. Compressive Strength Results at 7 Days

Variation	Specimen	Diameter (cm)	Cross-sectional Area (cm^2)	Load (kg/cm^2)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
0%	I	10.10	80.08	2200	2.70	2.53
	II	10.17	81.19	1950	2.36	
	III	10.14	80.71	2100	2.55	
10%	I	10.10	80.08	1760	2.16	1.90
	II	10.10	80.08	1500	1.84	
	III	10.09	79.92	1400	1.72	
20%	I	10.07	79.60	1420	1.75	1.84
	II	10.15	80.87	1500	1.82	
	III	10.14	80.71	1600	1.94	
30%	I	10.03	78.97	1100	1.37	1.39
	II	10.09	79.92	1190	1.46	
	III	10.03	78.97	1070	1.33	

Figure 4 further confirms this trend, showing a clear reduction in compressive strength with increasing fly ash content. The decline becomes more pronounced at higher substitution levels (20% and 30%), suggesting that excessive replacement adversely affects early-age strength development.

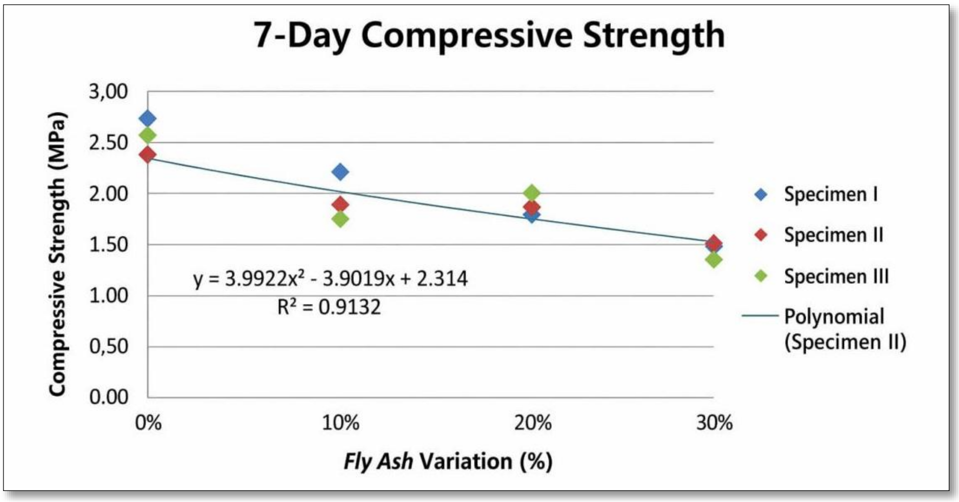

Figure 4. Compressive Strength Results at 7 Days

At 14 days, as shown in Table 5, all mixtures exhibit an increase in compressive strength compared to the 7-day results, indicating ongoing hydration. The control mixture reaches 2.70 MPa, while the 10% fly ash mixture achieves 2.25 MPa, both of which satisfy the minimum requirement. However, the 20% and 30% mixtures remain below the required strength.

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Table 5. Compressive Strength Results at 14 Days

Variation	Specimen	Diameter (cm)	Cross-sectional Area (cm^2)	Load (kg/cm^2)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
0%	I	10.12	80.40	2300	2.81	2.70
	II	10.13	80.55	2200	2.68	
	III	10.12	80.40	2150	2.62	
10%	I	10.05	79.29	1850	2.29	2.25
	II	10.05	79.29	1900	2.35	
	III	10.04	79.13	1700	2.11	
20%	I	10.08	79.76	1550	1.91	1.97
	II	10.05	79.29	1640	2.03	
	III	10.08	79.76	1610	1.98	
30%	I	10.09	79.92	1290	1.58	1.52
	II	10.09	79.92	1200	1.47	
	III	10.05	78.29	1220	1.50	

This indicates that although hydration continues over time, the contribution of fly ash at higher substitution levels remains limited, with a significant portion acting as a filler rather than a reactive binder. This interpretation is consistent with XRD-based findings reported in previous studies, which show the persistence of crystalline phases indicating lower reactivity [25]. Figure 5 illustrates that the strength development trend remains similar across all mixtures, but the relative differences persist.

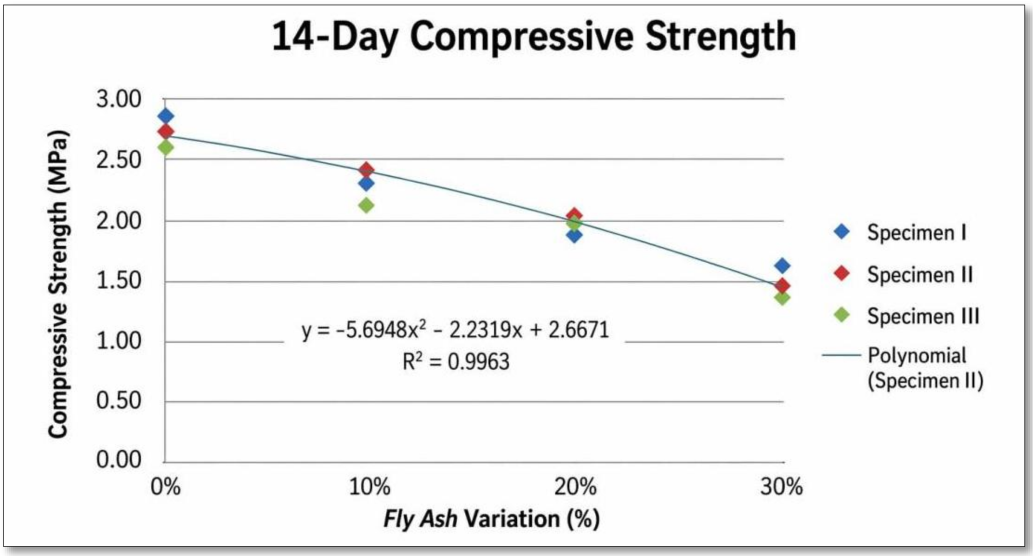

Figure 5. Compressive Strength Results at 14 Days

Data Variability and Reliability

The statistical evaluation presented in Table 6 indicates that mixtures with lower fly ash content (0% and 10%) generally exhibit more stable and consistent compressive strength results compared to higher replacement levels. This is reflected in the relatively lower standard deviation and coefficient of variation values across both curing ages. In particular, the 10% fly ash mixture demonstrates the most favorable overall performance, being classified as "Excellent" at 7 days and remaining within the "Good" category at 14 days, indicating a stable response of the material under repeated testing conditions.

Table 6. Standard Deviation of Compressive Strength at 7 and 14 Days

Fly Ash Variation	Specimen Age (Days)	Compressive Strength (MPa) (Xi)	Average (MPa) (X)	(Xi−X)²	Average (Xi−X)²	Standard Deviation (s)	Coefficient of Variation (Cv)	Classification
0%	7	2.70	2.53	0,0289	0.0194	0.098	5.07	Good
		2.36		0,0289				
		2.55		0,0004				
	14	2.81	2.70	0,0114	0.0063	0.056	8.92	Fair
		2.68		0,0004				
		2.62		0,0069				
10%	7	2.16	1.91	0.0642	0.0345	0.131	3.81	Excellent
		1.84		0,0044				
		1.72		0,0348				
	14	2.29	2.25	0,0016	0.0104	0.072	6.93	Good
		2.35		0,0100				
		2.11		0,0196				
20%	7	1.75	1.84	0,0075	0.0062	0.055	9.01	Fair
		1.82		0,0003				
		1.94		0,0107				
	14	1.91	1.97	0,0040	0.0024	0.035	14.37	Poor
		2.03		0,0032				
		1.98		0,0000				
30%	7	1.37	1.39	0,0003	0.0030	0.038	13.01	Poor
		1.46		0,0054				
		1.33		0,0032				
	14	1.58	1.52	0,0040	0.0022	0.033	15.23	Poor
		1.47		0,0022				
		1.50		0.0003				

At the 0% fly ash condition, although the compressive strength is the highest, a slight increase in variability is observed at 14 days. This suggests that even in conventional foamed concrete without fly ash, internal pore distribution and hydration progression can still introduce minor inconsistencies in strength development. However, the overall variability remains within an acceptable range according to ASTM-based interpretation, indicating reliable material behavior.

In contrast, mixtures containing higher fly ash content (20% and 30%) show a clear increase in data scatter, reflected by higher standard deviation and coefficient of variation values, particularly at 14 days where the 30% mixture falls into the "Poor" category. This trend suggests a reduction in material uniformity as fly ash content increases. The behavior can be associated with a less homogeneous internal structure, where cement dilution becomes more dominant and the distribution of partially unreactive particles may lead to non-uniform stress transfer during loading. Similar tendencies in strength dispersion have been reported in previous experimental observations of fly ash-modified cementitious systems [26, 29], where micro-level inconsistencies contribute to macro-level variability in mechanical response.

From an engineering perspective, this variability is critical because consistency is as important as strength, particularly for field applications such as lightweight embankments. A material with moderate strength but stable performance is generally more desirable than one with higher variability, as it ensures predictable behavior under service conditions.

Standard deviation in this study is used to quantify the dispersion of compressive strength data relative to the mean value, where lower values indicate more consistent results. Based on ASTM-based interpretation, values below 5% indicate very high consistency, while values below 10% are considered acceptable. The results clearly show that lower fly ash substitutions (0% and 10%) provide better reliability in terms of both strength and uniformity, whereas higher substitutions (20% and 30%) tend to reduce data reliability due to increased variability in mechanical performance..

CONCLUSION

Fly ash incorporation significantly affects the performance of foamed concrete with a target density of 800 kg/m^3, where increasing substitution levels consistently reduce both flowability and compressive strength. The flow diameter decreases from 180 mm to 140 mm, indicating a loss of workability beyond acceptable limits, while compressive strength at 7 and 14 days shows a similar downward trend due to cement dilution and the lower early reactivity of fly ash. Based on the flow requirement (180 ± 20 mm), only mixtures up to 10% fly ash meet the workability criteria, while higher replacements fail to maintain suitable fresh properties for practical application.

The 10% fly ash mixture provides the optimum performance, achieving compressive strength above 2 MPa at 14 days while maintaining acceptable flowability (170 mm). At this level, fly ash primarily acts as a micro-filler that improves particle packing without significantly compromising the cementitious matrix. Therefore, 10% fly ash is identified as the most suitable replacement level for lightweight embankment applications on soft soils, offering a balanced combination of mechanical performance, workability, and material efficiency, while supporting more sustainable cement usage.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Munawir: conceptualization, methodology, supervision. **Sriyani:** data curation, writing-original draft preparation. **Manovri Yeni** and **Haris Saputra:** visualization, investigation, software, validation, writing- reviewing and editing.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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