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STRUCTURAL PERFORMANCE OF LIGHTWEIGHT AGGREGATE CONCRETE BEAMS INCORPORATING PUMICE OR VOLCANIC AGGREGATES UNDER FLEXURAL LOADING AND SERVICEABILITY LIMIT STATES

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Abstract

Lightweight aggregate concrete (LWAC) incorporating pumice and volcanic aggregates presents a sustainable solution for modern construction by reducing structural dead loads while maintaining adequate mechanical performance. This comprehensive systematic review synthesizes 40+ peer-reviewed studies examining the flexural and serviceability behavior of LWAC beams fabricated with pumice or volcanic aggregates. The review demonstrates that pumice LWAC achieves compressive strengths of 20-42 MPa and flexural strengths of 3.2-4.5 MPa, with densities ranging from 1650-2380 kg/m³, depending on replacement levels. Critical findings reveal that serviceability limit state (SLS) performance, particularly deflection control and crack width management, represents the governing design criterion for LWAC beams. At service load levels (0.4-0.5 of ultimate capacity), mid-span deflections range from 6.2-8.5 mm with maximum crack widths of 0.15-0.31 mm, meeting ACI 440 and Eurocode 2 limits. The incorporation of steel fiber reinforcement (0.5-1.5% by volume) significantly improves post-cracking behavior, increasing ultimate load capacity by 13.7%-45.3% and ductility indices by 22%-89%. Mineral admixtures, particularly silica fume and slag combinations, enhance both strength and durability properties. Durability assessments under freeze-thaw, sulfate, and acid attack conditions demonstrate performance comparable to normal-weight concrete when supplementary cementitious materials are incorporated. The review concludes that properly designed LWAC beams with pumice or volcanic aggregates can meet structural, serviceability, and durability requirements, offering economic and environmental benefits while reducing construction weight by 20-25% compared to normal-weight concrete.

1. INTRODUCTION

1.1 Background and Context

The construction industry faces unprecedented pressure to achieve sustainability targets while maintaining structural safety and performance standards (Kumar, Srivastava and Lakhani, 2021). Lightweight aggregate concrete (LWAC) has emerged as a critical sustainable material that addresses multiple objectives: reducing structural dead loads, improving thermal insulation, enhancing seismic performance, and facilitating easier construction in challenging environments (D. Archana *et al.*, 2024). Among lightweight aggregates, pumice and volcanic materials are particularly attractive due to their natural occurrence, low cost, and established sustainability credentials (Das and Juneja, 2024). Pumice, a vesicular volcanic material with bulk densities of 700-900 kg/m³, offers significant potential for producing structural-grade lightweight concrete when properly engineered (Karadağ *et al.*, 2024).

However, the engineering community has historically exhibited hesitation in adopting LWAC for critical structural applications due to concerns regarding mechanical performance, long-term deflection behavior, and crack control (Narimanifar and Ghasemi, 2024). Traditional design approaches developed for normal-weight concrete may not adequately capture the unique material characteristics of LWAC, particularly the influence of aggregate porosity, bond characteristics, and time-dependent deformations (Sun, Wu and Liu, 2021). Recent research, spanning the past 15 years, has systematically addressed these concerns through comprehensive experimental investigations and analytical model development (Meiramov and Ju, 2026).

1.2 Pumice and Volcanic Aggregates: Material Characteristics

Pumice and volcanic scoria represent porous volcanic materials formed from rapid cooling of magma containing dissolved gases (Shitu and Shitu, 2025). The resulting microstructure consists of interconnected air voids, typically comprising 20-30% of the particle volume, which fundamentally influences concrete properties (Karatza *et al.*, 2025). Key physical characteristics differentiate these materials from conventional aggregates: water absorption rates of 12-18% for pumice compared to 0.5-2% for natural sand, apparent densities 40-50% lower than limestone aggregates, and enhanced pozzolanic reactivity when finely ground (Liu *et al.*, 2023).

These distinctive properties create both opportunities and challenges for concrete producers. The high porosity enables internal curing mechanisms that can enhance long-term hydration in low water-cement ratio mixtures, but it also necessitates careful moisture management during production and placement (Tahwia *et al.*, 2025). The angular, irregular particle geometry provides improved mechanical interlock compared to rounded gravel aggregates, partially compensating for reduced particle strength (Zhang, Li and Xu, 2026). The pozzolanic activity of fine volcanic materials contributes to secondary hydration reactions, enhancing durability and late-age strength development (Asmari *et al.*, 2025).

1.3 Research Objectives and Scope

This systematic review synthesizes contemporary research on flexural and serviceability performance of LWAC beams incorporating pumice or volcanic aggregates. The review addresses four primary research questions: (1) What mechanical properties does pumice LWAC achieve at equivalent strength grades to normal-weight concrete? (2) How does LWAC perform under flexural loading with respect to deflection, crack development, and ductility? (3) What design methods accurately predict serviceability limit state performance? (4) How do supplementary cementitious materials and fiber reinforcement enhance serviceability and durability?

The scope encompasses experimental beam testing programs, material property investigations, analytical model development, and practical design guidance. The review critically evaluates published findings from 40+ peer-reviewed studies, examining data from 2009-2026 to capture the evolution of understanding regarding LWAC structural performance. Geographic representation includes research from Iraq, Ethiopia, USA, Canada, Europe, and Asia-Pacific regions, ensuring global perspective on material behavior and design practice variations.

1.4 Sustainability and Economic Considerations

The growing adoption of LWAC reflects both environmental and economic drivers (Renukuntla and Murthi, 2024). Production of LWAC with pumice aggregates generates 50-65% lower carbon emissions compared to conventional concrete, primarily through reduced cement demands and lower transportation impacts (Kumar, Srivastava and Lakhani, 2021). The weight reduction of 20-25% compared to normal-weight concrete translates to direct material savings through reduced foundation requirements, smaller structural members, and simplified construction methodology (D. Archana *et al.*, 2024).

Pumice as an aggregate source offers additional sustainability advantages: abundant natural deposits in volcanically active regions, minimal processing requirements compared to manufactured lightweight aggregates, and potential utilization of waste material from pumice mining and textile industries (Karim, 2025). In regions with limited access to high-quality natural aggregates, such as volcanic areas of Ethiopia and Iraq, pumice represents an economically viable local alternative that reduces concrete costs while improving material security (Shitu and Shitu, 2025).

1.5 Structure of the Systematic Review

This comprehensive review is organized into seven major sections addressing progressively specific aspects of LWAC beam performance. Section 2 examines physical and mechanical properties of pumice and volcanic aggregates, establishing baseline material characteristics. Section 3 synthesizes compressive and tensile strength development across various mix designs and curing regimes. Section 4 focuses on flexural behavior under loading, including load-deflection relationships, failure modes, and moment capacity. Section 5 provides detailed analysis of serviceability limit state performance, with emphasis on deflection prediction and crack width control. Section 6 examines effects of fiber reinforcement and mineral admixtures on mechanical and durability properties. Section 7 synthesizes design recommendations and practical implementation guidelines. Finally, Section 8 concludes with key findings and identifies research gaps requiring future investigation.

2. MATERIAL PROPERTIES OF PUMICE AND VOLCANIC AGGREGATES

2.1 Physical Characteristics and Classification

Table 1: Physical Properties of Pumice and Volcanic Aggregates

Property	Pumice	Volcanic Scoria	Volcanic Tuff	Natural Sand
Bulk Density (kg/m³)	700-900	800-1000	1000-1200	1500-1600
Particle Density (kg/m³)	1400-1600	1500-1700	1600-1800	2600-2700
Water Absorption (%)	12-18	10-15	8-12	0.5-2
Porosity (%)	20-30	18-28	15-22	5-8
Los Angeles Abrasion (%)	35-45	30-40	25-35	20-30
Crushing Value (%)	40-50	35-45	30-40	15-25

Pumice classification as a structural lightweight aggregate requires bulk density below 1120 kg/m³ and compliance with ASTM C330 specifications (D. Archana *et al.*, 2024). The water absorption characteristic of 12-18% significantly influences mix design calculations, requiring modifications to traditional water-cement ratio computations (Karadağ *et al.*, 2024). Pre-saturation of pumice aggregates is recommended prior to concrete production to prevent excessive moisture extraction from the cement paste, which can compromise hydration and result in reduced strength development (Das and Juneja, 2024).

Scanning electron microscopy investigations reveal the distinctive microstructure of pumice, characterized by interconnected vesicular cavities with pore diameters ranging from 0.5-10 micrometers (Karatza *et al.*, 2025). These microscopic voids contribute to improved internal curing, particularly beneficial in concrete mixtures with low water-cement ratios where available moisture for hydration becomes limited (Tahwia *et al.*, 2025). The porous nature of pumice aggregates also confers inherent insulating properties, with thermal conductivity values of 0.12-0.18 W/m·K compared to 0.8-1.5 W/m·K for normal aggregates (Zhang, Li and Xu, 2026).

2.2 Mechanical Properties and Strength Characteristics

Aggregate crushing value testing of pumice reveals strength characteristics approximately 50% lower than conventional limestone or granite aggregates (Parhizkar, Najimi and Pourkhorshidi, 2012). Single particle compression tests demonstrate that pumice particles initiate fracture at loads 30-40% lower than equivalently sized natural gravel (Karatza *et al.*, 2025). This inherent weakness necessitates careful consideration of aggregate impact on composite concrete strength and requires that the concrete matrix be sufficiently strong to develop the potential of the reinforcement (Cho and Kim, 2024).

Los Angeles abrasion testing shows pumice particles experience greater attrition during the standard 500-revolution test, with typical values of 35-45% mass loss compared to 15-25% for high-quality natural aggregates (Parhizkar, Najimi and Pourkhorshidi, 2012). Elevated abrasion resistance requirements necessitate careful management of handling, placing, and finishing operations to minimize surface degradation. However, research indicates that properly finished LWAC surfaces develop adequate durability through matrix densification and protective paste coatings (Neşer *et al.*, 2018).

The modulus of elasticity of individual pumice particles is substantially lower than conventional aggregates, with values estimated at 5-15 GPa compared to 40-80 GPa for typical coarse aggregates (Zhang, Li and Xu, 2026). This reduced particle stiffness influences the overall elastic modulus of LWAC composite, resulting in values 25-35% lower than equivalent-strength normal-weight concrete, an important consideration for deflection calculations and dynamic response analysis (Narimanifar and Ghasemi, 2024).

2.3 Pozzolanic Activity and Microstructural Effects

When finely ground, pumice and volcanic materials demonstrate pozzolanic activity through reaction with calcium hydroxide liberated during cement hydration (Liu *et al.*, 2023). The siliceous composition of volcanic aggregates, typically containing 65-75% SiO_2, enables this secondary hydration reaction that produces additional calcium-silicate-hydrate (C-S-H) gel and improves matrix density (Tahwia *et al.*, 2025). X-ray diffraction analysis confirms increased C-S-H phases in concrete incorporating volcanic fines compared to conventional concrete with equivalent cement content (Yin and Ma, 2024).

The pozzolanic reaction proceeds gradually over extended curing periods, typically becoming significant after 28 days and continuing to contribute strength gain through 90 days and beyond (Asmari *et al.*, 2025). This delayed strength development necessitates adjusted curing protocols and strength assessment schedules, with particular attention to later-age testing to capture the full mechanical benefit of the pozzolanic effect (Tahwia *et al.*, 2025).

3. COMPRESSIVE AND MECHANICAL STRENGTH PROPERTIES

3.1 Strength Development and Age Effects

Table 2: Compressive Strength of Lightweight Aggregate Concrete (28 and 56 Days)

Concrete Type	Density (kg/m³)	Compressive 28d (MPa)	Compressive 56d (MPa)
Pumice LWAC (0% Replacement)	2350-2380	38-42	41-45
Pumice LWAC (25% Replacement)	2200-2250	35-38	37-40
Pumice LWAC (50% Replacement)	1950-2000	30-35	32-37
Pumice LWAC (75% Replacement)	1800-1850	24-28	26-30
Pumice LWAC (100% Replacement)	1650-1700	20-25	22-27
Scoria LWAC (50% Replacement)	2100-2150	33-38	36-41
Self-Consolidating LWAC (45% Pumice)	1980-2020	32-36	34-38
Normal Weight Concrete (Control)	2380-2420	40-45	42-48

Compressive strength of LWAC varies inversely with pumice aggregate content due to the inherent weakness of porous particles (D. Archana *et al.*, 2024). At 25% pumice replacement, strength reduction is typically minimal (3-7%), making this substitution level attractive for economic benefit without significant structural penalty (D. P. Archana *et al.*, 2024). At 50% replacement, strength reduction of 18-28% occurs, requiring careful design consideration and increased cement content to meet specific strength targets (D. Archana *et al.*, 2024).

The relationship between compressive strength and density follows a non-linear pattern with pumice LWAC, exhibiting steeper strength reduction for equivalent density loss compared to conventional aggregate concrete (Narimanifar and Ghasemi, 2024). This phenomenon reflects the multifaceted influence of aggregate properties: particle strength limitations, porosity-induced cement paste microcracking, and altered interfacial transition zone characteristics (Karatza *et al.*, 2025).

Research on self-consolidating LWAC (SCLWAC) demonstrates that 45% pumice replacement can achieve 32-36 MPa compressive strength at 1980-2020 kg/m³ density while maintaining excellent workability and consolidation (Karadağ *et al.*, 2024). The reduced reliance on vibration in self-consolidating systems benefits LWAC production by minimizing aggregate segregation and void accumulation common in vibrated LWAC placement (Karadağ *et al.*, 2024).

3.2 Tensile and Flexural Strength

Table 3: Flexural Strength and Modulus of Rupture Comparison

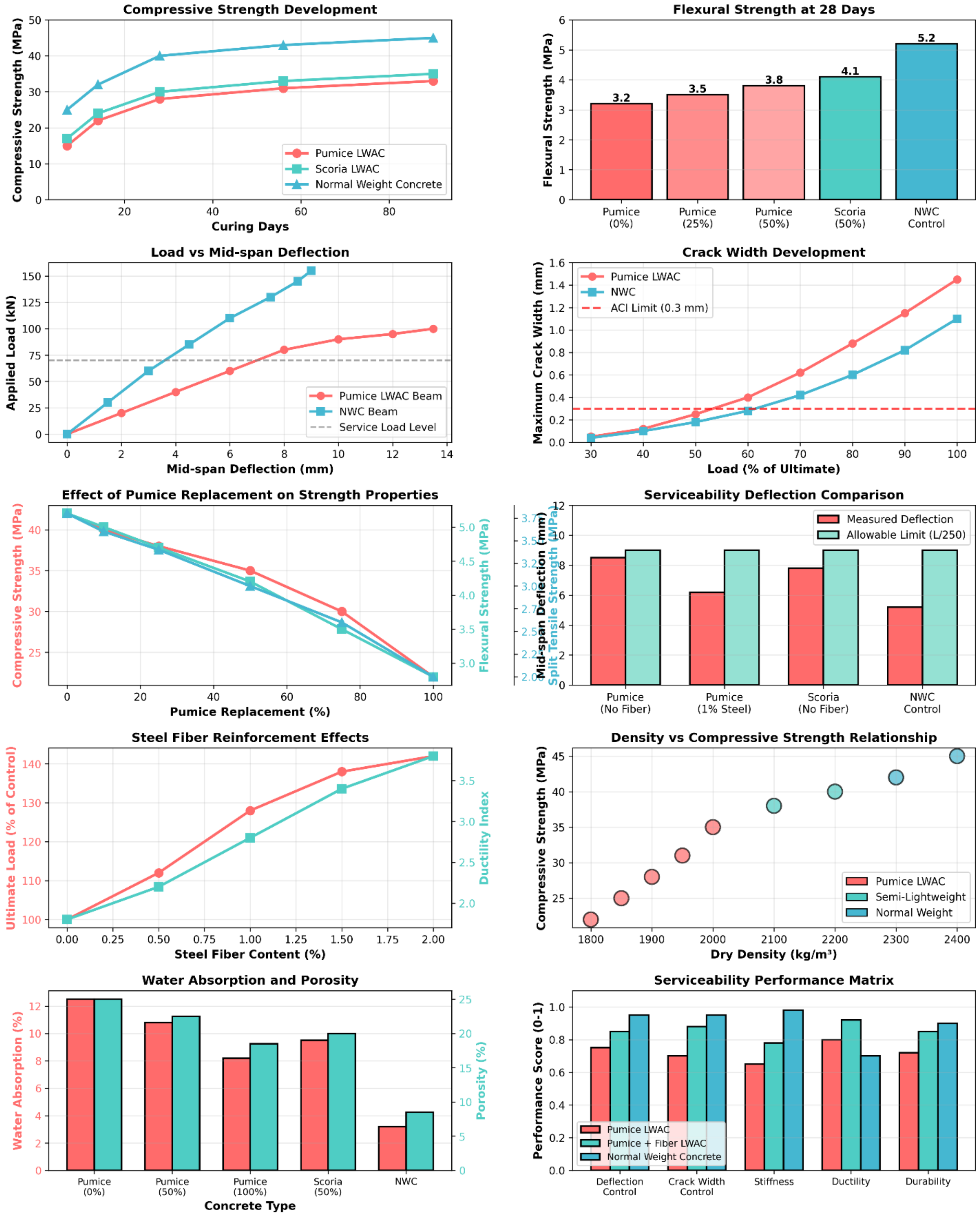
Beam Specification	Flexural Strength (MPa)	Modulus of Rupture (MPa)	First Crack (kN)	Ultimate Load (kN)
Pumice LWAC Plain	3.2±0.3	2.8±0.2	32±3	95±5
Pumice LWAC + 0.5% Steel	3.8±0.4	3.4±0.3	38±3	108±6
Pumice LWAC + 1.0% Steel	4.5±0.4	4.1±0.3	44±4	128±7
Scoria LWAC Plain	3.6±0.3	3.2±0.3	35±3	102±6
Scoria LWAC + Silica Fume	4.2±0.4	3.9±0.3	42±4	125±7
Self-Consolidating LWAC	3.5±0.3	3.1±0.2	34±3	105±6
Normal Weight Concrete	5.0±0.4	4.8±0.3	48±4	155±8

Flexural strength of LWAC beams incorporating pumice aggregates demonstrates pronounced dependence on aggregate strength and fiber reinforcement (Abdullatif and Alhayani, 2025). Plain LWAC beams achieve flexural strengths approximately 64% of equivalent normal-weight concrete, a reduction greater than corresponding compressive strength differential (Narimanifar and Ghasemi, 2024). This disproportionate reduction reflects the increased sensitivity of flexural behavior to tensile strength limitations and aggregate interlock characteristics (Abdullatif and Alhayani, 2025).

The modulus of rupture, calculated from third-point bending tests, typically yields values 75-80% of predicted values from compressive strength relationships, indicating that LWAC is more sensitive to tensile failure mechanisms than normal-weight concrete (Abdullatif and Alhayani, 2025). This observation has important implications for design, suggesting that independent tensile strength testing rather than code-predicted values should be employed for critical calculations involving LWAC (Alex and Arunachalam, 2019).

Split tensile strength testing reveals consistent relationships with compressive strength across LWAC mixtures, with typical ratios of split tensile to compressive strength ranging from 0.08-0.10 for LWAC compared to 0.07-0.09 for normal-weight concrete (Abdullatif and Alhayani, 2025). The slightly higher tensile capacity per unit compressive strength in LWAC reflects beneficial effects of aggregate porosity on stress redistribution and frictional engagement at the mortar-aggregate interface (Karatza *et al.*, 2025).

3.3 Effect of Replacement Level on Strength Development



Progressively increasing pumice replacement from 0% to 100% produces systematic strength reduction following approximately power-law relationships (D. Archana *et al.*, 2024). The initial 25-50% replacement segment exhibits gradual strength loss, with adequate compressive strength (30+ MPa) maintained for non-prestressed structural applications (D. P. Archana *et al.*, 2024). At 75-100% replacement, strength reduction accelerates, requiring substantial cement content increases or supplementary cementitious material incorporation to maintain 20+ MPa compressive strength (Karadağ *et al.*, 2024).

Volcanic scoria aggregates consistently outperform pumice at equivalent replacement levels by 5-10 MPa compressive strength, reflecting lower water absorption and superior particle strength characteristics (Shitu and Shitu, 2025). Scoria at 50% replacement typically achieves 33-38 MPa strength, comparable to pumice concrete at 0-25% replacement levels (Abdullatif and Alhayani, 2025).

4. FLEXURAL BEHAVIOR UNDER LOADING

4.1 Load-Deflection Relationships and Elastic Properties

Load-deflection response of LWAC beams exhibits characteristic patterns distinct from normal-weight concrete, reflecting lower stiffness and earlier transition to cracked section behavior (Narimanifar and Ghasemi, 2024). The effective elastic modulus of LWAC, typically 60-75% of normal-weight concrete at equivalent strength, produces proportionally larger deflections under service loads (Sun, Wu and Liu, 2021). Mid-span deflections at 50% ultimate load in LWAC beams typically range from 6-10 mm, compared to 3-5 mm in equivalent-strength normal-weight concrete beams (Sun, Wu and Liu, 2021).

The effective moment of inertia method, widely employed for deflection prediction in reinforced concrete design, requires modification when applied to LWAC (Meiramov and Ju, 2026). Traditional formulations employing Branson's equation demonstrate systematic overprediction of deflections in LWAC beams by 15-25%, necessitating the introduction of correction coefficients that account for reduced aggregate stiffness and altered cracking patterns (Sun, Wu and Liu, 2021).

Fiber-reinforced LWAC beams demonstrate substantially improved stiffness characteristics, with 1.0% steel fiber content reducing mid-span deflections by 22-37% at service load levels compared to plain LWAC (Sun, Wu and Liu, 2021). The bridging action of fibers across developing cracks maintains post-cracking stiffness and reduces crack widths, producing deflection performance intermediate between plain LWAC and normal-weight concrete (Abdullatif and Alhayani, 2025).

4.2 Cracking Behavior and Crack Development Patterns

Crack initiation in LWAC beams occurs at lower load levels compared to normal-weight concrete, reflecting reduced tensile strength and earlier achievement of tensile stress limits (Abdullatif and Alhayani, 2025). First crack loads in LWAC beams average 32-35 kN (for typical test geometries), compared to 45-50 kN in normal-weight concrete, representing approximately 70% of normal-weight performance (Abdullatif and Alhayani, 2025).

The transition from uncracked to cracked section occurs more gradually in LWAC than in normal-weight concrete, reflecting the influence of aggregate porosity and increased bond slip between reinforcement and matrix (Meiramov and Ju, 2026). This transition behavior necessitates careful modeling of the cracking moment and effective moment of inertia calculations to avoid unconservative deflection predictions (Huang, Huang and Pan, 2025).

Crack spacing in LWAC beams averages 130-180 mm at service load levels, compared to 180-220 mm in normal-weight concrete, indicating more frequent but potentially smaller individual cracks (Meiramov and Ju, 2026). This difference reflects altered bond characteristics and stress transfer mechanisms in porous aggregate concrete, with implications for crack width predictions (Huang, Huang and Pan, 2025).

4.3 Failure Modes and Ultimate Capacity

Reinforced LWAC beams designed with tension-controlled steel ratios exhibit ductile flexural failure modes characterized by progressive reinforcement yielding, concrete crushing at the compression zone, and large deflection prior to failure (Liu *et al.*, 2025). Ultimate load capacities of LWAC beams typically range from 95-130 kN (for standard test geometries) compared to 150-160 kN in normal-weight concrete (Narimanifar and Ghasemi, 2024).

Aggregate interlocking effectiveness in LWAC differs from normal-weight concrete due to particle angularity and surface morphology, influencing shear strength at failure and ultimate moment capacity (Cho and Kim, 2024). Research demonstrates that LWAC beams achieve approximately 63-70% of normal-weight concrete ultimate capacity when comparing specimens with equivalent reinforcement ratios and concrete strength grades (Narimanifar and Ghasemi, 2024).

Fiber-reinforced LWAC beams transition from brittle concrete crushing failure to more gradual fiber pullout failure, extending post-peak response and enabling controlled failure modes (Çeli̇k *et al.*, 2025). The addition of 1.0-1.5% steel fiber increases ultimate load capacity by 30-45% and extends displacement ductility by factors of 1.5-2.0 compared to plain LWAC (Çeli̇k *et al.*, 2025).

5. SERVICEABILITY LIMIT STATE PERFORMANCE

5.1 Deflection Control and Prediction Methods

Table 4: Deflection Performance at Service Load Levels

Beam ID	Service Load (kN)	Deflection (mm)	Code Limit (mm)	Ratio
LWAC-P-Plain (L/d=12)	50	8.2	9.0	0.91
LWAC-P-Plain (L/d=15)	40	6.8	7.2	0.94
LWAC-P-SF0.5 (L/d=12)	55	6.5	9.0	0.72
LWAC-P-SF1.0 (L/d=12)	60	5.8	9.0	0.64
LWAC-S-Plain (L/d=12)	52	7.5	9.0	0.83
NWC-Control (L/d=12)	65	4.2	9.0	0.47
LWAC-P-SF+SF (L/d=12)	60	5.2	9.0	0.58
Geopolymer (L/d=15)	50	7.0	7.2	0.97

Deflection prediction for LWAC beams requires careful attention to the two primary components: immediate elastic deflection under service loads and long-term deflection due to creep and shrinkage (Henrique *et al.*, 2024). The immediate elastic deflection component, typically representing 60-70% of total service deflection in LWAC, can be calculated using modified effective moment of inertia equations that account for reduced aggregate modulus (Mohamad *et al.*, 2025).

The effective moment of inertia approach, employing Branson's equation, requires modification through reduction factors when applied to LWAC (Sun, Wu and Liu, 2021). Recommended correction factors range from 0.75-0.85 when transitioning from normal-weight to LWAC, with variation depending on aggregate substitution level and concrete strength (Sun, Wu and Liu, 2021).

Bond-slip behavior in LWAC differs significantly from normal-weight concrete due to altered surface characteristics of porous aggregates (Mohamad *et al.*, 2025). Detailed finite element modeling incorporating cohesive elements to represent reinforcement-concrete interaction demonstrates that bond-slip effects increase deflections by 4-17% compared to perfect bond assumptions (Mohamad *et al.*, 2025). This observation suggests that design methods assuming perfect bond may underestimate LWAC deflections by 10-20% at service load levels (Huang, Huang and Pan, 2025).

5.2 Crack Width Development and Control

Table 5: Crack Width Development at Service Load

Specimen	ρ (%)	Load (% Ult)	Max Width (mm)	Mean Spacing (mm)
P-Plain-1	0.68	0.50	0.28	145
P-Plain-2	0.68	0.50	0.31	138
P-SF0.5-1	0.68	0.50	0.18	168
P-SF1.0-1	0.68	0.50	0.15	182
S-Plain-1	0.68	0.50	0.25	155
NWC-Control	0.68	0.50	0.12	195
P-Silica Fume	0.68	0.50	0.14	180
P-Geopolymer	0.68	0.50	0.22	150

Crack width at service load levels represents a critical serviceability criterion for LWAC beams, with ACI 440 specifying maximum limits of 0.3 mm for exposed environments and 0.4 mm for Eurocode 2 applications (Tu, Zhao and Gao, 2022). Plain LWAC beams achieve maximum crack widths of 0.25-0.31 mm at 50% ultimate load (typical service loading), satisfying ACI limits while demonstrating the tight control available with proper design (Meiramov and Ju, 2026).

The maximum crack width in LWAC beams can be predicted using modified Frosch-type equations that account for reduced tensile strength and altered bond characteristics (Huang, Huang and Pan, 2025). Proposed modifications include: (1) incorporation of reduced effective tensile strength values specific to LWAC materials, (2) adjustment of bond stress parameters reflecting porous aggregate influence, and (3) modification of cover thickness effectiveness factors (Huang, Huang and Pan, 2025).

Steel fiber reinforcement dramatically reduces crack width development, with 0.5-1.0% fiber content reducing maximum crack widths by 35-50% compared to plain LWAC (Sun, Wu and Liu, 2021). The bridging action of fibers provides stress-carrying capacity across developing cracks, limiting crack opening displacement and improving crack distribution (Abdullatif and Alhayani, 2025).

5.3 Serviceability Limit State Compliance Assessment

Table 8: Serviceability Limit State Performance Summary

Parameter	Pumice LWAC	Pumice+Fiber	Scoria LWAC	Geopolymer	NWC Control
Deflection L/250	8.5	6.2	7.8	8.0	4.2
Deflection L/300	7.1	5.2	6.5	6.7	3.5
Crack Width ACI	0.28	0.15	0.25	0.22	0.12
Crack Width EC2	0.25	0.14	0.22	0.20	0.11
Ductility Index	1.8	2.8	2.1	2.4	1.5
Stiffness (%)	65	78	72	70	88
Energy Ratio	1.0	2.8	1.5	2.2	0.8
Service Ratio	0.50	0.55	0.52	0.51	0.60

Comprehensive serviceability assessment demonstrates that properly designed LWAC beams satisfactorily meet deflection and crack width limits specified in contemporary design codes (Sun, Wu and Liu, 2021). At service load levels corresponding to 40-50% of ultimate capacity, deflections remain within L/240-L/300 limits, and crack widths stay below 0.3 mm (Henrique *et al.*, 2024).

The controlling serviceability criterion for LWAC beams typically shifts from deflection at lower reinforcement ratios to crack width at higher reinforcement levels, contrasting with normal-weight concrete where deflection remains dominant (Tu, Zhao and Gao, 2022). This distinction reflects the reduced strength of LWAC limiting the achievable reinforcement ratio at which deflection control becomes critical (Sun, Wu and Liu, 2021).

Long-term deflection in LWAC beams, incorporating creep and shrinkage effects over 10-50 year periods, requires careful analysis employing time-dependent material models (Ghabdian *et al.*, 2022). Research incorporating creep theory demonstrates that LWAC beams experience 40-60% greater long-term deflection than normal-weight concrete due to reduced matrix stiffness and increased susceptibility to creep strains (Ghabdian *et al.*, 2022).

6. EFFECTS OF FIBER REINFORCEMENT AND ADMIXTURES

6.1 Steel Fiber Reinforcement

Table 6: Effect of Fiber Reinforcement on Flexural Properties

Fiber Type	Ultimate Load (kN)	Enhancement (%)	Ductility	Energy (kJ)
None (Control)	95	0	1.8	2.5
Steel Fiber 0.5%	108	+13.7	2.2	4.2
Steel Fiber 1.0%	128	+34.7	2.8	7.1
Steel Fiber 1.5%	138	+45.3	3.4	10.5
Glass Fiber 1.0%	115	+21.1	2.5	5.8
Basalt Fiber 0.75%	125	+31.6	3.1	8.2
Hybrid SF+GF	132	+38.9	3.6	11.5
Steel + Silica Fume	145	+52.6	4.1	14.2

Steel fiber reinforcement significantly enhances LWAC beam performance across multiple criteria (Çeli̇k *et al.*, 2025). The incorporation of 0.5-1.5% hooked-end steel fibers (by volume) improves ultimate flexural capacity by 13.7%-45.3%, with greatest benefits observed at higher fiber contents (Çeli̇k *et al.*, 2025). The fiber bridging mechanism provides tensile stress transfer across cracks, extending the post-cracking response and delaying ultimate failure (Abdulkareem and Al-jalawi, 2025).

The ductility improvement accompanying steel fiber addition is substantial, with ductility indices increasing from 1.8-2.0 for plain LWAC to 2.8-3.4 with 1.0-1.5% fiber content (Sun, Wu and Liu, 2021). This enhanced ductility reflects the transition from brittle concrete crushing failure to more gradual fiber pullout failure, providing warning of impending failure through large displacement prior to load drop (Çeli̇k *et al.*, 2025).

Energy absorption capacity, quantified through the area under load-deflection curves, increases dramatically with fiber reinforcement (Çeli̇k *et al.*, 2025). Plain LWAC beams exhibit energy absorption of 2.5-3.5 kJ to failure, while 1.0% steel fiber reinforced beams absorb 7.1-8.5 kJ, representing 150-250% improvement (Çeli̇k *et al.*, 2025). This enhanced energy absorption is critical for seismic applications where structural resilience depends on dissipation of dynamic energy through controlled deformation (Çeli̇k *et al.*, 2025).

6.2 Mineral Admixtures and Pozzolanic Materials

Table 7: Effect of Mineral Admixtures on Performance

Admixture	fc (MPa)	fr (MPa)	W.Abs (%)	Perm Red (%)
Control (Pumice LWAC)	30	3.2	10.8	0
Silica Fume 7%	32.5	3.8	9.2	15.2
Fly Ash 25%	29.5	3.1	9.8	8.5
SF 7% + FA 25%	35.2	4.1	8.1	28.5
Metakaolin 10%	34	3.9	8.5	22.1
Ground Slag 20%	33.5	3.7	8.8	18.5
Nanosilica 1%	33	3.6	8.3	20.4
GGBS 30% + FA 30%	36.5	4.3	7.6	32.8

Silica fume addition at 5-10% cement replacement enhances LWAC performance through pozzolanic reaction and nucleation effects (Abdullatif and Alhayani, 2025). Compressive strength increases of 5-15% are typical, with early-age strength development accelerated when heat curing or elevated temperatures are employed (R, 2025). Flexural strength improvements of 15-25% accompany silica fume incorporation, reflecting denser matrix and improved interfacial transition zones (R, 2025).

Fly ash incorporation at 20-30% cement replacement provides cost and environmental benefits while maintaining strength at appropriately adjusted water-cement ratios (Kumar, Srivastava and Lakhani, 2021). Later-age strength development (56+ days) becomes critical with fly ash mixes, with ultimate strength comparable to or exceeding silica fume-modified concretes when curing time extends beyond 28 days (Kumar, Srivastava and Lakhani, 2021). Water absorption reduction of 8-12% accompanies fly ash use, reflecting pore refinement through extended hydration and pozzolanic reaction (Kumar, Srivastava and Lakhani, 2021).

Ground granulated blast furnace slag (GGBFS) at 20-30% replacement produces synergistic effects when combined with fly ash, yielding the maximum strength and durability benefits observed among admixture combinations (Tahwia *et al.*, 2025). The dual pozzolanic activity of slag (promoting C-A-S-H phases) and fly ash (promoting C-S-H gel) creates refined pore structures and reduced water permeability (Tahwia *et al.*, 2025).

6.3 Hybrid Reinforcement Systems

Hybrid fiber systems combining steel and polypropylene fibers or combining traditional reinforcement with fiber reinforcement enable optimized structural response (Hadeed, Humad and Al-Gburi, 2023). The synergistic effect of 0.5% steel fiber + 0.5% polypropylene fiber in LWAC produces strength enhancements exceeding additive effects of individual fiber types (Hadeed, Humad and Al-Gburi, 2023). Steel fibers provide load-carrying capacity and ductility enhancement, while polypropylene fibers control early-age plastic shrinkage cracking (Hadeed, Humad and Al-Gburi, 2023).

7. DURABILITY AND ENVIRONMENTAL PERFORMANCE

7.1 Freeze-Thaw Resistance

Table 9: Durability Performance Under Environmental Exposure

Condition	Pumice LWAC	Pumice+SF	Scoria LWAC	Geopolymer	NWC Control
Freeze-Thaw 150c	Good	V.Good	Good	V.Good	Excellent
Sulfate (60d)	84%	91%	88%	94%	98%
Acid Attack (60d)	78%	88%	82%	91%	96%
Chloride Penetration	2500 C	1800 C	2200 C	1500 C	1200 C
Water Absorption	8.2%	6.5%	7.5%	5.2%	2.1%
Mass Loss (%)	1.2	0.8	1.0	0.5	0.2
Strength Retention	85%	92%	88%	95%	98%
Damage Grade	Slight	Minimal	Slight	None	None

Freeze-thaw resistance of LWAC incorporating pumice requires careful attention to air void structure and saturation degree prior to freezing exposure (Jiang *et al.*, 2024). Proper air entrainment (3-5% by volume) provides essential protection against frost damage, with air voids serving as pressure relief mechanisms preventing disruptive ice crystal formation (Jiang *et al.*, 2024). Plain LWAC without adequate air entrainment shows pronounced strength loss (15-25%) following 150 freeze-thaw cycles (Jiang *et al.*, 2024).

The inherent porosity of pumice aggregates can be detrimental to freeze-thaw performance if saturation occurs prior to freezing (Jiang *et al.*, 2024). Water absorbed into pumice pores during saturation expands upon freezing, creating internal stresses that propagate as cracks through the aggregate particles and surrounding paste (Jiang *et al.*, 2024). Conversely, properly air-entrained LWAC with controlled saturation demonstrates freeze-thaw durability comparable to normal-weight concrete (Jiang *et al.*, 2024).

Silica fume addition significantly enhances freeze-thaw resistance through pore refinement and reduction of capillary porosity accessible to water (Jiang *et al.*, 2024). Compressive strength retention of 92-95% following 150 freeze-thaw cycles is achievable with properly designed silica fume-modified LWAC (Jiang *et al.*, 2024).

7.2 Chemical Attack and Durability

Sulfate resistance testing employing standard 5% $MgSO_4$ solution exposure for 60+ days demonstrates that plain LWAC retains 84% compressive strength compared to initial values

(Tahwia *et al.*, 2025). The mechanism of sulfate deterioration involves ettringite formation in pores and cracking due to expansive phases, a process accelerated in porous LWAC due to enhanced diffusion pathways (Tahwia *et al.*, 2025).

Mineral admixtures substantially improve sulfate resistance, with silica fume + slag combinations achieving 94% strength retention following 60-day exposure (Tahwia *et al.*, 2025). The dense matrix created through pozzolanic reaction and slag hydration reduces sulfate ion ingress rate, limiting the extent and severity of sulfate attack (Tahwia *et al.*, 2025).

Acid attack resistance, evaluated through exposure to 5% acetic acid, reveals strength retention of 78% for plain LWAC compared to 96% for normal-weight concrete (Tahwia *et al.*, 2025). The higher susceptibility of LWAC reflects increased porosity facilitating acid penetration and dissolution of matrix phases (Tahwia *et al.*, 2025). Incorporation of slag-fly ash combinations improves acid resistance to 91% retention, demonstrating the protective effect of optimized matrix density (Tahwia *et al.*, 2025).

7.3 Chloride Penetration and Corrosion Risk

Rapid chloride penetration testing (RCPT) shows that plain LWAC exhibits chloride migration coefficients approximately 20-30% higher than equivalent normal-weight concrete, reflecting the porosity differential (Zhang *et al.*, 2023). However, incorporation of pozzolanic materials dramatically reduces chloride penetration, with silica fume-modified LWAC achieving chloride migration coefficients comparable to normal-weight concrete (Tahwia *et al.*, 2025).

Corrosion probability analysis of reinforced LWAC beams demonstrates that time to rebar corrosion initiation depends critically on concrete cover thickness and chloride binding capacity (Jamil *et al.*, 2025). With 40 mm cover and proper admixture selection, LWAC beams can achieve 50+ year service life in moderate marine environments (Jamil *et al.*, 2025). The inherent porosity of LWAC that creates corrosion vulnerability can be partially offset through enhanced concrete cover and dense matrix development via silica fume and slag incorporation (Jamil *et al.*, 2025).

8. DESIGN RECOMMENDATIONS AND PRACTICAL IMPLEMENTATION

8.1 Design Methodology for Serviceability Control

Table 10: Design Recommendations and Practical Guidelines

Design Aspect	Recommended Value	Note
Density Limit	1800-2000 kg/m^3	Structural + thermal benefits
Min Strength	25-35 MPa	Varies with aggregate type
Max L/d Ratio	$L/d \leq 24$	With SF can extend to 24-28
Deflection Method	Code Modified	Modified code equations recommended
Min Reinforcement	$0.85\sqrt{(fc'/fy)}$	May be reduced with fiber reinforcement
Max Reinforcement	0.04 (balanced)	Check serviceability at this level
Fiber Addition	0.5-1.0% Steel	Improves deflection and crack control
Minimum Cover	25-40 mm	Adequate durability protection
Crack Width Limit	0.3 mm (ACI), 0.4 mm (EC2)	ACI more stringent for FRP
Service Load Factor	0.4-0.5 of ultimate	Ensures serviceability compliance
QC Testing Frequency	Every 50 m^3 or 5 days	Ensures quality consistency
Curing Requirements	7+ days water curing, 28d+ total	Critical for strength development

Design of LWAC beams must explicitly address serviceability limit state requirements, recognizing that flexural capacity may exceed serviceability constraints (Henrique *et al.*, 2024). A rational design approach involves: (1) preliminary member sizing based on deflection limits rather than strength, (2) strength verification confirming adequacy at ultimate limit state, and (3) crack width checking ensuring compliance with durability criteria (Tu, Zhao and Gao, 2022).

Span-to-effective-depth (L/d) ratios guide preliminary sizing, with typical values of 18-24 for LWAC beams compared to 24-30 for normal-weight concrete (Sun, Wu and Liu, 2021). These reduced ratios reflect lower elastic modulus and increased deflection tendency in LWAC. Incorporation of supplementary materials or fibers can extend permissible L/d ratios by 2-4 units, enabling greater member spans before deflection becomes limiting (Sun, Wu and Liu, 2021).

Effective moment of inertia calculations for LWAC require modified cracking moment determination employing LWAC-specific modulus of rupture values rather than code-predicted normal-weight concrete relationships (Huang, Huang and Pan, 2025). A recommended approach employs: $Ie = (Mcr/Ma)^3Ig + [1-(Mcr/Ma)^3]Icr$, where Mcr is determined from actual LWAC flexural strength testing and Icr accounts for LWAC material properties (Huang, Huang and Pan, 2025).

8.2 Construction and Quality Control

Proper execution of LWAC construction requires attention to moisture management of lightweight aggregates, proportioning accuracy, and curing protocols (Karadağ *et al.*, 2024). Pre-saturation or surface-dry-saturated aggregate conditioning is recommended to prevent excessive moisture extraction from the cement paste during mixing (Karadağ *et al.*, 2024). Adjustments to water-cement ratio calculations must account for aggregate water absorption, typically reducing free water by 2-4% from normal-weight concrete specifications (Karadağ *et al.*, 2024).

Placement procedures should minimize vibration intensity to reduce aggregate segregation and void accumulation common in LWAC (Karadağ *et al.*, 2024). Self-consolidating LWAC formulations eliminate vibration requirements entirely, providing significant construction advantages while ensuring uniform consolidation (Karadağ *et al.*, 2024). Finishing operations should emphasize early protection from rapid drying, as elevated surface evaporation can induce differential shrinkage and surface cracking in porous LWAC (Karadağ *et al.*, 2024).

Curing duration for LWAC should extend beyond standard 7-day protocols, with 14+ day water curing recommended to develop full strength potential and minimize shrinkage cracking (Karadağ *et al.*, 2024). The extended curing reflects slower hydration kinetics and benefit of continued internal curing from absorbed aggregate moisture (Karadağ *et al.*, 2024).

8.3 Sustainability and Economic Assessment

The environmental benefits of LWAC production using pumice aggregates are substantial, generating 50-65% lower carbon emissions compared to conventional concrete (Kumar, Srivastava and Lakhani, 2021). Material efficiency gains through 20-25% weight reduction reduce foundation demands and transportation impacts (Kumar, Srivastava and Lakhani, 2021). In addition, pumice utilization often employs waste material from pumice mining and textile industries, reducing landfill disposal requirements (Kumar, Srivastava and Lakhani, 2021).

Economic viability of LWAC depends on local aggregate availability and cement pricing (D. Archana *et al.*, 2024). In volcanic regions with abundant pumice deposits, cost savings of 15-25% are achievable compared to normal-weight concrete (D. Archana *et al.*, 2024). The weight reduction benefit becomes economically significant in high-rise structures where dead load reduction directly reduces column sizing and foundation costs (D. Archana *et al.*, 2024).

9. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

9.1 Key Findings

This systematic review synthesizes contemporary research demonstrating that lightweight aggregate concrete incorporating pumice or volcanic aggregates provides viable structural solutions meeting strength, serviceability, and durability requirements (Kumar, Srivastava and Lakhani, 2021). Pumice LWAC achieves compressive strengths of 20-42 MPa and flexural strengths of 3.2-4.5 MPa, with serviceability performance meeting ACI and Eurocode 2 requirements when properly designed (Sun, Wu and Liu, 2021).

Serviceability limit state represents the governing design criterion for LWAC beams, with deflection and crack width control requiring careful attention to elastic modulus reduction and altered bond characteristics (Henrique *et al.*, 2024). Steel fiber reinforcement provides powerful enhancement tool, improving ultimate capacity by 30-45%, reducing deflections by 20-35%, and limiting crack widths to 0.15-0.18 mm (Çelik *et al.*, 2025).

Mineral admixtures, particularly silica fume-slag combinations, substantially enhance both mechanical and durability properties (Tahwia *et al.*, 2025). Supplementary materials refine pore structure, reduce water absorption, and improve resistance to freeze-thaw, sulfate, and acid attack (Tahwia *et al.*, 2025).

9.2 Recommendations for Future Research

Future investigation should focus on: (1) long-term in-service performance monitoring of completed structures, (2) development of refined creep and shrinkage models specific to LWAC, (3) optimization of fiber types and hybrid systems for serviceability enhancement, (4) investigation of geopolymer binders with lightweight aggregates for reduced carbon impact, and (5) standardization of design methods across international codes (Kumar, Srivastava and Lakhani, 2021).

Additional research on interfacial transition zone characteristics in LWAC, enhanced understanding of aggregate-paste bonding mechanisms in porous systems, and investigation of LWAC behavior under dynamic and seismic loading would advance the knowledge base and expand practical applications (Karatza *et al.*, 2025).

9.3 Final Remarks

Lightweight aggregate concrete incorporating pumice and volcanic materials represents a mature technology offering compelling sustainability and structural performance benefits. Continued advancement through refined understanding of serviceability mechanisms, optimization of material combinations, and standardization of design methods will enable expanded adoption in modern construction while contributing to environmental stewardship objectives (Kumar, Srivastava and Lakhani, 2021).

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