A review on the stability of mineral foam in the fresh state: influencing factors

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ABSTRACT Minerals foam with a low density has excellent thermal and acoustic insulation properties due to its highly porous structure. However, the reduction of density, can be achieved by reducing the solid phase fraction (cement paste) versus the air phase in the foam, leads to instability and collapse of foam at its fresh state. To improve the mineral foam stability during the fresh state, it is very important to better understand the mechanisms and the major factors influencing bubble stability. The progress in foamed concrete production techniques and foam destabilization phenomena (drainage, coarsening and coalescence) in the fresh state are investigated. The influence of major factors such as density, surfactants, cement paste rheology, additives (superplasticizer and accelerator), the type of cement, pozzolanic additions and the production temperature on foam stability is analysed. In general, the current approaches to provide an optimal foam stability are based on optimizing the binder mixtures, adjusting the preformed foam method to produce the material, controlling the binder rheology and curing conditions, and modifying the gas-liquid interface with selected surfactants and incorporating nanomaterials.

Mots-clefs Mineral foam, Foam collapse, Foam stability, Drainage, Coalescence, Coarsening

I. INTRODUCTION

The construction industry represents a major source of global energy consumption (34%) and CO_2 emissions (37%) (United Nations Environment Programme, 2024). Innovations such as foamed concrete are being developed to respond to climate change due to their low density, insulating properties, and fire resistance (Chica and Alzate, 2019) (Priyatham *et al.*, 2023).

Foamed concrete can be classified by density: above 800 kg/m^3 for structural use (NF EN 206 A2 CN, 2022) and below for insulation. Mineral foams, ultra-light concretes without aggregates, are used for thermal and acoustic purposes (Hamada *et al.*, 2023) (Mortada, 2021). There are three methods for introducing air bubbles into a cement matrix: chemical foaming, mechanical pre-foaming and mechanical direct-foaming. Chemical foaming produces cellular concrete by adding reagents to the mixture that, by reacting with the cement's hydration products, generates a bubble gas, giving a porous structure. Mechanical foaming uses a foaming agent to stabilize air bubbles in the cementitious matrix, controlling pore formation. Air bubbles are introduced either by adding aqueous foam to the paste (pre-foaming) or by mechanically agitating water, binder, and foaming agent (Mortada, 2021) (Jiang *et al.*, 2016) (Sang *et al.*, 2015). Pre-foaming allows better control but increases water content (Jiang *et al.*, 2016). However, at very low densities (i.e. < 300 kg/m^3), fresh mineral foam presents significant stability problems. The foam structure tends to evolve over time due to the relative movements between the cement paste and the air bubble or of the interstitial fluid and the binder particles caused by drainage, air exchanges between bubbles (coarsening), and rupture of the films separating bubbles (coalescence) (Mortada, 2021). The stability of low-density mineral foam at fresh state depends on several factors, such as the nature and proportions of surfactants and additives (setting agents and superplasticizers), rheology of the binder pastes including pozzolanic additives.

This review primarily focuses on evaluating the effect of these different parameters on the fresh state stability of low-density cement based mineral foam, in order to highlight improvements in the design proportions of the mineral foam and the selection of components to improve its performance in fresh state and after hardening. Mechanical and thermal properties were not included in the present review.

II. MINERAL FOAM PRODUCTION

A. Components

Mineral foam is composed of a binder, water, a surfactant, and sometimes additives. The binder ensures cohesion and solidifies the structure during curing, forming a continuous matrix that traps air bubbles and stabilizes the foam (Petit *et al.*, 2014). The mineral paste composition, at a given air volume, influences the size and distribution of the pores (Batool and Bindiganavile, 2017). Common binders include Portland cement, rapid-hardening Portland cement, calcium sulphoaluminate cement, and calcium sulphate. Cement can be partially replaced by industrial by-products such as silica fume, fly ash, or limestone, while geopolymers or alkali-activated binders are also alternatives (Raj and Ramamurthy, 2023). Water serves two key roles: it hydrates the binder for solidification and adjusts the rheology of the mix (direct foaming) or foam-paste system (pre-foaming), facilitating bubble formation. Water content directly affects bubble formation, fresh-state foam stability, and use properties (Liu *et al.*, 2016). Surfactants control porosity by reducing water surface tension, which promotes bubble formation and stabilization. They form membranes around air bubbles, thereby limiting their coalescence and influencing their size, thus affecting porosity and hardened foam properties (Tunstall *et al.*, 2021) (Sun *et al.*, 2018). Synthetic and protein-based surfactants are commonly used. Additives, such as superplasticizers and accelerators, optimize foam performance. Accelerators promote rapid setting to stabilize the fresh foam when cement alone is insufficient (Xiong *et al.*, 2023). Superplasticizers reduces water demand, giving a more homogeneous and stable mineral foam with a controlled porosity. Selection of the appropriate superplasticizers and accelerators based on chemical interactions and pH helps maintain the foam structure. However, incompatibility or excessive use of these additives may lead to foam destabilization.

B. Foaming methods

Mineral foam is typically produced using either the "pre-foaming method", the "direct-foaming method" or the "chemical foaming method":

1. Pre-foaming Method

In this method, the foaming process is separated from the preparation of the cement paste. The principal steps are as follows:

- Independent Preparation: An aqueous foam is generated using a surfactant, either by mechanical agitation in a mixer (using a whisk or high-speed tool) or by mixing air flow and water flow by shearing using a foam generator. In the latter case, a compressed air volume is injected into a porous medium through which the surfactant solution flows. Such a foaming solution generates bubbles with a quite controlled size. On the other hand, the cement paste is prepared separately.
- Combination and Mixing: the preformed aqueous foam is then mixed with the cement paste to produce a mineral foam with a uniform distribution of bubbles in the matrix. The homogeneity and stability of the mineral foam obtained depend on the shearing conditions during the mixing of the aqueous foam and the paste. A static mixer is preferred.

Pre-foaming is recommended to produce mineral foam, as it allows better control of the air content and bubble size distribution (Xu and Garrecht, 2024), providing precise control of the final density. This method appears more efficient for producing low-density mineral foams and requires low surfactant concentrations (Chandni and Anand, 2018). However, the water required for foam generation leads to higher total water content, which can promote drainage and consequently reduce the stability at fresh state (Jiang *et al.*, 2016).

2. Direct-Foaming Method

This method combines cement paste mixing operation and foam formation. The surfactant is added directly to the binder or placed in solution in water. Direct mixing of all components leads to the formation of foam using a blade to obtain a continuous paste, then whisked for the foam. The surfactant induces the formation of a porous structure in the cement paste and contributes to the stabilization of bubbles and the development of a uniform porous structure. This method requires relatively high surfactant dosages and allows for the adjustment of foam rheology by modifying the W/B ratio and overall formulation. Foam generation and stability are strongly influenced by mixing duration and speed, as well as the type of equipment used (Chandni and Anand, 2018) (Sang *et al.*, 2015). It is particularly effective for producing high-density mineral foams, but it requires strict control of mixing parameters to achieve a stable porous structure (Mohamad, 2021) (Markin *et al.*, 2025).

3. Chemical Foaming Method

The chemical foaming method involves adding reagents to the mixture which, when they react with the cement hydration products, generate a gas with bubbles, resulting in a porous structure. Aluminum powder is frequently used, as it reacts chemically (at high pH) with the cement hydration products, generating hydrogen gas. Porosity can be controlled by the size and quantity of the aluminum grains (Wu *et al.*, 2024). Other solutions include the use of manganese or H_2O_2, which decompose and generate oxygen bubbles that form a porous structure (Yan *et al.*, 2024). However, the distribution of the bubbles is less controlled (Sang *et al.*, 2015) .

III. FOAM STABILITY ASSESSMENT

Foams are dispersions of gas in a liquid or solid matrix and consist of three structural elements: Plateau borders, nodes at bubble intersections, and liquid films separating the bubbles (Langevin, 2016). Foam formation and stability depend on gas-liquid interfacial interactions. Foam degradation is a complex process resulting from three main mechanisms acting simultaneously (Figure 1). However, these mechanisms are complicated by the potential evolution of the fluid phase (the paste) that can be analyzed as a concentrated suspension. Internal drainage of interstitial water and binder grains may occur, changing the solid volume fraction of the paste. As a consequence, the rheology of the past evolves. In addition, the grain size in the concentrated suspension may interact with the size of the liquid film (Auriol, 2018).

Drainage: Immediately after foam formation, the liquid drains by gravity from the films to Plateau borders (Safouane, 2006) (Koehler *et al.*, 2004). As the drainage process continues, the films become thinner and the bubbles transform into polyhedral shapes (Amani *et al.*, 2022). In cement pastes, drainage is delayed by high viscosity and may stop if the paste develops yield stress. However, pressure gradients appear in the fluid phase of the foam due to the interaction between the bubble interfaces. These pressure gradients lead to possible flows of water through the grains of the concentrated suspension. This drainage is then associated with a local increase of the solid volume fraction of the concentrated suspension, leading to an increase in the paste viscosity until yield stress appears. The separation of binder grains and water in plateaus between bubbles under pressure gradient is amplified by the exclusion of grains due to steric effect (interaction of grain size with the plateau and/or with the surfactant layer thickness). As a consequence, the membrane between two bubbles evolves, excluding binder grains. In some cases, the membrane becomes only a water membrane with lower stability. This phenomenon leads to interconnection between bubbles in the hardened mineral foam (Auriol, 2018).

Coalescence: When the thickness of liquid films reaches a critical value, it leads to the rupture of liquid films separating adjacent bubbles, fusing them into a single bigger bubble (Mortada, 2021). Film rupture with coalescence occurs when the local quantity of liquid is insufficient to form films (Liu *et al.*, 2024) (Biance *et al.*, 2011). This instability remains fully possible in the case of concentrated suspension as the fluid phase.

Coarsening (or Ostwald ripening): This involves gas transfer between bubbles, where smaller bubbles with higher internal pressure transfer their gas to larger bubbles through the surrounding liquid films, increasing the average size of the bubbles over time (Mortada, 2021). The main factors controlling this process are the pressure of the gas in the bubbles and the surface tension at the interfaces between the bubbles and the continuous phase (Dittmann *et al.*, 2016). If the fluid phase is a concentrated suspension, gas transfer through the concentrated suspension may be delayed.

The foam lifetime is determined by the combined effects of these mechanisms. As drainage reduces the liquid fraction, the films weaken, promoting coalescence and collapse. In mineral foams, drainage is further complicated by the evolving in the rheology of the paste, depending on its solid content and physicochemical characteristics. Developing a predictive model for mineral foam lifetime, from formation to collapse, remains a challenge.

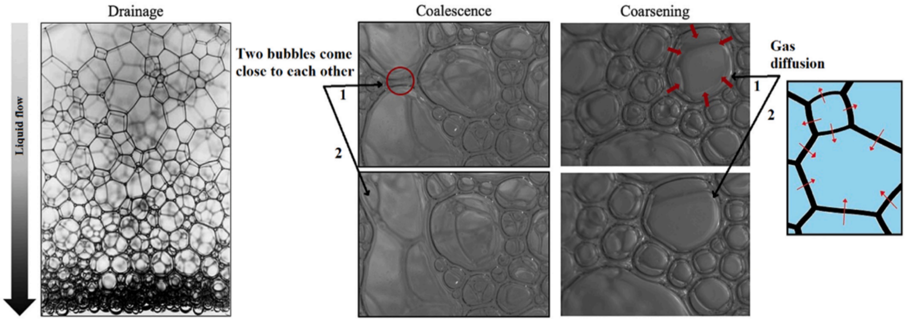

FIGURE 1. Illustration of Foam Evolution Mechanisms: Drainage, Coalescence, and Coarsening, in aqueous foams (Amani *et al, 2022*).

The complexity of interacting factors makes it difficult to develop a universal theory on foam stability. Most drainage models are theoretical and apply mainly to aqueous (biphasic) foams, with limited experimental validation for mineral (triphasic) foams (Wang *et al.*, 2016). Several experimental methods assess the influence of parameters on mineral foam stability. The foam drainage test (Wang *et al.*, 2019) is commonly used. It involves direct foaming: water, cement, a water-reducing agent (WRA), and an air-entraining agent (AEA) are mixed at 3000 rpm for 30 seconds. The foam (≥ 1000 ml) is placed in a graduated cylinder, and the liquid drainage (V_d) is measured at the bottom over 60 minutes. The foam initial liquid volume (V_0) is then estimated. Results show that foam stability varies significantly with the type of AEA, especially during the first five minutes. For example, AEA2 produces stable foam with minimal drainage, compared to AEA5, that produces unstable foam from the beginning (Figure 2).

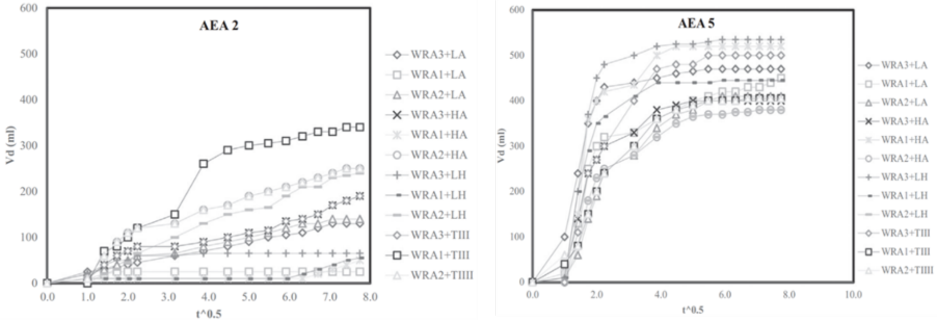

FIGURE 2. Liquid drained (V_d) vs. √t. (With LA: Type I low alkali Cement; HA: Type I high alkali Cement; LH: Type I high C3A Cement; TIII: Type III Cement.) (Wang *et al.*, 2019)

The volume of fluid (V_d) can be modeled by a function of (1/t) (Eq. 1) (Gutmann, P. F., 1988).

$$V_d = V_0 - \frac{1}{k.t} \tag{1}$$

V_d: Volume of water at time t;

V_0: Liquid volume in the foam at t = 0;

t: time;

1/k: slope of the V_d curve as a function of 1/t;

(Ke *et al.*, 2020) applied the same foam drainage method to evaluate the ability of an AEA to introduce air bubbles into a cementitious mixture and to stabilize these bubbles. (Wi *et al.*, 2024) also used this approach, extending it using fly ash and AEAs. The most common way to assess drainage in mineral foams is by measuring drainage and sedimentation rates. The drainage rate, calculated as the percentage of liquid drained relative to the initial foam volume, and the sedimentation rate, determined by foam height reduction over time, both reflect foam stability: lower rates mean better stability. (He *et al.*, 2019) used this test with three anionic foaming agents: sodium alpha-olefin sulfonate (AOS), sodium dodecyl sulfate (SDS), and sodium alcohol ether sulfate (AES). AOS and SDS gave lower drainage rates, indicating more stable foams. Similarly, (Hou *et al.*, 2019) tested SDS, cetyltrimethylammonium bromide (CTAB), emulsifier OP-10, and hydrolyzed protein (HP). While drainage rates were similar, SDS and CTAB foams had lower sedimentation rates than HP and OP-10 foams. (Hou *et al.*, 2019) also showed that adding small amounts of SiO_2 nanoparticles to the foaming agent reduced drainage rates, improving foam stability. (Ji and Sun, 2022) found that sodium carboxymethyl cellulose, especially below 0.4 w% of water, significantly reduced drainage and improved foam stability in cellular concrete.

IV. PARAMETERS IMPACTING THE MINERAL FOAM STABILITY

The foam stability depends on several key factors: density, surfactant type and quantity (which influence bubble formation and coalescence), and the cement paste rheology, which supports the foam structure over time. Additives (superplasticizers and accelerators) also impact stability, either positively or negatively. The cementitious matrix composition is critical, as changes in the cement chemistry and fineness affect hydration and stability. The production temperature also influences the reaction kinetics, setting time, and foam resistance to collapse. Understand the interaction of these factors appears to be essential for optimizing the stability of fresh mineral foams.

A. Effect of Density

(Jones *et al.*, 2016 and 2017) showed that bubble instability in foam concrete results from combined effects of buoyancy, gravity, paste pressure, and internal pressure. This instability is significant in smaller bubbles, promoting coalescence and increasing bubble size. Using the pre-foaming method, they found that increasing the foam content increased coalescence, reducing stability and leading to collapse. (Jones *et al.*, 2016) defined the primary forces acting on bubbles in fresh foam concrete: confinement force (F_c), related to wet density and rheology; drainage force (F_d) from the gravitational segregation of liquid; internal bubble pressure (P_i); surface tension force (F_{st}) from surfactants; and buoyancy force (F_b) (Figure 3). Stability is achieved when these forces are in equilibrium. At lower wet densities (≤ 500 kg/m^3), the reduced solid fraction decreases F_c, leading to larger bubbles with increased F_b. This reduction in confinement force increases the drainage force (F_d), promoting bubble coalescence and coarsening (She *et al.*, 2018). These processes lead to the formation of larger, more buoyant bubbles. Consequently, the bubbles are more susceptible to destabilizing the system. When F_b exceeds F_c, bubbles migrate toward the surface until they rupture, causing segregation and collapse. The study also demonstrates that blending calcium sulfoaluminate (CSA) cement with Portland cement can significantly accelerate setting, which immobilizes the bubble structure before instability begins. This approach enables the production of ultra-low-density foamed concrete (lower than 150 kg/m^3) that is more stable.

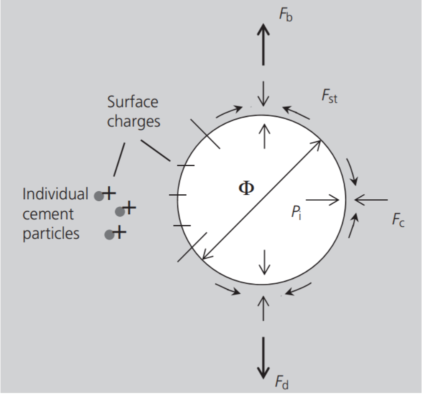

FIGURE 3. Theoretical schematic of the forces acting on an air bubble in a fresh foamed concrete mix (Jones *et al.*, 2016).

(Jiang *et al.* 2016) reported that when the density decreased from 272.8 to 109.1 kg/m^3, the median pore diameter (D_{50}) increased from 0.220 to 0.582 mm, and the (D_{90}) increased from 0.575 to 1.345 mm. Also, the total porosity (at dry state) increases from 88.5% to 95.4% (Figure 4). They attributed these changes to the reduced quantity of cement paste available to cover the bubbles, which promoted their coalescence. (Feneuil *et al.* 2019) studied foams containing initially monodisperse bubbles with radius between 0.2 and 0.9 mm, with a gas volume fraction between 81 and 84%. They showed that the solid volume fraction of the interstitial paste, which ranged from 0.32 to 0.46, controls foam rheology and stability.

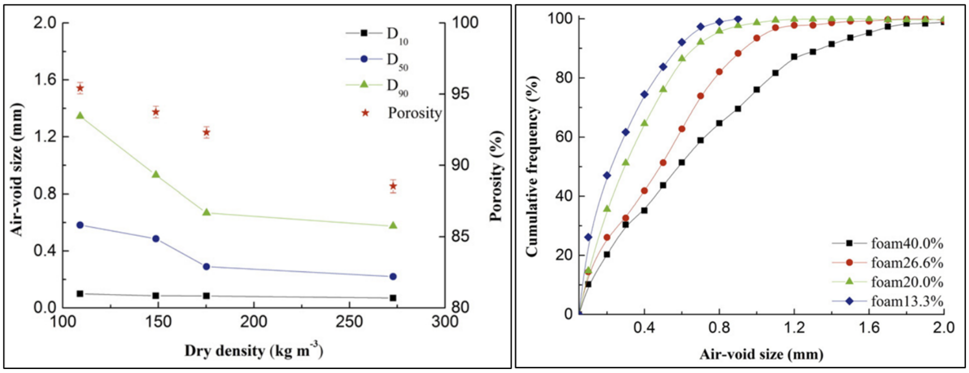

FIGURE 4. (Right): Effect of the dry density on D_{10}, D_{50}, D_{90}, and the porosity. (Left) Effect of the dry density on the cumulative frequency distribution of the pores size, with (foam 40%: 109.1 kg/m^3, foam 26.6%: 148.7 kg/m^3, foam 20%: 175.2 kg/m^3, foam 13.3%: 272.8 kg/m^3) (Jiang *et al.* 2016).

(Xiao *et al.*, 2023) studied how cement paste affects bubble stability in foamed concrete (600 kg/m^3). They defined the viscous force as the force applied by the interstitial paste on bubbles, showing that sufficient viscosity increases buoyancy resistance: bubbles rise when the sum of viscous and gravitational forces is lower than buoyancy. Low viscosity favors coalescence. At low density, the liquid film's binding force decreases with variations in fresh density and W/B, reducing yield stress (Lu *et al.*, 2024). This binding force depends on the solid fraction, where particles form structured layers enhancing stability. Film size and particle concentration influence this effect (Sethumadhavan *et al.*, 2004). High solid content raises confinement force, improving bubble stability. Below this critical size, the film can develop areas free of particles (phenomenon describe in section III) (spots), weakening the film and increasing rupture risk (Sethumadhavan *et al.*, 2004).

B. Effect of surfactant

The Mineral foams tend to collapse in the fresh state, making the choice of an efficient surfactant essential to create stable, uniform bubbles that limit drainage and coalescence. Surfactants lower surface tension and modify bubble interfacial properties (Panesar, 2013). They can be either natural (protein or plant-based) or synthetic (Amran *et al.*, 2015). Synthetic surfactants have a hydrophobic part and a hydrophilic part (the head), either ionic (cationic or anionic) or nonionic. Anionic surfactants form more stable foams than cationic, due to the electrostatic repulsion at the air-water interface and interactions with cement particles (Sargam *et al.*, 2021). *Samson et al.* (Samson *et al.*, 2016) showed that with constant surfactant content, decreasing density (551 to 254 kg/m^3) in gypsum foamed concrete changed CTAB foam from monodisperse to a more connected structure, which could be due to bubble coalescence during the fresh state.

Surfactant concentration affects surface tension until the critical micelle concentration (CMC), above which micelles form and surface tension stabilizes (Mortada, 2021). Excess or insufficient surfactant alters cement particle interactions and yield stress. (Feneuil *et al.*, 2017) showed that anionic surfactants (Steol, Bio-Terge) first increase yield stress through hydrophobization of cement particles (cf. following section III) but decrease it above a critical residual concentration (C_{Crit}) due to micelle formation. In contrast, cationic TTAB causes a gradual yield stress reduction due to limited adsorption and micelle size. (Liu *et al.*, 2021) found that SDS (anionic) and DTAB (cationic) lead to less uniform bubble sizes, while AEO-9 (nonionic) creates more uniform bubbles.

Proteins, composed of amino acids, also stabilize foam due to their hydrophobic regions (Garrn *et al.*, 2004). Their properties depend on composition, structure, charge, and environment (pH, ionic strength, temperature) (Mortada, 2021). (Gochev *et al.*, 2014) found that electrostatic repulsion in β-lactoglobulin films varies with pH and ionic strength. A higher electrostatic repulsion leads to a larger average distance between adsorbed proteins, which reduces the surface shear viscosity values. In addition, the surface shear viscosity increases as the solution pH is approached to the isoelectric point of the protein (Wierenga and Gruppen, 2010). Proteins large molecular weight enhances interfacial viscoelasticity, reducing coalescence and Ostwald ripening (Wan *et al.*, 2016). Proteins can unfold, exposing hydrophobic groups and improving foam formation (Benazzouk *et al.*, 2006) (Delahaije and Wierenga, 2022). In contrast to synthetic surfactants, proteins don't have a CMC (Samson *et al.*, 2016) (Mortada, 2021). (Hashim and Tantray, 2021) showed that protein-based surfactants (using prefoaming method) form aqueous foams with higher collapse resistance, and foamed concretes (600–1200 kg/m^3) with finer pores, higher compressive strength, and lower shrinkage compared to synthetic surfactants. (Hou *et al.*, 2021) reported that a hydrolyzed protein-based surfactant showed a moderate interaction with cement, also resulting in the formation of a calcium-protein layer around the bubbles. (Sun *et al.*, 2018) compared three surfactants (synthetic, vegetable and animal) to produce foamed concrete (600 kg/m^3). The foam produced with the synthetic surfactant showed higher stability due to a solid network formed by chemical bonds and the presence of stabilizing nanoparticles. Proteins behave differently in a cementitious environment. This variability is due to differences in surface charge, hydrodynamic size, surface tension and viscosity. The high pH environment in a cementitious medium can increase the negative charge and reduce the size of proteins, thereby improving their solubility and foaming capacity (Tale Masoule *et al.*, 2023 and 2024).

C. Effect of paste rheology and Additives

The rheological properties of cement paste critically influence bubble stability and distribution in fresh mineral foam, determining resistance to coalescence and collapse before setting (Xiao *et al.*, 2023). The yield stress must be adjusted to have sufficient flow and maintain bubble network structural integrity (Feneuil *et al.*, 2019). (Feneuil *et al.*, 2019) showed that foam yield stress ($\tau_{y,foam}$) increases with paste yield stress ($\tau_{y,0}$). A critical threshold $\tau^*_{y,0}$ (~10 Pa) was identified: above this, the paste behaves as a fluid, destabilizing the foam; below, it behaves as a confined granular medium, improving bubble stability. Cement paste rheology is commonly adjusted by the water/cement (W/C) ratio. Increasing W/C reduces viscosity and yield stress, enhancing flow but reducing bubble stabilization. This results in an increase in average size, reduced numbers of small bubbles, and a tendency have a more rounded shape (Liu *et al.*, 2016). The effect is higher in low-density foams: (Bian *et al.*, 2023) found that increasing the W/C ratio from 0.45 to 0.55 in 470 kg/m^3 concrete caused a fivefold rise in pores larger than 0.40 mm, due to lower paste viscosity. High W/C reduces the solid fraction (Jiang *et al.*, 2016), reducing confinement force (F_c) and increasing drainage (F_d), promoting bubble coalescence and Ostwald ripening (She *et al.*, 2018) (Xiao *et al.*, 2023).

To improve rheology while reducing W/C, superplasticizers are used. (Chandni and Anand, 2018) found polycarboxylate ether (PCE) more effective than sulfonated naphthalene formaldehyde (SNF) in reducing W/C, which reduces macropores. (Al-Shwaiter *et al.*, 2023) showed that adding PCE to 1500 kg/m^3 cellular concrete reduced viscosity, stabilized foam, and optimized pore structure at 1.35 w% of cement, increasing hydration and densifying the matrix. Higher doses (> 1.65w%) caused anti-foaming effects. Incompatibility between a superplasticizer and a surfactant can promote coalescence and drainage (Wang *et al.*, 2019).

Setting time is also important for achieving stable foam. Accelerators promote fast hydration and ettringite formation, stabilizing bubbles (Dorn *et al.*, 2022) (Tian *et al.*, 2016). (Xiong *et al.*, 2023) showed that 1w% (of cement) formic acid produced a finer pore structure and increased yield stress evolution, improving foam stability; excess formic acid, however, caused instability. Compatibility between accelerator and surfactant, especially regarding pH, is crucial to prevent foam collapse (Siva *et al.*, 2017). (Sathya Narayanan and Ramamurthy, 2012) reported that conventional accelerators (calcium chloride, calcium nitrate, triethanolamine) were incompatible with anionic surfactants such as sodium lauryl sulfate (SLS). A high pH of calcium chloride caused instability, while calcium nitrate and triethanolamine preserved foam but did not accelerate setting time. Triethanolamine even had a retarding effect, while the performance of calcium nitrate depended on the cement composition.

D. *Effect of cement*

As a three-phase system (solid/liquid/gas), fresh mineral foam stability is significantly affected by the solid phase (cement), particularly its chemical composition and particle size, which influence bubble behaviour and paste rheology. A continuous network of solid particles at the bubble interface is important for stability. Particles with appropriate wettability and size compact at the interface, while electrostatic attractions reduce repulsion, forming a rigid structure that prevents coarsening (Shen *et al.*, 2024). Particle concentration also affects drainage, as concentration increases, the drainage regime changes from a node dominated regime to a plateau border dominated regime (Jin *et al.*, 2024). (Haffner *et al.*, 2015) studied how particle size and trapping impact foam drainage, introducing a confinement parameter ($\lambda = d_P / d_c$) comparing particle size (d_P) to foam constriction size (d_c). This concept was also employed by (Kaddami 2019) to evaluate the relationship between λ and the solid volume fraction of concentrated suspensions to produce stable metakaolin geopolymer foams. She demonstrated that, above a critical solid fraction (φ_p between 0.11 and 0.25), packing of particles into confined canals blocks drainage and significantly improves rheological properties, such as viscosity and yield stress. This stabilization preserves the bubble size distribution, leading to monodisperse pores (0.2–1 mm), and limiting the coarsening of foam with pore sizes bigger than 0.5 mm.

Pozzolanic additives, used to partially replace Portland cement, also influence foam properties. Silica fume reduces large bubble sizes, promoting a more uniform bubble distribution (Hilal *et al.*, 2015). (Liu *et al.*, 2021) found that silica fume enhances foam stability by densifying the matrix but can decrease bubble stability over time due to water absorption from its high surface area. At higher dosages (10–16w% of cement), silica fume improves overall foam stability. Fly ash acts as a filler, reducing paste viscosity and bubble coalescence, improving bubble dispersion and foam stability (Li *et al.*, 2021). (Gökçe *et al.*, 2019) showed that the fineness of fly ash and silica fume enhances bubble distribution, especially with fly ash, but this effect decreases in mixtures with high foam content. A precise adjustment of the W/C ratio remains essential when using pozzolanic materials to balance workability, cohesion, and durability (Batool and Bindiganavile, 2018).

E. *Effect of temperature*

A study on cement-limestone foamed concrete (Zeng *et al.*, 2024) showed that raising the temperature from 27°C to 40°C increases viscosity by 2.6 times, accelerates foaming by a factor of 20. At low temperatures (27–30 °C), a homogeneous distribution of bubbles (between 0.5 and 1 mm) is observed. The median bubble size (D_{50}) increases progressively, from 0.65 mm at 27 °C to 1.01 mm at 42 °C. However, higher temperatures reduce the pH and fluidity. (Jin *et al.*, 2021) reported that increasing the production temperature from 35°C to 40°C accelerates cement hydration, reducing pore size and enhancing compactness. The temperature of the surfactant solution is also important. At 20°C, foamed concrete forms smaller, more uniform bubbles, limiting coarsening and improving strength and durability (Xiong *et al.*, 2023). For example, at a density of 500 kg/m^3, a 20°C foaming solution improved foam stability and produced a uniform pore structure. Moreover, rising temperatures increase drainage and bubble film thickness, accelerating coalescence (Ping *et al.*, 2023).

V. CONCLUSION

This study highlights the key parameters that govern the fresh stability of mineral foams. It focuses on the interdependent roles of cement paste rheology, the nature and dosage of surfactants, the content of superplasticizers and accelerators. An optimally adjusted cement paste stabilizes air bubbles by minimizing coalescence and drainage before setting. Consequently, a uniform microstructure is formed, improving the mechanical strength and reducing the thermal and acoustic conductivity of the hardened foam.

The results showed that optimizing the amount of surfactant (synthetic or protein-based) and ensuring its compatibility with superplasticizers and accelerators is critical to control the size of bubbles in fresh foams. Adjusting the cement paste rheology, particularly through the water-to-cement ratio and superplasticizer addition, provides precise control of yield stress, another critical factor in maintaining bubble network integrity.

Future work will focus on optimizing the interactions between these parameters under industrial processing conditions. Adopting a combined approach that includes fresh-state characterization and hardened-state thermomechanical and acoustic performance assessment will facilitate the development of optimized, low-density mineral foams with better functional properties for construction and insulation applications.

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