Acidic Sophorolipid (ASL): A Novel Bio-Based Air-Entraining Agent for Cementitious Systems

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Abstract:

Air-entraining agents are widely used in cement technology to improve durability; however, *their incorporation often leads to a reduction in compressive strength due to increased porosity. In this study, a bio-based glycolipid surfactant, acidic sophorolipid (ASL), is investigated as a novel air-entraining agent for cementitious systems. Cement pastes containing varying ASL concentrations (0.005–0.09 wt%) were prepared and evaluated at different hydration ages (3, 7, 28, 90, and 360 days).*
The results demonstrate a significant increase in air content with increasing ASL dosage, accompanied by a corresponding decrease in bulk density. Despite this, compressive strength exhibited a non-linear behavior, with an optimal performance achieved at 0.025 wt% ASL. Microstructural analysis revealed a refined and homogeneous pore structure with uniformly distributed air voids.
The improved performance is attributed to the amphiphilic nature of ASL and its ionization under alkaline conditions, which enhances interaction with Ca^{2+} *ions and stabilizes air bubbles. These findings highlight the potential of ASL as a sustainable and efficient air-entraining agent for lightweight cementitious materials.*

Keywords: air-entraining agents; acidic sophorolipid (ASL); biosurfactants; compressive strength; bulk density; microstructure; SEM; cementitious materials

I. Introduction

The pore structure of hardened cement pastes plays a fundamental role in determining their physical and mechanical properties. The incorporation of air-entraining agents (AEAs) is a well-established approach in cement technology, primarily aimed at improving workability and enhancing resistance to freeze–thaw cycles (Lea, 2004). However, the increase in entrained air content leads to higher porosity, which negatively affects compressive strength and structural integrity (Whiting & Nagi, 1998).

In recent years, significant attention has been directed toward foam concrete and aerated cementitious systems due to their lightweight nature and thermal insulation properties. Several studies have highlighted the critical role of pore structure in controlling both mechanical and durability performance of foam concrete (Zhou & Su, 2023; Gencel et al., 2022). The distribution, size, and stability of air voids have been identified as key factors influencing compressive strength and long-term durability.

Furthermore, recent developments in sustainable construction materials have emphasized the use of bio-based and geopolymer foam concretes. These materials incorporate environmentally friendly components and advanced design approaches, including artificial intelligence modeling for strength prediction (Abdellatief et al., 2025). Additionally, innovative bio-foam concrete systems utilizing waste-derived materials and microbial agents have demonstrated promising improvements in mechanical and durability properties (Al-Shaeer et al., 2025). The integration of nanomaterials has also been shown to enhance compressive strength and microstructural performance in green concrete systems (Sabarudin, 2025).

Despite these advances, the role of surfactants—particularly bio-based surfactants—in controlling air entrainment and microstructural development remains insufficiently explored. Conventional surfactants often exhibit limitations in terms of environmental impact and stability under highly alkaline conditions (Rosen, 2004; Carmel et al., 2003).

Acidic sophorolipid (ASL), a glycolipid biosurfactant produced by yeast such as *Candida bombicola*, represents a promising alternative due to its amphiphilic structure and biodegradable nature. Unlike conventional surfactants, ASL exhibits ionizable functional groups that interact with calcium ions (Ca^{2+}) under alkaline conditions, potentially enhancing air bubble stabilization and modifying hydration behavior.

To the best of the authors' knowledge, the application of acidic sophorolipid as an air-entraining agent in cementitious systems has not been systematically investigated. Therefore, this study aims to evaluate the effect of ASL concentration on air content, bulk density, compressive strength, and microstructure of cement pastes, supported by X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses.

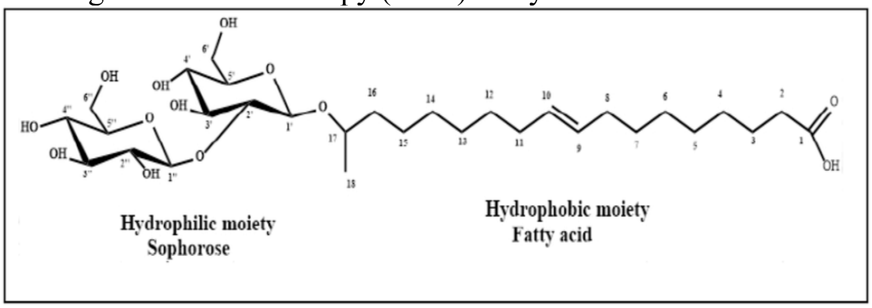

Figure 1: Acidic Sophorolipid (ASL)

2. Experimental

2.1 Materials

Ordinary Portland cement (OPC), classified as CEM I 52.5N, was obtained from El-Arish Cement Factory (Egypt). The chemical composition of the cement is presented in Table 1.
Acidic sophorolipid (ASL), a bio-based glycolipid surfactant, was supplied by Merck and used as received without further purification. Due to the presence of ionizable functionaASLroups, ASL exhibits surface activity and can interact with calcium ions (Ca^{2+}) under the highly alkaline conditions of cement pastes.

Table (1): Chemical composition of the used ordinary Portland cement (OPC).

ASL concentration (wt%)	**0.000**	**0.005**	**0.025**	**0.035**	**0.060**	**0.090**
Air content (%)	0.00	5.01	11.05	13.21	16.87	19.81
Bulk density (g/cm³)	2.00	1.74	1.61	1.52	1.49	1.37

2.2 Techniques and Instrumentation

2.2.1 Paste Preparation

Cement pastes were prepared by incorporating different concentrations of acidic sophorolipid (ASL) as a bio-based air-entraining agent. The water-to-cement ratio (w/c) was fixed at 0.43, following the procedure reported by Carmel et al. (2003).
Predetermined amounts of ASL (0.005–0.09 wt% of cement) were first dissolved in 650 g of water and then mixed with 1500 g of Portland cement (CEM I 52.5N). Mixing was carried out under continuous and vigorous stirring for approximately 3 minutes to ensure homogeneity.
The fresh pastes were cast into steel molds with dimensions of 12 × 4 × 4 cm³ and kept at approximately 100% relative humidity at room temperature for 24 hours. After demolding, the specimens were cured in water until the designated hydration ages (3, 7, 28, 90, and 360 days).

2.2.2 Compressive Strength

The compressive strength of hardened cement pastes was determined using three specimens for each mix at each hydration age (3, 7, 28, 90, and 360 days). The average value of the three measurements was reported as the compressive strength.
Testing was performed using a point-load testing machine (CEMASCO, Model 20063, Controls, Milano, Italy).

2.2.3 Stopping of Hydration

After compressive strength testing, approximately 10 g of crushed hardened cement paste was immersed in a solution of acetone and ethanol (1:1 by volume) to stop the hydration process. The mixture was stirred for 30 minutes, followed by filtration and washing with ethanol.
The samples were then dried at 50 °C for 24 hours and stored in a desiccator for subsequent physicochemical analyses.

2.2.4 Determination of Bulk Density

The bulk density of hardened cement pastes was determined by measuring the mass of the specimens in air and under water. The density was calculated in accordance with ASTM C138-08 (2008).

2.2.5 Determination of Air Content

The air content of hardened cement pastes was determined based on the difference in weight between specimens prepared with and without ASL, according to the following equation:

$$\text{Air content (\%)} = \frac{A - B}{A} \times 100$$

where:

A = weight of hardened cement pastes without surfactant

B = weight of hardened cement pastes with surfactant

2.2.6 Scanning Electron Microscopy (SEM)

The morphology and microstructure of hydrated cement pastes were examined using a scanning electron microscope (JEOL JXA-840). The dried samples were coated with a thin gold layer under vacuum prior to analysis to improve conductivity and imaging quality.

3. Results and Discussion

3.1 Effect of ASL on Air Content and Bulk Density of Cement Pastes

Air content is a critical parameter governing the physical and mechanical performance of cement pastes, as it directly influences bulk density, compressive strength, and workability. The incorporation of surfactants as air-entraining agents promotes the formation and stabilization of microbubbles within the cement matrix.

Upon the addition of acidic sophorolipid (ASL), its amphiphilic molecules adsorb at the air–water interface, leading to a significant reduction in surface tension. This reduction facilitates the formation of stable air bubbles and enhances their resistance to coalescence and rupture during mixing and hydration processes. Furthermore, under the highly alkaline conditions of cement paste, ASL molecules undergo partial ionization (–COOH → –COO⁻), which enhances their interaction with calcium ions (Ca^{2+}), contributing to improved electrostatic stabilization of the entrained air void system.

The experimental results at 90 days of hydration (Table 2) demonstrate a clear and progressive increase in air content with increasing ASL concentration. The air content increased from 0.00% in the control sample to 19.81% at 0.09 wt% ASL, indicating a strong efficiency of ASL as a bio-based air-entraining agent. Although slight variations in air content were observed at earlier hydration ages (3–90 days), the maximum and most stable air content was consistently achieved at 90 days.

In contrast, bulk density exhibited an inverse relationship with air content. As the ASL concentration increased, the density decreased from 2.00 g/cm³ for the control sample to 1.37 g/cm³ at 0.09 wt% ASL. This reduction is attributed to the increased volume of entrained air within the cement matrix, which leads to a more porous structure. The results confirm that the introduction of ASL effectively modifies the pore structure, resulting in lightweight cementitious materials.

Notably, the relationship between air content and density follows a consistent inverse trend, where an increase in air content of approximately 14% corresponds to a density reduction of about 0.3 g/cm³. This behavior is in agreement with previously reported findings and highlights the dominant role of air voids in controlling the bulk properties of cement pastes.

Table (2): effect of ASL concentration on the air content and the density of the hardened cement paste at 90 days.

Surf. conc. (Wt %)	0.00	0.005	0.025	0.035	0.06	0.09
% of air entrained	0.00	5.01	11.05	13.21	16.87	19.81
ρ (g/ cm^3)	2.00	1.74	1.61	1.52	1.49	1.37

3.2 Effect of ASL on the Compressive Strength of Hardened Cement Pastes

Compressive strength is a key performance indicator in the design of lightweight cementitious materials and must be evaluated alongside bulk density. Due to the time-dependent nature of cement hydration, strength development is strongly influenced by hydration age.

The compressive strength results of Portland cement pastes incorporating different concentrations of acidic sophorolipid (ASL) at various curing ages (3, 7, 28, 90, and 360 days) are presented in Figure 2.

In general, all mixtures exhibit a progressive increase in compressive strength with increasing hydration time, which is attributed to the continued formation of hydration products, primarily calcium silicate hydrate (C–S–H). The development of a denser and more interconnected microstructure over time contributes to this strength gain.

At all curing ages, the incorporation of ASL shows a non-linear effect on compressive strength. The strength increases with increasing ASL concentration up to an optimum value of 0.025 wt%, beyond which a gradual decline is observed. The maximum compressive strength values recorded at this optimal concentration confirm the existence of a balance between beneficial air entrainment and structural integrity.

This behavior can be explained by the dual role of ASL in the cement system. At low to moderate concentrations (≤0.025 wt%), ASL enhances the dispersion of cement particles and promotes a more uniform and stable air void system. Additionally, under the highly alkaline environment of cement paste, ASL undergoes partial ionization, which facilitates interaction with Ca^{2+} ions and improves adsorption at the solid–liquid interface. These effects collectively contribute to improved hydration kinetics and a more homogeneous microstructure, resulting in enhanced compressive strength.

However, at higher concentrations (>0.025 wt%), excessive air entrainment leads to increased porosity and reduced solid connectivity within the cement matrix. The formation of larger or interconnected air voids weakens the load-bearing structure, resulting in a decrease in compressive strength despite continued hydration.

The results clearly indicate that the optimal ASL dosage is 0.025 wt%, at which a favorable balance between density reduction and mechanical performance is achieved. This finding highlights the critical importance of dosage control when employing bio-based surfactants in cementitious systems.

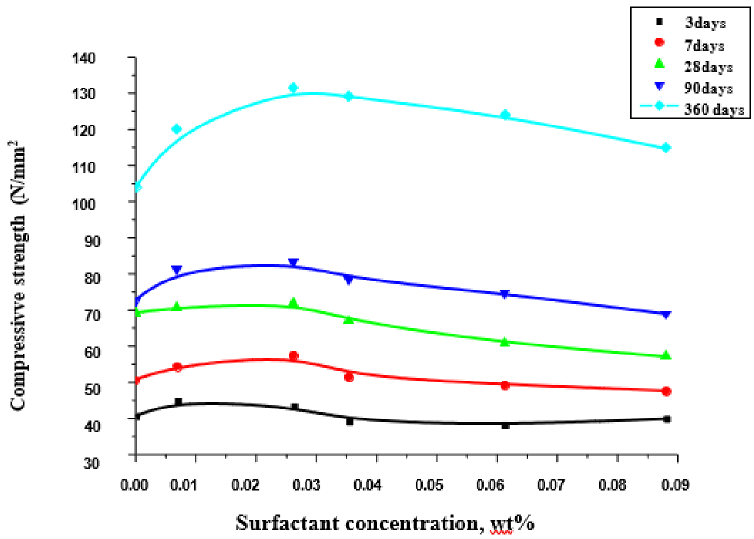

Figure 2. Compressive strength of hardened cement pastes containing different ASL concentrations at various hydration ages (3, 7, 28, 90, and 360 days).

3.3 Effect of ASL on the Microstructure and Morphology of Hardened Cement Pastes

Scanning electron microscopy (SEM) provides critical insight into the microstructural evolution of cement pastes and the morphology of hydration products. Due to its high resolution and depth of field, SEM enables detailed visualization of calcium silicate hydrate (C–S–H), calcium hydroxide (CH), and pore structure distribution.

The SEM micrographs of hardened cement pastes after 7 days of hydration are presented in Figure 4 (a–b). The control sample (Figure 4a) exhibits a typical hydrated cement structure characterized by well-defined hexagonal calcium hydroxide (CH) crystals, needle-like ettringite formations, and a relatively heterogeneous fibrous C–S–H network.

In contrast, the ASL-modified sample (Figure 4b) shows a noticeable refinement in microstructure. The hydration products appear more uniformly distributed, with an increased presence of layered calcium hydroxide and a denser C–S–H network. This behavior suggests enhanced dispersion of cement particles and improved hydration kinetics in the presence of ASL.

The SEM observations after 360 days of hydration (Figure 5a–b) further confirm the long-term influence of ASL on microstructural development. The control sample exhibits a relatively compact structure; however, the ASL-containing sample demonstrates a significantly more homogeneous and integrated matrix dominated by well-developed C–S–H phases. This increased compactness is consistent with the observed improvement in compressive strength over time.

Moreover, the incorporation of ASL leads to the formation of a well-distributed and stable air void system with relatively uniform pore sizes (~76.92 µm). Unlike random and irregular voids typically observed in untreated samples, the ASL-induced air voids are more evenly dispersed and better stabilized within the cement matrix.

This behavior can be attributed to the amphiphilic nature of ASL and its ionizable carboxylic group. Under alkaline conditions, ASL molecules interact with Ca^{2+} ions, promoting adsorption at interfaces and stabilizing air bubbles during mixing. As a result, a controlled pore architecture is formed, which enhances the balance between porosity and structural integrity.

The improved microstructural homogeneity and controlled air void distribution explain the simultaneous reduction in density and enhancement in compressive strength at optimal ASL dosage. These findings confirm that ASL not only acts as an air-entraining agent but also plays a key role in modifying hydration behavior and microstructural organization.

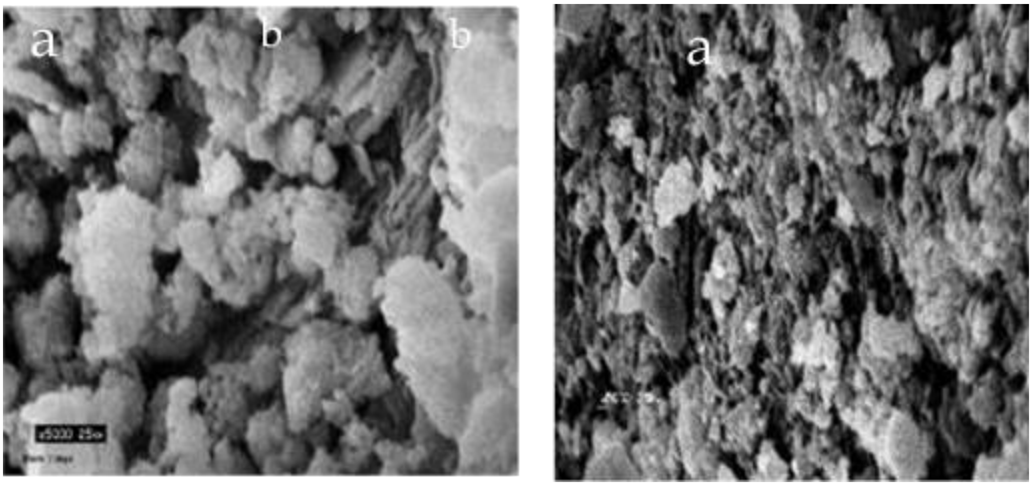

Figure (4): SEM of hardened cement pastes after 7 days hydration (X = 5000).
a) Without surfactant b) With 0.025% ASL

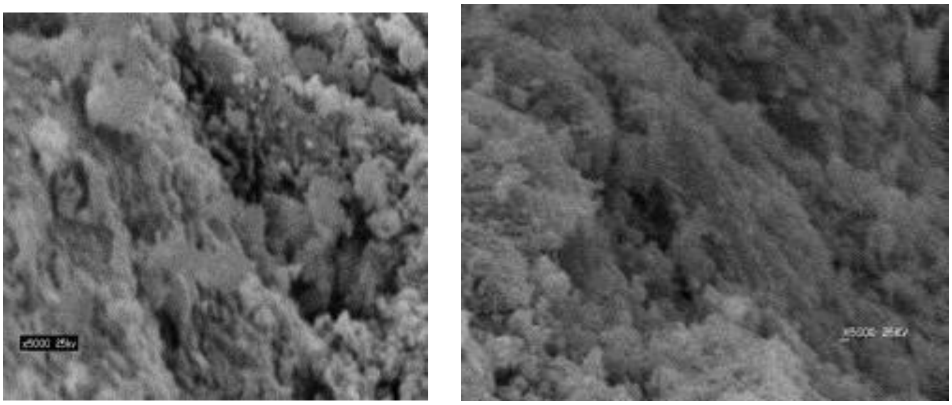

Figure (5): SEM of hardened cement pastes after 360 days hydration (X = 5000).
a) Without surfactant b) With 0.02% ASL.

Conclusion and Future Work:

The present study demonstrates that acidic sophorolipid (ASL) is an effective bio-based air-entraining agent capable of simultaneously modifying the microstructural and mechanical properties of cement pastes.The incorporation of ASL resulted in a significant increase in air content, leading to a reduction in bulk density and the formation of a well-distributed and stable air void system. Despite the increase in porosity, the compressive strength exhibited a non-linear behavior, with an optimal performance achieved at 0.025 wt% ASL. At this concentration, a balance between pore formation and structural integrity was established, resulting in enhanced mechanical performance.

Microstructural analysis confirmed that ASL promotes a more homogeneous and compact cement matrix, characterized by a refined distribution of calcium silicate hydrate (C–S–H) phases and uniformly dispersed air voids. This improvement is attributed to the amphiphilic nature of ASL and its ionizable functionaASLroups, which facilitate interaction with Ca^{2+} ions under alkaline conditions, thereby enhancing bubble stabilization and hydration processes.

Overall, ASL demonstrates a dual functionality as both a surface-active agent and a hydration-modifying additive, offering a promising pathway toward the development of lightweight and sustainable cementitious materials without significant loss of mechanical strength.

Future Work

Future investigations should focus on evaluating the long-term durability performance of ASL-modified cementitious systems, including resistance to freeze–thaw cycles, permeability, and chemical attack. Additionally, comparative studies involving different classes of biosurfactants and conventional air-entraining agents are recommended to further elucidate the structure–performance relationship. The influence of ASL on large-scale concrete applications and its potential role in sustainable construction practices also warrant further exploration.

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