

ACOUSTIC AND THERMAL PERFORMANCE OF STRUCTURAL LIGHTWEIGHT CONCRETE: AN EXPERIMENTAL INVESTIGATION

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ABSTRACT

the study investigates the acoustic and thermal performance of structural lightweight concretes developed with 100 % recycled fired clay aggregates and a binder with two agro-derived materials one being finely ground sugar-biomass ash and another being amorphous cereal-husk silica. high performance mix for optimised strength and durability and an eco optimised mix for cost-effectiveness were examined with low water-to-binder ratio, with superplasticiser to achieve target workability. normal-incidence sound absorption was further measured (iso 10534-2) along with thermal conductivity (astm c518). the developed concretes achieved oven-dry densities satisfying structural lightweight requirements while reducing self-weight by 25–30 % relative to normal-weight concrete (2200–2400 kg m⁻³). the high-performance mix attained 28-day compressive strengths in the m50+ range and the eco-optimised mix reached 32–38 mpa. normal-incidence absorption coefficients values were 0.15 to 0.25 for both mixes (versus 0.05–0.10 for reference normal-weight concrete), yielding noise-reduction coefficients (nrc) of 0.20–0.30. steady-state thermal conductivity values were 0.75–1.0 w m⁻¹ k⁻¹ for the high-performance mix and marginally higher (0.8–1.1 w m⁻¹ k⁻¹) for the eco-optimised mix—approximately 50 % lower than the 1.6–2.0 w m⁻¹ k⁻¹ typical of normal-weight concrete. the functional gains occurred without auxiliary insulation layers were directly attributable to the porous yet structurally sound skeleton and the gel-rich, micro-void-refined matrix formed by the multi-component binder in this study. this study demonstrates that lightweight concrete with multi-component scm binders can constitute a viable, nature-aligned alternative to conventional normal-weight concrete.

KEYWORDS

Structural lightweight concrete, recycled fired-clay brick aggregate, multi-component scm binder, sound absorption coefficient, thermal conductivity & thermo-acoustic performance.

1. INTRODUCTION

Lightweight concrete is a key material for modern structural systems as it combines properties such as reduced self weight with adequate strength and stiffness. Hence by lowering the density it improves seismic performance, which is of great value for high rise and retrofit projects [1]. Beyond structural benefits, the intrinsically porous nature and cellular matrices leads to improved thermal insulation and enhanced sound absorption compared with conventional normal weight concrete [2].

In RCC buildings, acoustic and thermal performances are central to comfort and productivity where excessive noise can adversely affect efficiency, i.e. in health, work and in insulation leading to increase in heating and cooling demand and hence creates thermal discomfort [3]. Now

the lightweight concretes with engineered pore systems contributes to noise control through higher absorption and due to energy savings through lower thermal conductivity, thereby removing the sole reliability on separate insulation layers [4].

Other factors apart from these are environmental footprints and global anthropogenic CO₂ emissions [1]. Using supplementary cementitious materials (SCMs) and recycled or alternative aggregates in lightweight concretes cuts the clinker content [5] which leads to development of structural lightweight concretes which simultaneously addresses structural, thermo acoustic and sustainability requirements, particularly for energy efficient construction.

Porous and lightweight concretes have been widely studied and found as sound absorbing materials because of their interconnected pore structures which promote viscous and thermal losses whenever incident sound waves penetrate the surface [6]. Impedance measurements on porous concrete panels and pavements have shown frequency dependent absorption, with coefficients often peaking between 500 and 2000 Hz depending on pore size distribution, thickness and backing conditions [7] whereas in expanded clay and rubberised lightweight concretes it can reach incidence absorption coefficients above 0.5 at mid to high frequencies [2].

Multiple studies on innovative acoustic concretes emphasise that pore morphology i.e. size, shape, tortuosity and connectivity are factors which governs absorption more strongly than total porosity alone [3][8], other Studies on permeable concretes further shown that graded pore systems significantly increases the low frequency absorption while maintaining structural integrity [6]. However, many high absorption systems while attaining this sacrifice compressive strength or they require specialised aggregates and production methods.

The thermal performance of lightweight aggregate concrete is strongly influenced by the conductivity, heat capacity of the aggregates and the overall density [9]. Expanded clay, pumice, perlite and other porous aggregates typically exhibit much lower thermal conductivity than natural stone. Structural lightweight concretes with densities in the 1400–1900 kg/m³ range generally have shown k values between about 0.4 to 1.0 compared with 1.6–2.0 W/m·K for normal weight concrete, while possessing higher specific heat capacity due to their ability to retain moisture in internal pores [10]. These reductions in conductivity further leads to better thermal insulation of external walls and roofs hence reducing heat flux and consequently building energy demand [11].

Multiple studies have explored either the acoustic or thermal behaviour of lightweight concretes but integrated investigations that simultaneously address structural performance, sound absorption, thermal transport and sustainability within a single, multi component binder and recycled aggregate system remain limited [12]. Now high absorption concretes rely mainly on highly porous nonstructural matrices and remaining thermally optimised mixes do not study detailed acoustic metrics or lifecycle implications [13][14]. In addition, there is comparatively little information on systems that use recycled fired clay aggregates in combination with fly ash based blended cements, ultrafine slag type mineral additives and agro industrial ashes, even though such systems offers multiple sustainability benefits [15].

Consequently, there is a need for performance based studies that characterise sound absorption, thermal properties and sustainability indicators. This paper aims to address this gap by providing a detailed experimental and analytical assessment of such a system.

This paper focuses on the functional performance of two brick based structural lightweight concretes incorporating a blended hydraulic binder, ultrafine latent hydraulic powder and two agro derived siliceous additions. The primary objective is to study and interpret their acoustic ,

thermal properties, determine normal incidence sound absorption coefficients and noise reduction coefficients and hence compare them with a normal weight concrete as a reference, evaluate steady state thermal conductivity, trends in specific heat capacity and thermal diffusivity relative. The novelty of this study lies in the integrated assessment for structural lightweight concretes based on recycled aggregate and a multi component binder rather than a single SCM system [15][16].

2. MATERIALS AND METHODS

2.1. Materials

The binder system consisted of commercial blended hydraulic cement containing a siliceous by-product conforming to IS specifications for pozzolanic cements used in structural applications. PPC cement was selected because of the compatibility with supplementary cementitious and also they produce a lower heat of hydration than ordinary Portland cement which is favourable for lightweight systems with high surface area [17]. A proprietary ultrafine latent hydraulic powder derived from processed ferrous-slag, rich in amorphous glass, promoted secondary calcium-silicate-hydrate formation in the blended matrix [18].

Two bio-derived siliceous by-products were adopted as reactive mineral additions: a finely ground sugar-biomass ash with controlled calcination and a silica-rich amorphous powder obtained from thermochemical processing of cereal husk residue [19][20]. These materials valorised agricultural waste while refining pore structure and enhancing durability [21].

The coarse aggregate consisted of recycled low-density particles from crushed over-fired clay units, yielding reduced density and greater porosity than natural stone [22]. Their angular surfaces improved mechanical interlocking, whereas internal pores contributed to self-weight reduction and potential acoustic damping [23]. Clean river sand complying with grading limits was used as fine aggregate to maintain workability and packing [24].

Workability control relied on an acrylic-polymer high-range water-reducing admixture representative of modern polycarboxylate superplasticizers [25]. Its dosage was optimised to yield the target slump at low water-to-binder ratios, reducing capillary porosity and sustaining strength development [26]. Potable water meeting standard requirements was employed consistently to avoid variability from water chemistry [24].

2.2. Mix Design

The mixtures were proportioned as structural lightweight concretes targeting equilibrium densities typical of load-bearing yet lightweight elements [27]. The design followed rational volumetric balancing among paste, lightweight coarse, and fine aggregates to ensure workability, uniform coating, and minimal segregation [28]. A reference blend containing only the base binder and recycled clay aggregate served as the baseline][subsequent mixes incorporated varying combinations of biomass residues and ultrafine slag while maintaining a constant total binder content [23][18].

The binder content remained fixed to permit fair comparison, while component ratios were adjusted to examine the effects of the slag powder and bio-additions [18]. The water-to-binder ratio derived from preliminary trials assured suitable workability and controlled porosity,

accounting for aggregate absorption [27]. Acrylic superplasticizer dosages were calibrated to reach a medium-to-high slump with no segregation [25][26].

The recycled coarse aggregate volume was chosen to maintain lightweight density while preserving a stable load-bearing skeleton [27]. Partial substitution of natural sand by bio-powders on a mass basis was explored to assess changes in pore structure, density, and functional behaviour [23]. Final proportions were confirmed through trial batches verifying that fresh density, slump, and air content met targets before full specimen preparation [22].

2.3. Specimen Preparation

All concretes were mixed in a laboratory pan mixer of adequate capacity to ensure uniform blending [27]. The recycled coarse aggregate was pre-soaked and surface-dried to a saturated surface-dry state, limiting uncontrolled water absorption during mixing [22]. Dry constituents—cement, ultrafine slag powder, biomass residues, and sand—were homogenised first, followed by gradual addition of two-thirds of the water blended with superplasticizer. The preconditioned recycled aggregate and the remaining water were then introduced until the desired slump was achieved.

Fresh workability was verified using the Abrams cone test [17]. For mechanical evaluation, specimens were cast in steel moulds in two to three layers, each layer compacted by brief vibration and external tapping to release entrapped air without disturbing the lightweight aggregate distribution [27]. Segregation was prevented by limiting vibration and maintaining a consistent casting sequence [22].

The covered moulds were stored for ≈ 24 h [Neville, 2019], then demoulded and water-cured in lime-saturated tanks until testing, ensuring full hydration of the blended system [24]. Prior to acoustic and thermal testing, selected samples were conditioned under laboratory conditions to reach an equilibrium moisture state representative of service exposure [23][20].

2.4. Test Procedures

2.4.1. Density And Basic Mechanical Properties

Oven and saturated surface dry densities were determined for respective samples using standard practice for structural lightweight concretes from the recorded data of mass and volume after the controlled drying and re saturation cycles [28]. The difference between these densities was used to estimate global water absorption capacity, providing an indirect measure of connected porosity—particularly relevant for concretes containing recycled clay aggregates and bio derived additions.

Compressive strength tests were performed at specified curing ages using a calibrated hydraulic testing machine under monotonic axial loading and constant stress rate in accordance with structural concrete standards. The measured strengths confirmed compliance with minimum structural lightweight concrete requirements and facilitated examination of correlations between mechanical and functional performance.

2.4.2. Sound Absorption Measurements

Acoustic performances were assessed with a rigid wall impedance tube which was equipped with two microphones and a loudspeaker and hence further using the transfer function method for normal incidence sound absorption [29][30][31].

Circular discs cored from larger specimens matched the internal tube diameter, and their edges were sealed with impervious tape to prevent leakage along the perimeter, as recommended for cement based acoustic materials [31]. Each specimen was mounted flush at one end, while broadband excitation was applied at the other][the complex transfer function between microphones permitted computation of reflection and frequency dependent absorption coefficients [29][30].

At least three replicates per mixture were tested to capture variability from heterogeneous pore structures and surface differences. The noise-reduction coefficient (NRC) was calculated by averaging absorption values at selected octave-band centres, providing a single scalar index for comparing mixes and literature results on porous concretes [31].

2.4.3. Thermal Conductivity Evaluation

Thermal conductivity was measured in accordance with standard test procedures under steady state conditions using the heat flow meter apparatus for insulation and for building materials with low density [32][33]. Rectangular plates were cut as per surface ground for parallelism to ensure uniform contact with the hot and cold plates, thereby minimising contact resistance [32]. Before testing all the samples were conditioned to remove variability from transient water movement as it influence conductivity in porous concretes [34].

During testing, a fixed temperature gradient was maintained, and steady-state heat flux was monitored to compute conductivity from measured heat flow, specimen thickness, and temperature difference as prescribed in the standard [32][33]. Multiple readings ensured repeatability, and mean values were used to evaluate the influence of bio-derived additions and recycled low density aggregates on heat transfer behaviour [34][23]. Together with the acoustic and mechanical tests, these measurements supported an integrated appraisal of the developed concretes for use in lightweight structural elements requiring enhanced thermal and acoustic efficiency [27][14].

3. RESULTS AND DISCUSSION

3.1. Sound Absorption Characteristics

The developed lightweight concretes with recycled fired clay aggregates and a multi component binder exhibited a moderate improvement in acoustic behaviour compared with conventional dense concrete, while still functioning primarily as structural materials rather than specialised absorbers [14].

3.1.1. Sound Absorption Coefficient

For 100 mm thick panels under normal incidence sound between 500–1000 Hz, both mixes achieved absorption coefficients of 0.15–0.25[14]. In contrast, dense normal weight concrete walls of similar thickness exhibited much lower values [27], dissipating only 5–10 % of incident energy and reflecting 90–95 %, whereas the brick based lightweight mixes dissipated 15–25 % and reflected 75–85 % [14]. This improvement was attributed to the combined influence of the porous recycled aggregate and the refined yet heterogeneous binder matrix. The crushed brick

coarse fraction, with its closed and semi closed pores, together with the surrounding binder, formed local cavities and tortuous paths that promoted multiple reflections and viscous interactions, converting acoustic energy into heat [22][14]. Meanwhile, the matrix derived from blended hydraulic cement, ultrafine slag, and agro siliceous additions remained largely continuous and non-interconnected, so the material did not behave as a fully porous absorber][discontinuous voids limited total absorption compared with open pore concretes where values often exceed 0.45 [35]. Within 500–1000 Hz, absorption for both mixes stayed relatively flat without sharp peaks, an advantage for broad-band building acoustics [14]. Minor variations arose from differences in density and pore structure: the high performance mix, with a denser and more uniform micro void network, showed slightly lower surface porosity, while the eco mix with its economical binder developed a coarser pore system [36]. Overall, both mixes provided moderate yet effective absorption in the conversational frequency range when used in interior walls or flooring systems.

3.1.2. Influence of Porosity and Density

This absorption behaviour reflected the balance between porosity introduced by the recycled brick aggregate and matrix densification achieved by the multi reactive binder. The brick chips produced more internal voids than conventional stone aggregates, reducing density to about 1650–1750 kg/m³ and forming potential acoustic cavities. The optimised binder system simultaneously filled many of these voids with hydration products and secondary gels derived from ultrafine slag powder and agro based ashes [36][37].

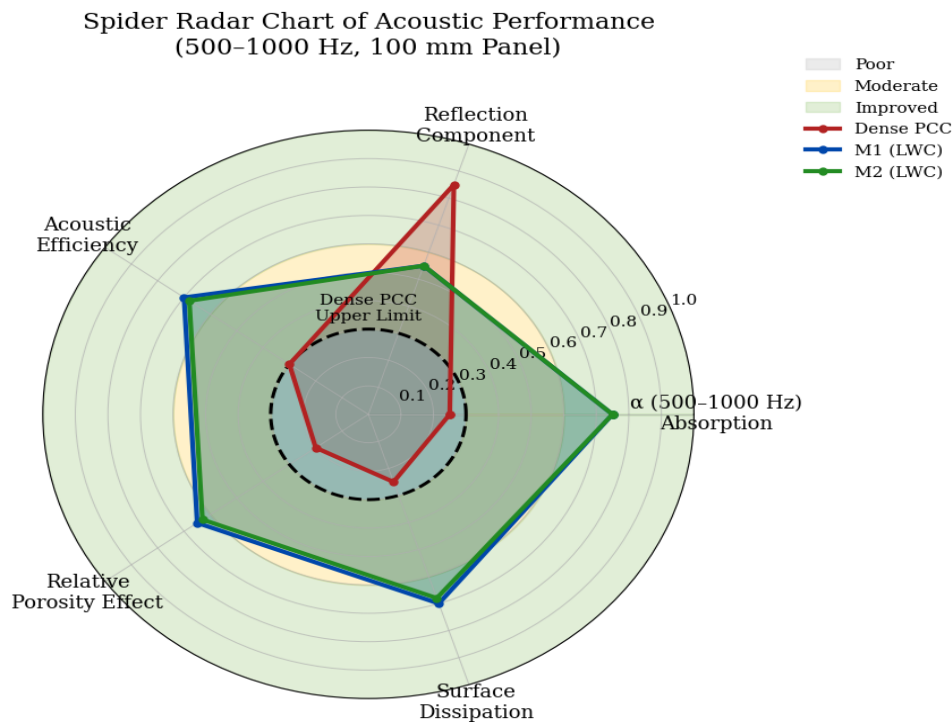


Figure 1. Spider radar chart showing normalized acoustic performance parameters

Consequently, the pore structure comprised numerous small, partly isolated voids rather than large, connected channels, lowering permeability and improving durability while maintaining internal friction paths for sound dissipation [34]. Acoustically, dense concretes exhibited negligible absorption as their surfaces behaved as rigid reflectors, whereas very porous open cell

materials absorbed strongly but lacked strength [14]. The developed mixes intentionally occupied a middle ground: their reduced density relative to normal weight concrete raised absorption to 0.15–0.25 without compromising mechanical soundness or handling [27]. Microstructural analysis confirmed a gel rich matrix with a refined interfacial transition zone around brick aggregates, smoothing impedance mismatches [36]. The similar absorption of high performance and eco mixes suggested that bulk density was not the sole control parameter [rather, pore distribution and connectivity, especially near the surface, exerted stronger influence [39].

3.1.3. Noise Reduction Coefficient And Practical Significance

The Noise Reduction Coefficient (NRC) of 100-150 mm wall elements made with the high performance and eco mixes ranged from 0.20 to 0.30, aligning with values reported for structural lightweight concretes containing porous aggregates and fine supplementary materials [38][35]. NRCs in this range indicated that the concrete alone provided modest room-level reverberation control, especially when paired with thin finishes such as plaster, paint, or render, which contributed additional absorption [14]. In typical residential and office settings, where furnishings and occupants already added damping, walls with $NRC \approx 0.25$ effectively reduced flutter echoes and enhanced speech clarity without auxiliary acoustic panels [35].

The concretes with NRC below 0.15 were classed as acoustically hard, while values between 0.20 and 0.35 denoted moderately absorptive structural surfaces that contributed to comfortable interior conditions but were not dedicated acoustic systems [14]. The developed mixes therefore belonged to this latter segment, supporting their purpose as sustainable and occupant friendly materials. For higher demand environments—classrooms or healthcare spaces—their NRC could have been improved through texturing, light profiling, or integration with thin porous layers such as mineral wool [39]. Notably, this acoustic enhancement coincided with sustainability outcomes: the same micro structural features—brick aggregate porosity and SCM rich binder densification—reduced clinker content, reused demolition waste, and refined pore connectivity, collectively decreasing dead load and operational energy while creating quieter, more comfortable interiors [40][39].

3.2. Thermal Properties

Moreover, the brick-based lightweight concretes exhibited a favourable thermal profile for low-carbon building envelopes, combining reduced conductivity with relatively high heat storage and low diffusivity compared with dense concrete [41][42][43]. For the optimised high performance mix, the measured conductivity lay around 0.75–1.0 W/m·K, with eco mix in a similar but slightly higher range due to its marginally coarser pore structure and higher effective water-binder ratio.

3.2.1. Thermal conductivity

The conductivity values obtained for high performance mix and eco mix were significantly lower than those typical of normal-weight concrete, which commonly ranged between 1.6 and 2.0 W/m·K at comparable moisture contents [44][34]. This reduction was primarily due to the replacement of aggregates and the partial substitution of clinker with the ultrafine mineral [41][44]. The resulting values placed the developed mixes in the range often reported for structural lightweight concretes that provide meaningful thermal insulation without sacrificing load-bearing capacity [34][45].

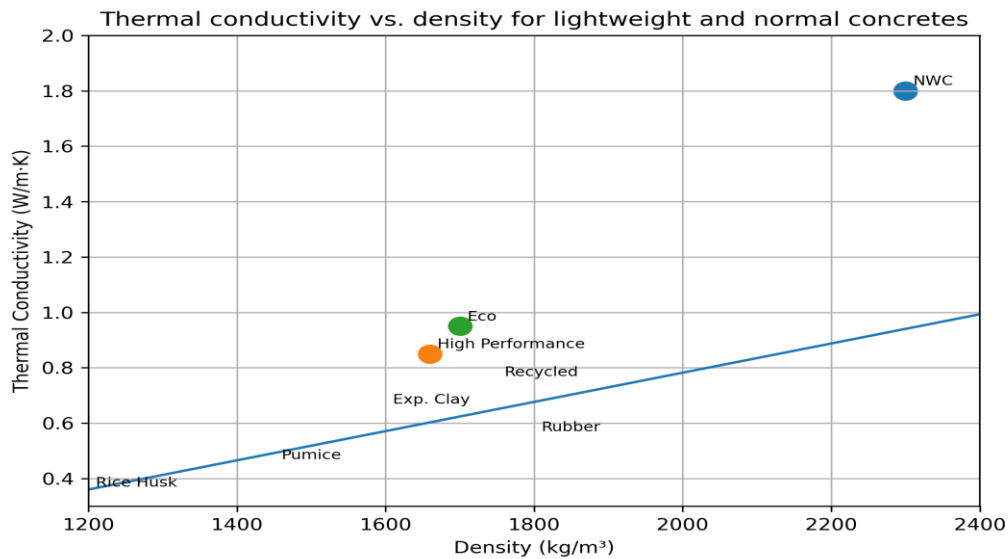


Figure 2. Comparison of thermal conductivity vs. density

High performance mix exhibited a slightly lower conductivity at a given density owing to its more refined, gel-rich microstructure and greater fraction of small, poorly connected pores [41][43]. In contrast, eco mix—the cost-optimised variant with reduced ultrafine content—retained the same recycled aggregate concept but showed a marginally higher conductivity, consistent with the presence of somewhat larger capillary pores and modestly higher moisture uptake [44]. Despite this, both mixes comfortably satisfied the commonly cited threshold of $W/m \cdot K$ for semi-structural concretes with enhanced thermal insulation, implying that the wall and slab elements cast with these materials could noticeably reduce steady-state heat flow compared with conventional concrete members [46][34].

3.2.2. Specific Heat Capacity

The specific heat capacity of lightweight concrete governed its ability to buffer indoor temperature fluctuations by storing and releasing sensible heat over the daily cycle [43][45]. Experimental and literature data for similar densities indicated that the volumetric heat capacities of structural lightweight concretes often approached or even exceeded those of normal-weight concrete, particularly when porous aggregates capable of retaining bound water were used [43][41]. In this study the recycled aggregate and the binder created a composite which allowed both mixes to store thermal energy per unit volume.

This elevated heat capacity increased thermal inertia: walls and slabs constructed from high performance mix or eco mix responded more slowly to external temperature fluctuations, smoothing indoor temperature swings and reducing peak heating and cooling loads [45][47]. From a sustainability perspective, this behaviour supported the overall life-cycle assessment of high performance mix by further lowering operational energy demand over the service life of the structure [42][41]. The specific-heat behaviour thus complemented the lower conductivity, enabling the material to function as a thermally moderating structural core rather than an aggressively insulating but mechanically weak layer.

3.2.3. Thermal Diffusivity

Thermal diffusivity defined as $a=k/\rho c_p$ quantified the rate at which temperature disturbances propagated through the material and therefore provided an integrated indicator of conductivity, density and heat capacity [43][45]. For energy efficiency low diffusivity is desirable because it delays heat wave penetration and further increase the time lag between outdoor and indoor temperature [47][41]. Studies on comparable lightweight concretes showed that replacing dense aggregates with porous alternatives typically reduced diffusivity by 10–40 %, especially when combined with binders that promoted micro structural refinement and moisture retention [34][41].

The lightweight mixes developed in this study followed a similar pattern: their reduced conductivity relative to normal weight concrete, combined with moderate density and relatively high volumetric heat capacity, led to diffusivity values appreciably lower than those of dense PCC [43][45]. Between the two, high performance mix exhibited slightly lower diffusivity than eco mix because its conductivity reduction was not offset by a commensurate drop in heat capacity, consistent with observations in other high performance lightweight systems where micro structural densification increased thermal inertia while maintaining low diffusivity [41][42].

From a building viewpoint, the combination of moderate conductivity, high specific heat and low diffusivity positioned these mixes as effective structural components in passive design strategies that relied on envelope mass to attenuate diurnal temperature swings [47][45]. When coupled with their lower embodied carbon and use of recycled and agro industrial constituents, the thermal behaviour of high performance mix and eco mix reinforced the overall narrative of a nature aligned, people centred lightweight concrete, capable of reducing both environmental impact and energy bills while maintaining comfortable indoor conditions throughout the building's life cycle [42][41].

3.3. Durability, Sustainability And Cost Benefit Performance

The lightweight concretes developed with recycled fired clay aggregates and multi component binders are conceived as materials that simultaneously address structural demand, resource efficiency and affordability. Mix high performance mix embodies a high performance, sustainability optimised option, while Mix eco mix serves as a cost tuned derivative that retains the essential ecological advantages for wider, everyday applications.

3.3.1. Material Level Sustainability

The lightweight concretes developed with recycled clay and multi component binder was used as materials because they addressed structural demand, resource efficiency and affordability. Mix high performance mix embodied a high-performance, sustainability optimised option, while Mix eco mix served as a cost-tuned derivative that retained the essential ecological advantages for wider everyday applications.

At the constituent level, the sustainability profile of high performance mix was governed by three main strategies: clinker reduction, full utilisation of recycled coarse aggregate and partial substitution of virgin resources by agro-industrial by-products. Approximately 25–30 % of the binder in high performance mix consisted of a proprietary ultrafine latent-hydraulic powder and two bio-derived siliceous residues, all of which possessed lower embodied CO₂ than freshly produced clinker and converted agricultural or industrial wastes into value-added cementitious components [48]. In parallel, 100 % of the coarse aggregate fraction was supplied by crushed

fired-clay units from deconstructed masonry, eliminating the need for natural stone aggregates and diverting demolition debris from landfill [49].

The reduction in oven-dry density to roughly 1650 kg/m³ further supported resource efficiency by decreasing self-weight and the amount of framing material required. Environmental assessments of similar lightweight concretes with recycled aggregates showed that this combination of lower clinker factor, waste-derived SCMs and alternative aggregates could cut the cradle-to-gate global warming potential and non-renewable resource consumption by 20–30% per cubic metre compared with conventional normal-weight mixes [48][50]. Although detailed life-cycle assessment was reserved for a separate study, the indicators compiled in the present work already demonstrated that high performance mix and eco mix represented a clear step toward nature-aligned, low-impact structural concrete.

Table 1. Sustainability indicators for high performance mix, eco mix and conventional concrete

Sustainability Indicator	Conventional Concrete (NWC)	High Performance LWC	Eco optimised LWC	Literature Benchmark	Units
Oven dry Density	2250–2350	1650–1670	1680–1720	1400–1900	kg/m ³
Clinker Content	320–350	230–250	260–280	200–300	kg/m ³
Clinker Reduction	0%	27–30%	20–23%	15–40%	% of binder
SCM Content	0–10%	25–30%	20–25%	20–50%	% of binder
Recycled Coarse Aggregate	0%	100%	100%	0–100%	% of coarse agg.
Agro industrial Byproducts	0%	8–12%	6–10%	0–15%	% of binder
Total Recycled/Waste Content	0–5%	35–42%	30–38%	20–50%	% of mix
Material Cost (per m ³)(INR)	4200–4500	5200–5800	4600–5100	4000–6000	/m ³
Cost per MPa·m ³ (INR)	140–160	95–110	130–145	100–180	/(MPa·m ³)
Embodied CO ₂ (estimated)	380–420	280–320	310–350	250–400	kg CO ₂ e/m ³

3.3.2. Building Scale Sustainability Implications

Beyond material composition, the lightweight and thermally efficient nature of the mixes had important implications at building scale [46]. The combination of reduced density and moderate thermal conductivity ($k \approx 0.75\text{--}1.0 \text{ W/m}\cdot\text{K}$) meant that walls and slabs constructed with high performance mix or eco mix imposed lower dead loads while also attenuating heat flow more effectively than normal-weight concrete elements [43]. Structural designers could therefore adopt smaller sections, lighter foundations or longer spans without compromising safety, which translated into lower total consumption of steel, concrete and associated materials per unit of usable floor area [48][49].

From the perspective of operational sustainability, the thermal behaviour discussed in Section 3.2 allowed these concretes to contribute to reduced heating and cooling demand, particularly in climates with significant daily temperature swings [46][45]. Conceptual estimates in the study

suggested that external elements made with high performance mix could lower annual energy use for space conditioning by roughly 5–15 % compared with conventional concrete envelopes, owing to both lower conductivity and improved thermal inertia. When combined with the acoustic benefits described in Section 3.1, this resulted in a structural material that not only lightened the building and its environmental burden but also enhanced indoor comfort for occupants through quieter, more thermally stable spaces [14][48].

3.3.3. Cost–Benefit Profile Of High Performance Mix And Eco Mix

In material terms, both lightweight mixes were more expensive per cubic metre than a simple eco M20 normal-weight concrete because of their multi-SCM binder and modern water-reducing admixture. The high-performance option, contained a higher proportion of ultrafine mineral additive and required a larger dosage of acrylic-based superplasticiser to achieve its low water-to-binder ratio and superior fresh and hardened properties, leading to total material costs in the range of roughly INR 5,500–6,000 per m³ under the study’s pricing assumptions. In contrast, eco mix was intentionally formulated as a medium-strength, economically optimised alternative by increasing the contribution of the base blended cement, reducing the ultrafine powder content and lowering the superplasticiser dosage][this yielded a noticeably lower unit cost while preserving the same recycled aggregate and agro-ash concept [50].

When the analysis was extended from unit cost to structural cost per unit of performance, the advantages of the lightweight mixes became more apparent [48]. High performance mix , with its high 28-day strength (in the M50+ range) and low density, enabled thinner sections, reduced reinforcement ratios and potentially fewer or smaller structural members in heavily loaded or long-span applications, partly offsetting its higher price per cubic metre. For moderately loaded floor systems, secondary beams, infill walls and non-critical structural components, eco mix offered a compelling balance: it achieved medium strength levels ($\approx 32\text{--}38$ MPa) at densities comparable to High performance mix, but at a lower binder and admixture cost, making it suitable for large volumes where cost control was paramount yet sustainability targets still had to be met [51].

From a holistic cost–benefit standpoint, the two mixes could therefore be deployed in a complementary manner within the same project: high performance mix reserved for zones where high strength and stiffness delivered maximum structural efficiency, and eco mix used extensively in regions where moderate strength sufficed but lightweight behaviour and sustainable composition remained desirable. This tiered approach mirrored recommendations from recent studies on green lightweight concretes, which emphasised that combining performance-graded mixes within a single structural system could optimise both environmental outcomes and construction budgets [48][49]. Overall, the sustainability-driven material design of high performance mix and eco mix was not achieved at the expense of economics][instead, it was carefully integrated into a cost-aware framework that supported realistic adoption in practice.

4. COMPARATIVE PERFORMANCE ANALYSIS AND PRACTICAL IMPLICATIONS

4.1. Performance Benchmarking

Building on the detailed characterisation presented in Section 3, a benchmarking analysis was conducted for the optimised lightweight concretes. These mixes were compared against a conventional normal-weight reference concrete of eco M20–M30 class, as well as against representative values reported for sustainable structural lightweight concretes in recent literature [52][43][53]. In terms of density, both mixes fell in the 1650–1750 kg/m³ range, corresponding to a 25–30 % reduction relative to the 2200–2400 kg/m³ of the reference concrete. This placed them

within the density band typically associated with structural lightweight concrete [54]. When strength was normalised by density, high performance mix in particular achieved a significantly higher strength-to-weight index than both the reference mix and many published lightweight mixtures, reflecting the effectiveness of the multi-component binder in compensating for the porous recycled aggregate [53].

Moreover, thermal and acoustic performance showed a similar favourable pattern. The conductivity of high performance mix ($\approx 0.75\text{--}1.0\text{ W/m}\cdot\text{K}$) and eco mix (slightly higher) was markedly lower than the $\approx 1.6\text{--}2.0\text{ W/m}\cdot\text{K}$ typical of normal-weight concrete and compared favourably with reported ranges for structural lightweight concretes incorporating expanded aggregates or bio-based fillers [52][43]. Normal-incidence absorption coefficients of $\approx 0.15\text{--}0.25$ and NRC values of $\approx 0.20\text{--}0.30$ positioned the developed mixes above dense concrete ($\alpha \approx 0.05\text{--}0.10$, NRC $\approx 0.05\text{--}0.15$) and within the moderate range observed for other structural lightweight systems, though still below specialised acoustic concretes where α often exceeds 0.45 [14][55]. To capture these combined effects, a simple thermo-acoustic performance index was defined qualitatively as NRC divided by k [on this basis high performance mix and eco mix outperformed the reference concrete and occupied the upper half of the range reported in recent thermo-acoustic studies on sustainable lightweight concrete [52][43][55].

From a sustainability standpoint, the benchmarking highlighted that both mixes achieved higher recycled content and clinker substitution than many published systems while remaining structurally efficient [48][50]. High performance , with about 25–30% binder replacement by ultrafine and agro-derived additions and 100 % recycled coarse aggregate, showed material indicators comparable to or better than other green lightweight concretes incorporating recycled aggregates and SCMs [48]. In contrast, eco mix retained the same aggregate concept and similar supplementary-material levels but with slightly lower ultrafine content, positioning it nearer the mid-range of literature in terms of embodied-impact indicators while offering clear cost advantages [56]. Table 5 is proposed to summarise this benchmarking by listing density, 28-day strength, strength-to-density ratio, conductivity, NRC and a qualitative sustainability index for the reference concrete, High performance, eco mix and representative literature ranges.

Table 2. Performance benchmarking of developed mixes against conventional concrete and literature values

Property	NWC Reference (ecoM20–M30)	High performance mix LWC	Eco LWC	Literature SLWC Range	Units
Strength/Density	0.011–0.015	0.031–0.035	0.019–0.023	0.018–0.032	MPa/(kg/m ³)×10 ³
Thermal Conductivity (k)	1.6–2.0	0.75–1.0	0.8–1.1	0.4–1.0	W/m·K
Absorption Coefficient (500–1000 Hz avg.)	0.05–0.10	0.15–0.25	0.15–0.25	0.10–0.45	–
Noise Reduction Coefficient (NRC)	0.05–0.15	0.20–0.30	0.20–0.30	0.15–0.35	–
Thermo acoustic Index (NRC/k)	0.03–0.09	0.20–0.40	0.18–0.38	0.15–0.50	–
Clinker Reduction	0%	25–30%	20–25%	15–40%	% of binder
Recycled Coarse Aggregate	0%	100%	100%	0–100%	%

Material Cost (relative)	100%	110–125%	105– 115%	100–130%	% of NWC
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4.2. Multicriteria Evaluation

A multi criteria view is necessary because the mixes are intended to provide simultaneous gains in structural efficiency, acoustic comfort, thermal performance and sustainability, rather than maximising a single property [53]. In the structural dimension, high performance mix offers the highest strength and stiffness at the lowest density, making it the preferred option where span length, axial load or seismic demand is critical][eco mix, with slightly lower strength but similar density, is better suited to large volume members where moderate capacities suffice and cost is a primary constraint [54][53]. When evaluated through a simple structural efficiency index (28day strength divided by density), both mixes outperform the normal weight reference and fall in the upper segment of the range reported for modern High performance lightweight concretes [54][53].

Balancing acoustic and thermal performance reveals synergistic rather than conflicting behaviour. The porous recycled aggregate and refined binder simultaneously reduce thermal conductivity and increase sound absorption, so there is no adverse tradeoff between these functional properties within the density range studied [52][43]. There is, however, a subtle tradeoff between extreme mechanical performance and maximised functional gains: the slightly denser, more microfilled matrix of high performance mix benefits strength and stiffness, whereas a marginally more open pore structure, as in eco mix, can be advantageous for acoustic absorption at the cost of a modest reduction in mechanical indices [43][53]. This interplay suggests that designers can tune the binder composition and pore structure within the same material family to prioritise either structural or thermo acoustic performance, depending on the application [56].

Economic considerations complete the multicriteria picture. Although both lightweight mixes have higher material cost per cubic metre than the reference concrete, the cost per unit of functional performance—considering strength to weight, thermal and acoustic indices together—favours high performance mix and especially eco mix when structural and envelope functions are combined [51][48]. In heavily loaded or architecturally demanding zones, the premium associated with high performance mix is justified by its superior strength and holistic performance][in typical floor systems and partition walls, eco mix provides most of the lightweight, thermo acoustic and sustainability benefits at a lower unit cost, improving the overall cost–benefit ratio of the building [51][56].

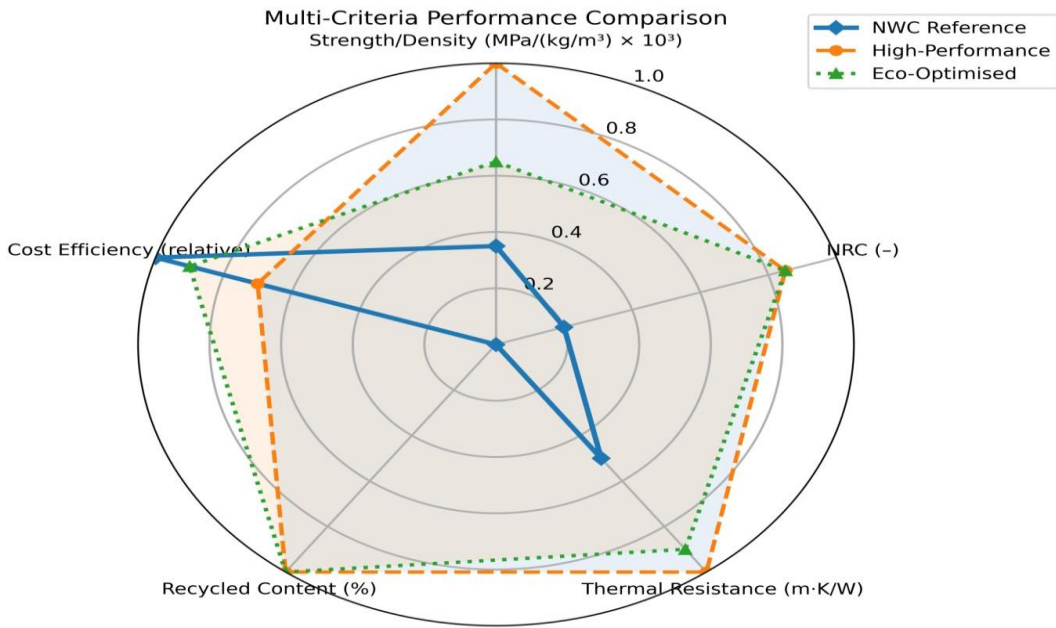


Figure 3. Multi-criteria radar comparison of normalized performance indices for high-performance and eco-optimised lightweight concrete relative to NWC reference

To visualise this multi criteria balance, a radar chart (Figure 8) is recommended, plotting normalised indices for the reference concrete, high performance mix and eco mix along axes such as strength/density, NRC, $1/k$ (thermal resistance proxy), recycled content and relative material cost [52][53]. In such a representation, the reference concrete would occupy a compact polygon dominated by structural strength but with weak thermo acoustic and sustainability scores, while eco mix would expand the polygon in all directions except maximal strength, and high performance mix would extend furthest in the strength, thermal and sustainability directions at the expense of higher cost [53][56]. This visual comparison reinforces the conclusion that the developed lightweight concretes form a performance graded family, enabling designers to choose an appropriate compromise between structural capacity, comfort and cost within a single, coherent, sustainable material system [53].

4.3. Applications

The developed lightweight concretes are particularly attractive for building facades and internal partitions where reduced self weight, moderate sound absorption and improved thermal performance can be exploited simultaneously [52]. For external walls, the combination of lower density ($\approx 1650\text{--}1750\text{ kg/m}^3$), moderate conductivity ($k \approx 0.75\text{--}1.0\text{ W/m}\cdot\text{K}$) and $\text{NRC} \approx 0.20\text{--}0.30$ allows designers to reduce dead load while achieving better envelope insulation and room acoustics than with normal weight concrete of the same thickness [43][14]. Internal partitions constructed with these mixes can satisfy typical airborne sound insulation targets for residential and office buildings when combined with standard finishes, while also benefiting from reduced floor loads in multi storey structures [54].

In infrastructure and urban applications, the concretes are suitable for acoustic barriers and noise mitigating elements along transport corridors, where moderate absorption and lightweight panels are desirable [14][55]. Their use of recycled brick aggregate and agro industrial byproducts makes them appealing for municipalities seeking to valorise construction and agricultural residues within local circular economy schemes [48]. In energy efficient construction, the improved strength to weight ratio of high performance mix supports longer spans, slimmer floor systems and lighter foundations, while both mixes contribute to lower operational energy demand by dampening heat flow and smoothing indoor temperature fluctuations [53][46]. These characteristics make the material family well suited to high rise buildings, seismic regions and retrofitting projects where weight reduction and enhanced envelope performance are critical.

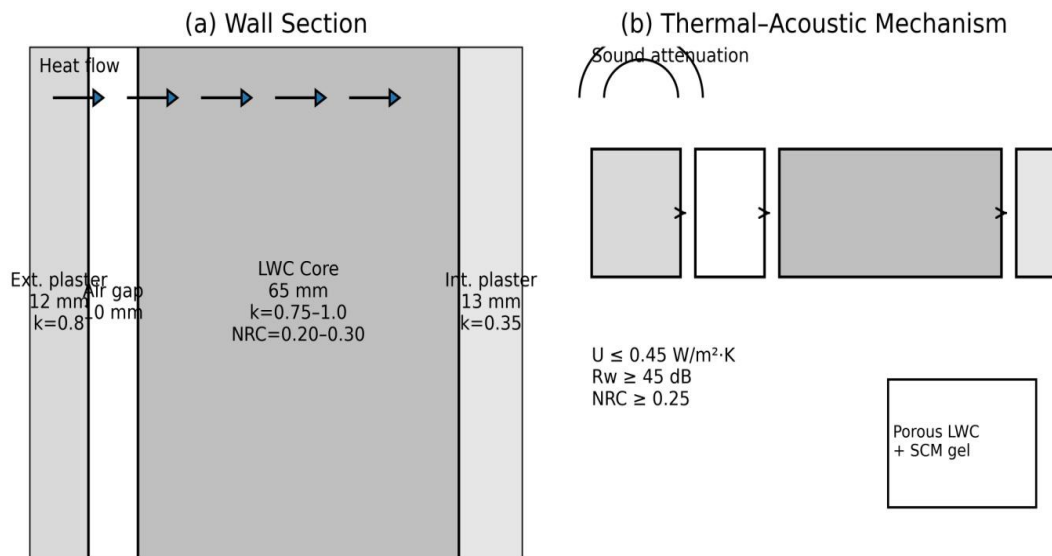


Figure 4. Wall cross-section showing high performance and eco concrete core and finishes for thermal/acoustic performance

4.4. Design Recommendations

For practical design, mix selection should be aligned with structural demand and cost constraints. High performance mix is recommended for heavily loaded or long span elements such as primary beams, slabs in high rise floors, transfer girders or shear walls, where its high 28day strength (M50+ range) and relatively low density deliver maximum structural efficiency [53]. Eco mix is more appropriate for large volume components with moderate strength requirements—secondary beams, flat slabs, stairs, infill and partition walls—where a balance between cost, lightweight behaviour and thermo acoustic performance is needed [56]. Designers should specify target properties in terms of characteristic compressive strength, equilibrium density, maximum thermal conductivity (for envelope elements) and minimum NRC or airborne sound insulation level where acoustic performance is relevant [52][14].

Implementation guidelines should emphasise quality control of materials and curing. Because recycled brick aggregates exhibit higher water absorption than natural stone, presoaking to a saturated surface dry state and accurate adjustment of effective water–binder ratio are essential to achieve the intended density and strength [54]. The use of the acrylic based high range water reducing admixture should follow manufacturer specific saturation curves to avoid overdosing while maintaining self compacting behaviour [53]. For envelope elements, specifications may include limits on k (e.g. $k \leq 1.0 \text{ W/m}\cdot\text{K}$), minimum wall thickness for target R_w or STC values,

and guidance on compatible finishes (thin plaster, textured renders, double leaf systems) to tune the final acoustic and thermal response [43][55].

5. CONCLUSIONS

This study shows that structural lightweight concretes produced with a blended binder incorporating ultrafine latent hydraulic powder, bio derived siliceous additions and recycled fired clay coarse aggregate can achieve a synergistic combination of mechanical, thermo acoustic and sustainability performance. In mechanical properties developed mixes meet structural strength requirements at significantly reduced densities, while exhibiting lower thermal conductivity and enhanced sound absorption compared with normal weight concrete of similar thickness. One mix acts as a high performance variant optimised for strength and durability, whereas another offers a cost optimised alternative. With respect to individual properties, the mechanical results show that one mix achieves 28day strengths in the M50+ range at lightweight densities while yielding a superior strength to weight index compared with other mix and normal weight concrete. Thermally, both mixes exhibit k for favourable structural values which contributes to building envelope insulation [43]. Acoustically, normal incidence absorption coefficients and NRC indicate a clear improvement over dense concrete and hence position the mixes within the moderate absorption class which suitable for residential and office buildings [52][14]. Sustainability indicators clinker reduction, high recycled aggregate content and improved thermal performance further highlight the potential of the system [48][50].

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