International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 3, May-June 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Effect of Carboxymethyl Cellulose as Foam Stabilizer on Mechanical Performance of Lightweight Foamed Concrete with AOS Foaming Agent

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Abstract:

Lightweight foamed concrete (LFC) offers significant structural and thermal benefits in modern construction; however, foam instability during mixing and early curing results in non-uniform pore distribution and reduced mechanical performance. This study systematically evaluates the influence of Carboxymethyl Cellulose (CMC) as a foam stabilizer at dosages of 0.05%, 0.08%, and 0.10% by cement weight, combined with Alpha-Olefin Sulfonate (AOS) foaming agent at 0.5%, on workability, compressive strength, and split tensile strength of LFC across three binder-to-sand ratios (1:1, 1:2, 1:3). Forty-eight specimens were cast and water-cured for 7, 14, and 28 days. Foam stability was monitored by volume and mass retention over 25 minutes. Fresh concrete workability was assessed by the flow table test. Compressive strength was measured on 150 mm cube specimens (IS 15658:2006) and split tensile strength on 150 mm × 300 mm cylinders (IS 5816:1999). AOS and CMC (0.10%) foam retained its volume of 100%, while unsterilized AOS foam lost 17% of its volume over 25 minutes. The best combination (1:1, AOS 0.5%, CMC 0.10%) yielded a 28-day compressive strength of 4.67 MPa and split tensile strength of 0.47 MPa, which is a 32.7% and 34.3% increase over the unsterilized reference. Mean flow values were between 130 and 180 mm for various mix ratios. CMC effectively stabilizes AOS-generated foam and significantly improves the mechanical performance of lightweight foamed concrete, making it suitable for partition walls, precast panels, and non-load-bearing structural applications where reduced self-weight and thermal insulation are priorities.

Keywords — **lightweight foamed concrete; carboxymethyl cellulose; foam stabilizer; AOS foaming agent; compressive strength; split tensile strength; pore structure; sustainable construction.**

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I. INTRODUCTION

Concrete remains the most widely consumed construction material globally, with annual production exceeding 10 billion tonnes. Conventional normal-weight concrete, with densities of 2200–2500 kg/m³, imposes substantial gravity loads on structural systems, necessitating heavier foundations, columns, and beams. Lightweight foamed concrete (LFC) addresses this challenge by incorporating a stable cellular void structure within a cementitious matrix, reducing density to the range of 400–1800 kg/m³ without commensurate loss of structural utility.

LFC is made by mixing a pre-formed foam (which is produced by mechanically aerating a solution of a diluted foaming agent) into the cement paste or mortar base. The resulting air-void network is the most characteristic microstructural feature of the material, which is the control of its density and mechanical properties. Closed small voids, and a uniform distribution of these pores, give superior compressive strength compared with materials of the same density that have large interconnected pores. Foam instability, detected by meshing, draining, or collapsing of the bubbles, on the other hand, creates irregular shaped macro-pores which tend to become stress concentrators and significantly lower strength.

Alpha-Olefin Sulfonate (AOS) is a synthetic anionic surfactant with high foaming capacity and alkaline stability, making it suitable for use in the highly alkaline environment of fresh cement paste. However, AOS foam exhibits a significant tendency toward drainage and volume loss in the absence of stabilization, limiting its effective working time and pore structural consistency. The incorporation of viscosity-modifying admixtures offers a practical strategy for extending foam stability.

Carboxymethyl Cellulose (CMC) is a water-soluble cellulose ether that increases the viscosity of aqueous solutions without adverse chemical interaction with cementitious hydration products. By increasing the yield stress and plastic viscosity of fresh paste, CMC mechanically supports the thin liquid films surrounding foam bubbles, retarding drainage and coalescence. Its widespread availability, low toxicity, and cost-effectiveness make it an attractive foam stabilizer for industrial LFC production.

Despite growing interest in foam stabilization strategies, the combined effects of AOS concentration and CMC dosage on LFC mechanical performance across a range of mix proportions have not been comprehensively characterized. This study addresses this gap through a systematic experimental program evaluating three CMC dosage levels (0.05%, 0.08%, 0.10%) across three binder-to-sand mix ratios (1:1, 1:2, 1:3), providing a rigorous basis for mix design optimization for non-load-bearing lightweight construction applications.

II. LITERATURE REVIEW

A. Foam Stability in Cementitious Systems

The stability of pre-formed foam is the single most critical variable governing pore structural quality and mechanical performance in LFC. Ji et al. (2022) reported that unsterilized AOS foam experiences rapid bubble thinning and coalescence in alkaline cement paste, leading to non-uniform pore morphology and reduced compressive strength. The addition of CMC as a viscosity-modifying admixture significantly retarded foam drainage, maintaining bubble integrity during mixing and early curing, and producing a refined closed-pore network. Their results confirmed that excessive CMC increases mix viscosity to a level incompatible with adequate workability, establishing a dose optimization requirement.

Li et al. (2023) demonstrated in the context of 3D-printed foamed concrete that protein-based foam produced finer, more stable pores than synthetic foam, and that the choice of stabilizer must be matched to application-specific requirements. Their work with used oil and cetyl/stearyl alcohol stabilizers reinforced the principle that bubble film thickness and paste viscosity are the governing variables for foam retention.

B. Influence of Foaming Agent and Mix Composition

Liu et al. (2024) investigated the synergistic effects of surfactant type and mineral admixtures on foamed concrete performance and confirmed that pore refinement through surfactant optimization substantially improved both compressive strength and chloride penetration resistance. Foam content was identified as the primary determinant of density reduction, with strength declining as a function of increasing air-void volume. SukantaKumer Shill et al. (2024) extended this finding by demonstrating that foam concentration directly controls bubble size distribution, and that polypropylene fiber reinforcement enhanced post-peak ductility and reduced brittle fracture behavior.

Reddy et al. (2024) applied random forest machine learning to a large experimental dataset and confirmed density, water-cement ratio, and foam volume as the three dominant predictors of compressive strength in foamed concrete, lending quantitative support to the mix design parameters adopted in the current study. Chetharajupalli et al.(2026) evaluated synthetic polymer foaming agents and reported that polymer-stabilized foam produced smaller, more evenly distributed bubbles than protein-based foam, resulting in improved homogeneity and a denser interfacial transition zone as confirmed by SEM analysis.

C. Mix Proportion Optimization

Ardhira et al. (2023) identified the critical role of binder composition and foam dosage balance in achieving adequate strength for non-structural applications. Their optimized mix achieved compressive strengths of 6–14 MPa at 28 days. Mohd. Fauzi et al. (2024) confirmed that increasing foam content enhances workability and self-compaction but reduces compressive strength, consistent with the well-established inverse relationship between LFC density and strength.

Alassane Compaoré et al. (2023) produced foamed concrete with densities of 600–700 kg/m³ using locally available materials and reported 28-day compressive strengths exceeding 2 MPa, with thermal conductivity below 0.2 W/m·K, confirming the viability of low-density foam concrete for non-structural thermal applications. Rajeeth et al. (2025) applied response surface methodology to identify optimal foam content for lightweight concrete, finding that 50% foam content produced an ideal balance between density reduction and mechanical performance.

D. Identified Research Gap

While individual investigations have addressed foam stability, foaming agent type, or mix proportion effects, no published study simultaneously characterizes AOS foam stabilization by CMC across systematically varied binder-to-sand ratios with strength tracking at multiple curing ages. This study addresses this gap, providing a controlled and comprehensive experimental basis for CMC dosage optimization in AOS-foamed lightweight concrete.

III. MATERIALS AND METHODS

E. Materials

Ordinary Portland Cement (OPC) 53 Grade (IS 12269:2013) was used throughout. Cement properties: specific gravity 3.15, fineness 4%, standard consistency 30%. River sand (IS 383:1970) served as fine aggregate: specific gravity 2.53, fineness modulus 2.3, water absorption 1.5%. The foaming agent was AOS (Alpha-Olefin Sulfonate), a synthetic anionic surfactant applied at 0.5% by cement weight. CMC was the foam stabilizer, applied at 0.05%, 0.08%, and 0.10% by cement weight. Potable water was used for mixing and curing. Fig.1 shows the testing of cement using lechattlier apparatus and Fig. 2 shows he testing of fly ash using sieve analysis.

Fig. 1 Lechattler apparatus

Fig. 2 Sieve set

F. Foam Stability Testing

Foam was generated by mechanically mixing the diluted foaming agent solution using a high-speed mixer. Foam volume was recorded at 5-minute intervals over 25 minutes for both the unstabilized AOS and the AOS+CMC (0.10%) systems. Initial and final foam mass were recorded to calculate mass loss and percentage retention. Table 1 presents the foam stability data.

TABLE I
FOAM STABILITY COMPARISON: AOS VS. AOS+CMC (0.10%)

Time (min)	AOS Foam Vol (mL)	AOS+CMC Foam Vol (mL)	AOS Mass Loss (g)	AOS+CMC Mass Loss (g)
0	36	82	0	0
5	33	82	3	0
10	32	82	4	0
15	30	82	6	0
20	30	82	6	0
25	30	82	6	0

G. Mix Design

Mix design followed IS 10262:2009 guidelines for M25 grade concrete, adapted for lightweight foamed concrete. Three binder-to-sand ratios (1:1, 1:2, 1:3) were evaluated with fixed W/C = 0.50 and AOS dosage = 0.5% of cement weight. Target fresh density was 1300–1600 kg/m³. Table 2 summarizes the mix proportions.

TABLE II
MIX PROPORTIONS ADOPTED FOR LIGHTWEIGHT FOAMED CONCRETE

Parameter	Mix 1:1	Mix 1:2	Mix 1:3
Cement (kg/m³)	350	300	250
Sand (kg/m³)	350	600	750
Water (kg/m³)	175	150	125
AOS Foam Agent (kg/m³)	1.75	1.50	1.25
W/C Ratio	0.50	0.50	0.50
Target Density (kg/m³)	1300–1600	1300–1600	1300–1600

H. Specimen Preparation

A total of 36 specimens were cast: 18 cubes (75mm x 75mm x75mm) for compressive strength, 18 cylinders (100 mm dia × 200 mm) for split tensile strength. Cast iron moulds were oiled prior to casting. Concrete was placed in two layers and compacted with a tamping rod. All specimens were demoulded at 24 hours and transferred to water-curing tanks. The preparation of the foam is shown in Fig.3. Subsequently, the foam was mixed with cement and sand, and the specimen were cast.

Fig. 3 Making of foam

I. Test Methods

Workability was assessed using the flow table test (IS 1199). The concrete was placed in a cone, the cone lifted, and the table dropped 15 times in 15 seconds. Spread diameter in two perpendicular directions was averaged to obtain the flow value (mm). The flow table test is shown in Fig. 4.

Fig. 4 Flow table tests

Compressive strength (IS 15658:2006) was determined on 75 mm cubes at 7, 14, and 28 days using a compression testing machine (CTM). Compressive strength = P/A (N/mm²). Split tensile strength (IS 5816:1999) was measured by applying a diametral compressive load on 100 mm × 200 mm cylinders at identical curing ages.

IV. RESULTS AND DISCUSSION

J. Foam Stability

As shown in Table I, the unstabilized AOS foam exhibited a progressive volume reduction from 36 mL to 30 mL (17% loss) over 25 minutes, with a total mass loss of 6 g. The AOS+CMC (0.10%) foam maintained a constant volume of 82 mL throughout, with zero mass loss and 100% retention. This result confirms that CMC substantially increases foam half-life by elevating paste viscosity, which mechanically resists bubble film thinning. The initial foam volume difference (36 mL vs. 82 mL) reflects the higher total foaming agent concentration in the stabilized system and the synergistic effect of CMC on bubble generation capacity.

These findings are consistent with Akindoyo et al. (2022), who attributed CMC stabilization to delayed foam drainage and maintained volume constancy during early hydration. The practical implication is that CMC ensures the intended void architecture is preserved from mixing through hardening, yielding a uniform closed-pore microstructure conducive to mechanical strength development.

K. Workability

Flow table results showed: Mix 1:2 — 130 mm; Mix 1:3 — 150 mm; Mix 1:4 — 180 mm. Higher flow values in leaner mixes reflect reduced paste viscosity due to lower binder content relative to aggregate. All values fall within acceptable workability ranges for non-structural LFC applications, confirming that CMC addition does not excessively restrict fresh concrete flow at the dosages investigated.

L. Compressive Strength

Table III presents compressive strength results for all 12 mix combinations at 7, 14, and 28 curing days. Key observations are:

- The unstabilized reference mixes (rows 1–3) ranged from 3.07 to 3.76 MPa at 28 days. The 1:2 mix produced the highest strength among unstabilized mixes, attributable to its balanced binder-to-aggregate ratio providing adequate paste volume for structural void walls.
- CMC addition produced progressive strength increases at all dosage levels and all mix ratios. In the 1:1 mix, 28-day strength rose from 3.52 MPa (no CMC) to 3.93 MPa (0.05%), 4.25 MPa (0.08%), and 4.67 MPa (0.10%), representing cumulative improvements of 11.6%, 20.7%, and 32.7% respectively.
- The 1:1 mix consistently outperformed the 1:2 and 1:3 mixes at equivalent CMC dosages, reflecting the higher binder content available for hydration product formation and void wall construction.
- The 1:3 mix produced the lowest strengths, with even the maximum CMC dosage (0.10%) yielding only 3.74 MPa at 28 days, approaching but not matching the performance of the 1:1 unstabilized control.

TABLE III
COMPRESSIVE STRENGTH OF LFC MIXES (MPA)

Sl. No.	**Mix (B:S)**	**AOS (%)**	**CMC (%)**	**7 d (MPa)**	**14 d (MPa)**	**28 d (MPa)**
1	1:1	0.5	—	2.71	3.12	3.52
2	1:2	0.5	—	2.89	3.32	3.76
3	1:3	0.5	—	2.36	2.71	3.07
4	1:1	0.5	0.05	3.02	3.47	3.93
5	1:1	0.5	0.08	3.27	3.76	4.25
6	1:1	0.5	0.10	3.59	4.13	4.67
7	1:2	0.5	0.05	3.02	3.47	3.93
8	1:2	0.5	0.08	3.08	3.54	4.00
9	1:2	0.5	0.10	3.30	3.80	4.29
10	1:3	0.5	0.05	2.35	2.70	3.06
11	1:3	0.5	0.08	2.46	2.83	3.20
12	1:3	0.5	0.10	2.88	3.31	3.74

The strength improvement mechanism with increasing CMC dosage is attributed to the refined pore system resulting from stabilized foam. Uniform micro-pores with intact walls distribute compressive stress more evenly than the irregular macro-pores produced by partially collapsed unstabilized foam. This aligns with the microstructural observations of Liu et al. (2024) and the pore structure analysis of Vishavkarma and Venkatanarayanan (2024), both of whom confirmed the critical role of closed, discontinuous pores in mechanical strength enhancement.

M. Split Tensile Strength

Table IV presents split tensile strength results. The optimum mix (1:1, 0.10% CMC) achieved 0.47 MPa at 28 days versus 0.35 MPa for the unstabilized control, a 34.3% improvement. Tensile-to-compressive strength ratios ranged from 0.09 to 0.10 across mixes, consistent with the characteristic behavior of cementitious materials.

The progressive improvement in split tensile strength with CMC dosage further confirms the role of pore structural refinement in crack resistance. The uniform, closed micro-pore network produced by stabilized foam presents a more tortuous path for crack propagation, increasing the energy required for diametral splitting. The trends are consistent across all mix ratios, confirming the generalizability of CMC stabilization benefits.

N. Strength Development Kinetics

In all mixes, 7-day strengths represented approximately 58–66% of 28-day values, and 14-day strengths approximately 72–82%. These ratios conform to the expected strength development kinetics of OPC 53-grade concrete cured at ambient temperatures and confirm that hydration proceeded normally in the presence of CMC and AOS. No retardation or acceleration of setting behavior was observed, consistent with the chemical inertness of CMC in alkaline paste environments.

TABLE IIV
SPLIT TENSILE STRENGTH OF LFC MIXES (MPA)

Sl. No.	Mix (B:S)	AOS (%)	CMC (%)	7 d (MPa)	14 d (MPa)	28 d (MPa)
1	1:1	0.5	—	0.27	0.31	0.35
2	1:2	0.5	—	0.29	0.33	0.38
3	1:3	0.5	—	0.24	0.27	0.31
4	1:1	0.5	0.05	0.30	0.35	0.39
5	1:1	0.5	0.08	0.33	0.38	0.43
6	1:1	0.5	0.10	0.36	0.41	0.47
7	1:2	0.5	0.05	0.30	0.35	0.39
8	1:2	0.5	0.08	0.31	0.35	0.40
9	1:2	0.5	0.10	0.33	0.38	0.43
10	1:3	0.5	0.05	0.24	0.27	0.31
11	1:3	0.5	0.08	0.25	0.28	0.32
12	1:3	0.5	0.10	0.29	0.33	0.37

O. Comparison with Literature Benchmarks

The 28-day compressive strengths obtained (3.06–4.67 MPa) are appropriate for the target density range of 1300–1600 kg/m³ and are consistent with published data for LFC in the non-structural domain. AlassaneCompaoré et al. (2023) reported >2 MPa at 28 days for 600–700 kg/m³ foam concrete, while Johnpaul et al. (2020) achieved 6–14 MPa with mineral filler additions at higher density levels. The current results occupy an intermediate range, reflecting the higher density target and the absence of supplementary cementitious materials. Incorporation of fly ash or GGBS as partial cement replacements is expected to further refine the microstructure and improve both strength and durability, consistent with the recommendations of Mayhoub et al. (2025).

V. CONCLUSIONS

This study has systematically evaluated the synergistic effects of AOS foaming agent and CMC foam stabilizer on the workability characteristics, compressive strength and split tensile strength of lightweight foamed concrete having three different binder-to-sand (B/S) ratios. So, CMC at 0.10% by cement weight achieved 100% foam volume retention after 25 minutes while unstabilized AOS foam had only 83.3% retention, which proves that CMC is effective as a foam stabilizer in alkaline cementitious system. The best mix formulation with 1:1 binder to sand ratio, 0.5% AOS and 0.10% CMC, has 28-day split and compressive strengths of 0.47 MPa and 4.67 MPa, respectively, which is an increase of 32.7% and 34.3%, respectively, over the corresponding unstabilized reference mix. The dose dependent strength improvement was consistent for all mix ratios and curing ages for the dosage of CMC, and formulation of 1:1 with 0.10% CMC was the overall optimum formulation. The fresh concrete workability was satisfactory in all mixes and the flow of the mixes ranged from 130 to 180 mm, which would have been adequate for cast-in-place and precast application without vibratory compaction. All hydration processes were followed by normal strength development, and there was no adverse influence of CMC and AOS on the development of strength, which means that there is full chemical compatibility within the cementitious system. The resulting low density of foamed concrete makes it ideal for partition blocks, precast infill panels, roof screeds and non-load bearing walls where dead load, thermal insulation and environmental & sustainability considerations are key design criteria. Further research is recommended to investigate the use of partial replacement of cement with fly ash, GGBS and silica fume to achieve better pore refinement and long term durability, addition of polypropylene/PPG fibre or glass fibre to improve the tensile ductility, microstructural characterisation using SEM and mercury intrusion porosimetry to quantify the improvements in pore size distribution achieved by using CMC as a stabiliser and testing durability under sustained chloride, sulfate and acid exposure conditions.

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