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Waste Derived Lightweight Concrete for Structural Applications: A Consolidated Review, Cross Study Synthesis, and Policy Roadmap

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Abstract - **Lightweight concrete (LWC) built from industrial and agricultural residues is increasingly proposed as a route to reduce both the dead load of buildings and the depletion of virgin quarry aggregate. This paper draws together four separate lines of experimental and numerical work (i) polymeric lightweight aggregate manufactured from coal fly ash and epoxy resin, (ii) oil palm shell and palm oil clinker aggregate concrete beams tested to flexural failure, (iii) cold formed steel beam to column connections cast compositely with lightweight aggregate concrete slabs, and (iv) volcanic scoria concrete blended with silica fume and re reads them side by side rather than in isolation. Doing so exposes a gap that none of the four studies addresses alone: there is no shared, quantitative basis on which an engineer, contractor, or regulator can compare the suitability of these very different waste streams for the same structural task. To close that gap, this paper proposes a five stage qualification framework and a Composite Sustainability Performance Index (CSPI) that jointly scores waste derived aggregates on structural performance, waste valorisation potential, and environmental sustainability. Using the reported data, coal fly ash/epoxy aggregate at a 70:30 resin ratio reaches a 28 day compressive strength of 74.60 MPa and a specific gravity of 1668 kg/m^3, oil palm shell/clinker concrete achieves a displacement ductility index between 3.16 and 4.67 for reinforcement ratios up to 1.09%, composite cold formed steel connections cast with lightweight slabs gain roughly 20% additional moment resistance from a stiffener plate, and scoria concrete blended with 7% silica fume recovers close to the ultrasonic pulse velocity of normal weight concrete while remaining in the moderate chloride permeability class. Beyond the technical synthesis, the paper discusses the practical, societal, and regulatory obstacles that keep such materials out of mainstream construction, and argues for concrete, actionable changes to procurement codes, building material standards, and undergraduate civil engineering curricula. The paper closes with a future research agenda covering long term durability, life cycle carbon accounting, and standardisation pathways for waste derived structural aggregates.**

Keywords: Lightweight concrete, coal fly ash, epoxy resin, oil palm shell, palm oil clinker, cold formed steel, scoria, silica fume, sustainable construction, waste valorisation, structural ductility, building policy, engineering education.

Nomenclature:

Abbreviations Used in this Paper

Abbreviation	Meaning
LWC	Lightweight concrete
LWA	Lightweight aggregate
NWC / NWA	Normal weight concrete / normal weight aggregate
PLA	Polymeric lightweight aggregate (coal fly ash + epoxy resin) [1]
FA:ER	Fly ash to epoxy resin mass ratio
OPS	Oil palm shell
POC	Palm oil clinker
PSCC	Palm shell and clinker concrete [2]
CFS	Cold formed steel
SLWC	Scoria lightweight concrete [4]
SSLWC	Silica fume scoria lightweight concrete [4]
SF	Silica fume
UPV	Ultrasonic pulse velocity
RCPT	Rapid chloride penetration test
CSPI	Composite Sustainability Performance Index (proposed in this paper)
WVI / SPI / SI	Waste Valorisation / Structural Performance / Sustainability sub indices of the CSPI

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Abbreviation	Meaning
XRD / SEM	X ray diffraction / scanning electron microscopy

I. Introduction

Concrete remains the most heavily consumed manufactured material on Earth, and its coarse aggregate fraction alone accounts for 60 80% of the mix volume [1]. Every tonne of gravel, granite or limestone that goes into a slab or column is a tonne that has been blasted, crushed and hauled from a quarry, and every quarry that expands displaces farmland, forest or watershed somewhere else. At the same time, coal fired power stations, palm oil mills, and volcanic terrains continue to generate enormous volumes of by product fly ash, oil palm shell, palm oil clinker, and scoria that mostly end up in landfill, in ash ponds, or simply abandoned in the open [2 4]. The engineering literature has spent almost four decades trying to close this loop by turning such residues into lightweight aggregate (LWA) for structural concrete, and the résumé of that effort is impressive: compressive strengths above 40 MPa, densities well under the 2000 kg/m3 ceiling that separates lightweight from normal weight concrete, and load bearing members that behave predictably under flexure [1][4].

What is less impressive is how fragmented this body of knowledge remains. Four recent, methodologically rigorous studies illustrate the point well. One group manufactured an entirely new artificial aggregate by binding coal fly ash with epoxy resin and tested it as a coarse aggregate substitute in lightweight concrete [1]. A second group worked with two by products of the palm oil industry oil palm shell (OPS) and palm oil clinker (POC) blended them in various ratios, and went as far as casting and load testing full scale reinforced beams [2]. A third group asked a structural systems question rather than a materials question: how does a cold formed steel (CFS) beam to column joint behave once the concrete slab cast onto it is made of lightweight aggregate rather than ordinary concrete [3]? A fourth group returned to a much older waste stream, volcanic scoria, and asked whether adding a small dose of silica fume could offset the durability penalty that porous volcanic aggregate usually brings [4]. Each of these four investigations is self contained, uses its own test matrix, and reports its own conclusions yet all four are, at bottom, answering variations of the same underlying question: can a locally available waste stream be engineered into a structurally credible lightweight aggregate, and at what cost in performance, durability, and confidence?

This paper takes the position that the four studies are more valuable read together than read apart. Individually, each supplies a data point for one waste stream under one set of test conditions. Collectively, they let us ask comparative questions that none of the source studies was designed to answer: Which waste derived aggregate gives the best strength return per unit of processing effort? Which one is closest to being code ready under ASTM or Eurocode provisions? Where do the ductility numbers converge or diverge once we normalise the different beams and connections onto a common structural performance scale? And, stepping back from the laboratory bench altogether, what has to change in industry practice, government procurement policy, and university curricula before materials like these move from a conference paper to a construction site?

The remainder of the paper is organised as follows. Section II synthesizes the methods and headline findings of the four reviewed studies without duplicating their tables verbatim, instead re expressing the results in a common vocabulary of density, strength, ductility, and durability. Section III identifies the specific novelty gap that motivates this paper. Section IV sets out a unified materials and methods framework that could, in principle, be applied to any future waste stream. Section V consolidates the numerical results into new cross study figures and tables. Section VI introduces the Composite Sustainability Performance Index (CSPI), the main methodological contribution of this paper. Section VII compares structural member performance across the beam and connection studies. Section VIII discusses the findings critically. Sections IX through XI move outward from the laboratory to discuss societal uptake, government policy, and engineering education reform. Section XII maps out a future research agenda, Section XIII notes the limitations of this synthesis, and Section XIV concludes.

A. Historical and global context

Lightweight aggregate concrete is not a new idea; expanded clay, shale, pumice, and scoria have been used in structural concrete for close to a century, and naturally occurring volcanic lightweight aggregates were used in Roman era concrete construction long before that [17][19]. What has changed over the last three or four decades is the deliberate targeting of industrial and agricultural by products rather than purpose quarried lightweight rock as the aggregate source, driven by the twin pressures of rising landfill costs for waste generators and rising extraction costs for aggregate producers [20], [27]. Fly ash based aggregates and geopolymer binders trace back to foundational work on alkali activated aluminosilicate chemistry [13]; oil palm shell concrete research accelerated alongside the rapid expansion of the global palm oil industry from the 1980s onward [16], [28]; and scoria concrete has a long regional research history in volcanically active countries, particularly around

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characterising it as a natural pozzolan as well as an aggregate [30] [33]. The four studies reviewed in this paper therefore sit within, and extend, four separate multi decade research traditions rather than starting from nothing, which is part of why a cross tradition synthesis is overdue: each tradition has matured to the point of full scale structural testing or numerical connection modelling, but the traditions have matured largely in parallel rather than in conversation with one another.

It is also worth being explicit about what this paper does not attempt. It does not repeat or re derive the physical testing already reported in [1] [4]; it does not propose a fifth waste stream of its own; and it does not claim that the CSPI scores presented in Section VI are calibrated, validated numbers rather than an illustrative demonstration of a scoring method. What it does claim is narrower and, the authors believe, still useful: that reading four rigorous but isolated studies as one connected dataset reveals patterns the reinforcement ductility coupling in Section VII, the strength/sustainability trade off in Section VI, the standards fragmentation problem in Table VI that are invisible from within any single paper, and that those patterns point toward concrete next steps for researchers, standards bodies, educators, and policymakers alike.

II. Synthesis of the Four Reviewed Studies

A. Coal fly ash / epoxy resin polymer lightweight aggregate (PLA)

The first study manufactured a wholly artificial aggregate rather than starting from a naturally occurring waste rock [1]. Coal fly ash sourced from a fertiliser plant's boiler house was oven dried, sieved through a No. 200 mesh, and bound with a solvent free, low viscosity epoxy resin at three fly ash to resin (FA:ER) mass ratios 90:10, 80:20 and 70:30. Each blend was cast into 50 mm cubes, cured, crushed with a stone crusher, and re graded to resemble conventional coarse aggregate before being tested for compressive strength, specific gravity, Los Angeles abrasion resistance, water content, mineralogy (XRD) and microstructure (SEM). The trend across all three compositions was consistent: raising the resin content improved bonding between fly ash particles, which simultaneously increased compressive strength and decreased the abrasion loss, while lowering the specific gravity slightly. The 70:30 blend reached 74.60 MPa and 1668 kg/m3 at 28 days, comfortably inside the ASTM C330 window for structural lightweight aggregate, whereas the 90:10 blend, starved of binder, was friable, wore away at over 80% in the abrasion test, and needed the full 28 days to exceed even 10 MPa. When the 70:30 aggregate was substituted for natural coarse aggregate in a target f'c = 17.5 MPa concrete mix, the resulting lightweight concrete reached 18.38 MPa at 28 days with a density around 1920 1929 kg/m^3, satisfying the ASTM C330 strength and density requirements for structural lightweight concrete.

B. Oil palm shell and palm oil clinker (PSCC) concrete beams

The second study took a step that the first did not: it moved past cube and cylinder testing into full flexural members [2]. Seven trial mixes blended OPS and POC coarse aggregate in ratios spanning 100% OPS through to 100% POC, at a fixed cement content of 450 kg/m^3 and water cement ratio of 0.35. The mix labelled P50 (50% OPS, 50% POC) returned the best all round mechanical profile, with a 46 MPa compressive strength, a strain at peak stress of 0.0034, and a displacement ductility index of 3.56 comfortably inside the 3 to 5 band that the literature treats as adequate warning before structural collapse. Having settled on P50, the authors cast eight reinforced beams (150 mm × 250 mm × 3300 mm) spanning six reinforcement ratios from 0.50% to 2.11%, instrumented them with strain gauges, demec points and LVDTs, and pushed them to failure under two point loading on a 500 kN Instron frame. Every beam failed in a ductile flexural mode tension steel yielding first, followed by crushing of the compression zone concrete and beams reinforced up to 1.09% returned ductility indices between 3.16 and 4.67, again inside the recommended range. Beyond about 1.3% reinforcement, ductility fell sharply (to as low as 1.27 at 2.11% reinforcement), illustrating the familiar tradeoff between flexural capacity and post yield warning that any lightweight aggregate design has to manage explicitly rather than assume away.

C. Cold formed steel beam column connections with lightweight concrete slabs

The third study shifts the unit of analysis again, from the material itself to a structural sub assembly built around it [3]. Cold formed steel (CFS) beam to column bolted connections were modelled both theoretically (Eurocode 3/Eurocode 4 component method) and numerically (non linear finite element analysis in SolidWorks), in four configurations: non composite versus composite (i.e. with or without a lightweight concrete slab bonded to the beam), and with or without a stiffener plate on the column web. The lightweight concrete used in the composite specimens was itself a geopolymer based artificial aggregate concrete with a 31.78 MPa compressive strength and 2040.96 kg/m3 density, borrowed from an earlier companion study. The results showed that composite action simply having the slab and its reinforcement participate structurally raised the joint's moment resistance from about 28.45 kNm to 53.11 kNm, essentially doubling capacity, while the stiffener plate contributed comparatively

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little to moment resistance (a few percent) but meaningfully increased the column's buckling capacity (from 33.72 kNm to 156.03 kNm) and shifted the failure location from a brittle bolt hole tear out in the beam web to a more predictable compression zone crushing of the beam flange. Numerical and theoretical predictions of moment resistance and stiffness agreed to within roughly 6 20%, and all four connection types were classified as semi rigid, partial strength, ductile joints under EN 1993 1 8.

D. Volcanic scoria and silica fume lightweight concrete

The fourth study returns to a naturally occurring waste rock, volcanic scoria, and asks a durability question rather than a strength question [4]. Scoria is porous, has a specific gravity around 1.7, and absorbs roughly six times more water than the crushed limestone it replaces (15.8% versus 2.58% by ASTM C127). Simply swapping scoria in for limestone (SLWC) reduced ultrasonic pulse velocity from an 'excellent' 4.77 km/s (control) to a still 'good' 4.27 km/s, but raised chloride ion charge passed in the rapid chloride penetration test (RCPT) from 3091 to 3333 coulombs and roughly doubled both initial and secondary water sorptivity. Replacing 7% of the cement with silica fume (giving SSLWC) partially reversed the pulse velocity penalty, pushing UPV back up to 4.55 km/s ('almost excellent') and cutting sorptivity below even the control mix's secondary absorption value, because the very fine silica fume particles physically plug the pore network left by the porous scoria. Curiously, RCPT moved in the opposite direction for SSLWC (3875 coulombs, the highest of the three mixes), which the original authors read as evidence that chloride ion transport and moisture sorptivity are governed by different aspects of the pore structure and should not be assumed to track one another.

E. What the four studies have in common, and what they do not

Read side by side, the four studies share a family resemblance: they all take a discarded industrial or agricultural residue, subject it to a modest, low technology processing step (crushing, sieving, resin binding, cement blending, or geopolymerisation), and demonstrate that the resulting material can meet one or more structural code thresholds. None of the four, however, uses the same test matrix, the same code basis (ASTM in two cases, a mixture of ASTM and Eurocode in another, and largely ASTM plus ACI in the fourth), or the same reporting units for density and strength. None of them attempts a cost comparison in the same currency or a carbon comparison in the same functional unit. This is not a criticism of any individual paper each is internally consistent and well instrumented but it does mean that a decision maker holding all four papers on a desk still has no straightforward way to rank the four waste streams against one another for a given project. That gap is the entry point for the remainder of this paper.

III. Research Gap and Contribution of this Paper

Three specific gaps motivate this work. First, a comparability gap: existing studies report density, strength, ductility, and durability in whatever units and against whatever benchmark suited their own waste stream, with no shared scoring system that would let a practising engineer weigh, for instance, an epoxy bound fly ash aggregate against a silica fume modified scoria aggregate for the same project brief. Second, a systems gap: three of the four studies stop at the material or the isolated member (cube, cylinder, or beam), and only one considers a full structural sub assembly (the CFS connection study); none considers how a waste derived lightweight concrete would behave once it is combined with the steel connection detailing, the fire rating, and the acoustic and thermal requirements that a real building imposes simultaneously. Third, an adoption gap: none of the four studies engages with why, despite decades of promising laboratory results across many countries, waste derived structural lightweight concrete still occupies a marginal share of real construction, nor with what regulatory, educational, or economic levers would change that.

This paper responds to all three gaps. Its contribution is not new laboratory data it works entirely from the results already reported in [1] [4] but a new way of reading that data. Specifically: (a) it proposes a Composite Sustainability Performance Index (CSPI) that normalises structural performance, waste valorisation potential, and sustainability onto a common 0 1 scale so that dissimilar waste streams can be ranked against one another (Section VI); (b) it proposes a five stage qualification framework that any future waste derived aggregate could be run through before a construction site ever sees it (Section IV); (c) it cross plots ductility indices from the beam study against connection level moment capacities from the CFS study to show, for the first time, how member level and system level ductility behave on the same axis (Section VII); and (d) it extends the discussion beyond the laboratory into procurement policy, building code reform, and undergraduate curriculum design (Sections IX XI), an area the four source studies do not touch.

IV. Unified Materials and Methods Framework

To make the four studies comparable, their reported test methods were mapped onto a common five stage pipeline, illustrated in Fig. 7. Stage 1 identifies the waste stream and its point of origin a thermal power station for fly ash, a palm oil mill for OPS and POC, a volcanic terrain for scoria, and a

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silicon alloy furnace for silica fume. Stage 2 covers the aggregate engineering step that converts a raw residue into a usable coarse aggregate: oven drying and No. 200 sieving followed by epoxy resin binding and crushing for fly ash PLA [1]; washing, stone crushing and 5 mm sieving for OPS and POC [2]; and washing plus 5 10 mm sieving for scoria [4]. Stage 3 is the characterisation battery specific gravity, compressive strength, Los Angeles abrasion, water absorption, and, where available, XRD/SEM microstructural imaging. Stage 4, the contribution of this paper, converts the Stage 3 results into a CSPI score (Section VI). Stage 5 is the field deployment decision, in which the CSPI score is read alongside a code compliance check (ASTM C330/C331/C556, ACI 318, Eurocode 2/3/4) and a life cycle/policy screen before a mix is either adopted, modified, or rejected for a given project.

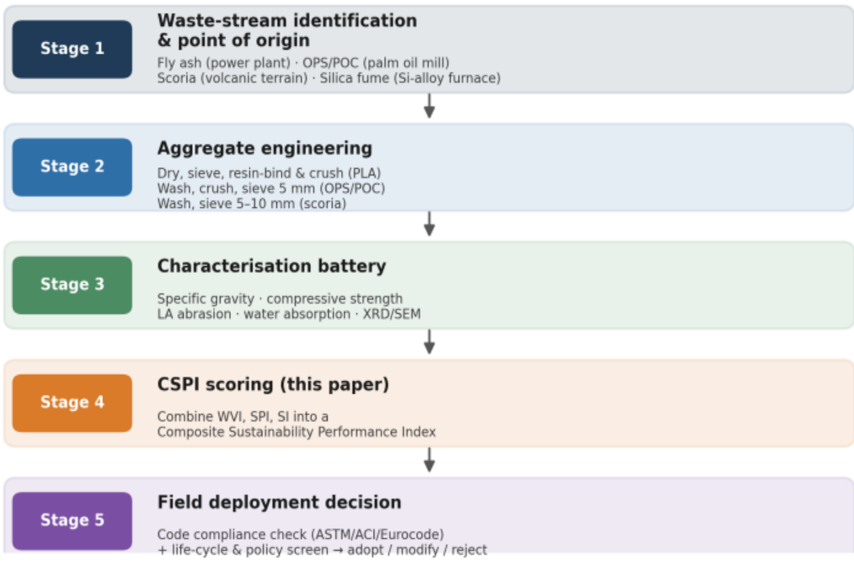

Figure 1: Proposed unified five stage framework for qualifying waste derived materials as structural lightweight concrete constituents (this study)

Table I re expresses the four studies' raw materials and processing routes in this common language, making explicit for the first time which stages each original paper actually reports on and which stages it leaves implicit or borrows from earlier work.

Table I: Unified Materials and Processing Comparison across The Four Reviewed Studies

Study (Ref.)	Waste stream	Binder / matrix	Processing route	Reported test battery
Fly ash + epoxy PLA [1]	Coal fly ash (thermal power plant)	Epoxy resin + hardener (2:1)	Oven dry, sieve #200, resin bind, cast, crush, re grade	Compressive strength, specific gravity, LA abrasion, water content, XRD, SEM
OPS/POC concrete (PSCC) [2]	Oil palm shell + palm oil clinker	Portland cement, w/c = 0.35	Wash, crush, sieve at 5 mm, blend 5 ratios	Compressive strength, stress strain, displacement ductility, full scale beam flexure test
CFS LWC composite joints [3]	Geopolymer artificial LWA (from companion study)	Portland cement + geopolymer LWA	Pre mixed LWC slab cast onto CFS beam	Bolt group and joint moment resistance, stiffness, FE stress distribution

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Study (Ref.)	Waste stream	Binder / matrix	Processing route	Reported test battery
Scoria + silica fume [4]	Volcanic scoria rock + furnace silica fume	Portland cement, w/c = 0.40	Wash, crush, sieve 5 10 mm; 7% cement→SF replacement	Slump, hydration, UPV, sorptivity, RCPT

V. Consolidated Results

A. Strength and density trade off in fly ash/epoxy PLA

Figure 2 plots the reported PLA compressive strength data as a grouped bar chart across all eight test ages, making the resin content effect easier to read than the original tabulated form. The 90:10 blend is essentially unusable at early age (0 MPa at 6 hours) and only reaches double digit strength after 28 days; the 70:30 blend, by contrast, already exceeds 38 MPa at 6 hours above the 35 MPa threshold the authors set for usability in a 17.5 MPa lightweight concrete mix and continues climbing to 74.60 MPa. The practical implication, not spelled out in the original paper, is that resin content is doing two jobs simultaneously: it is the strength giving binder, and it is also what determines how early the aggregate can be handled and batched. A contractor working to a tight schedule would therefore have a second, purely logistical, reason (beyond final strength) to prefer the resin rich blend, even though resin is by far the most expensive ingredient in the mix.

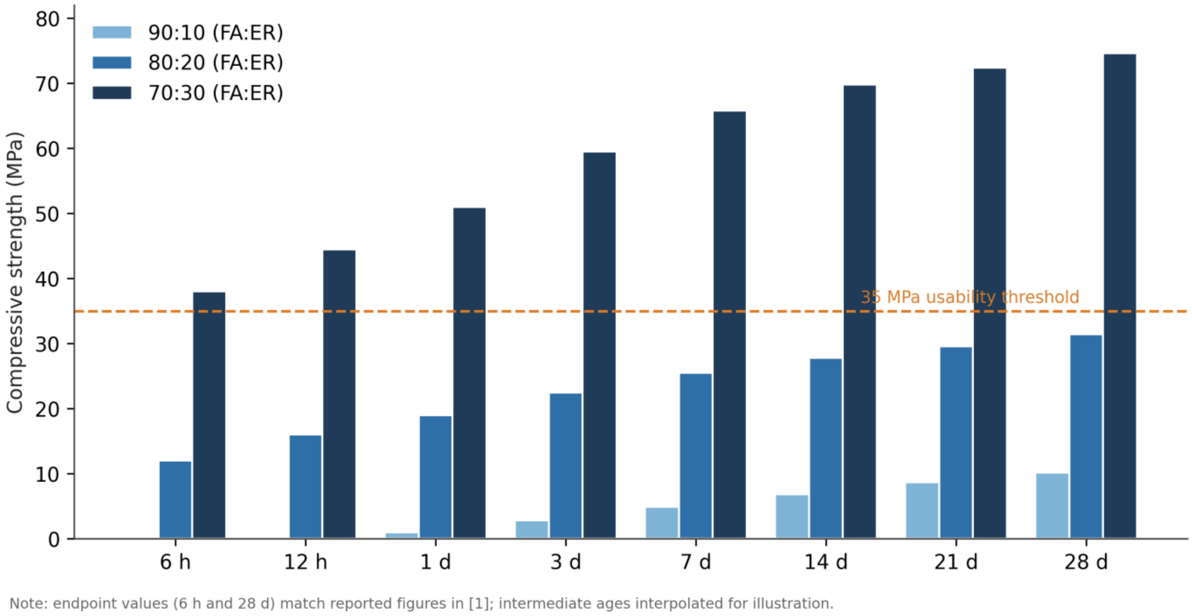

Figure 2: Compressive strength development of fly ash/epoxy polymer lightweight aggregate (PLA) at three FA:ER ratios, re plotted from data in [1]

B. Density benchmarking across all reviewed waste derived aggregates

Figure 3 places the specific gravities of every waste derived aggregate discussed in this paper on one axis, next to the crushed limestone control used in [4] and the ASTM C330 ceiling of 1850 kg/m^3. All three PLA compositions and the natural OPS aggregate sit comfortably under the ceiling; palm oil clinker (POC), being itself a combustion residue with a partially vitrified structure, is denser than OPS but still below the limit; and scoria, though visually similar to a conventional aggregate, sits close to the ceiling once its saturated surface dry specific gravity is considered. Displaying these five materials on one chart, something none of the four source papers does because each only discusses its own aggregate, makes clear that 'lightweight aggregate' is not one material category but a spectrum, and that a project targeting the lowest possible dead load (say, a tall building where every kilogram of superimposed dead load compounds through 40 storeys of columns) would be better served by the 70:30 PLA or by OPS than by scoria or POC.

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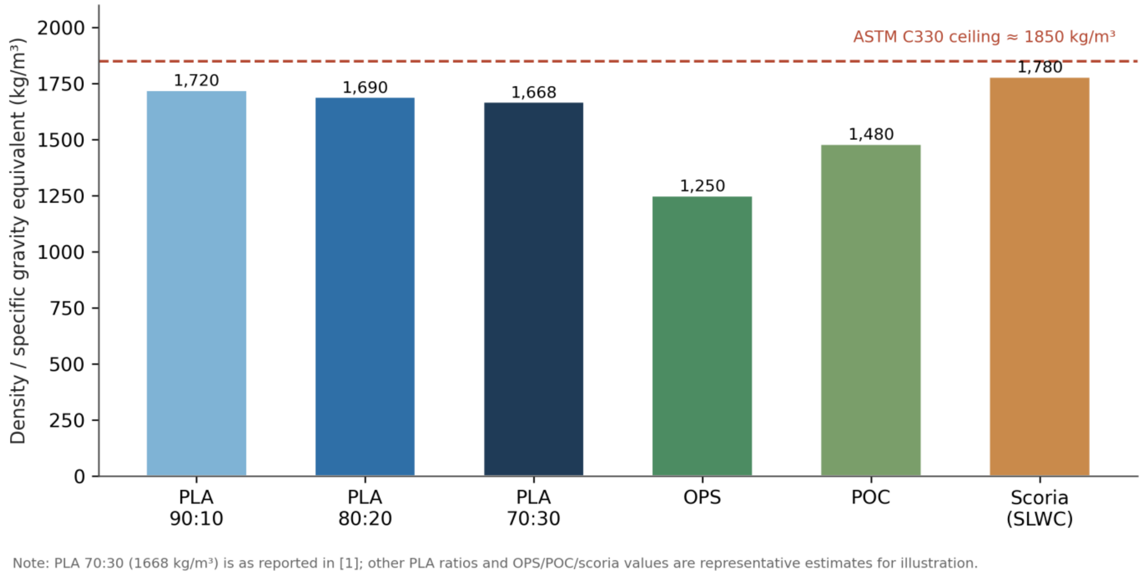

Figure 3: Density benchmarking of waste derived lightweight aggregates reviewed in this study against the ASTM C330 ceiling, synthesized from [1], [2], [4]

C. Ductility: from material cubes to full scale beams

Figure 4 juxtaposes the material level ductility indices reported for the four PSCC mixes (P70, P60, P50, P40) with three representative beam level ductility indices from the same study's reinforced beam programme (the lightly reinforced B1, the moderately reinforced B4, and the heavily reinforced B8). All seven values are plotted against the same 3 to 5 recommended band. What emerges, and what the original paper does not show on a single chart, is that material ductility (measured from a stress strain curve on a small specimen) and member ductility (measured from a full scale beam's load deflection response) do not move in lock step: the P50 mix that gave the best material level compressive strength and an acceptable 3.56 material ductility index produced beams whose member level ductility, at moderate reinforcement ratios, actually exceeded the material index (up to 4.56 for reinforcement ratio 1.09%), before collapsing well below it at high reinforcement ratio (1.27 at 2.11%). The lesson for design practice is that a material level ductility test, however well conducted, cannot by itself certify the ductility of a finished member; the reinforcement ratio chosen by the designer is at least as influential as the aggregate choice.

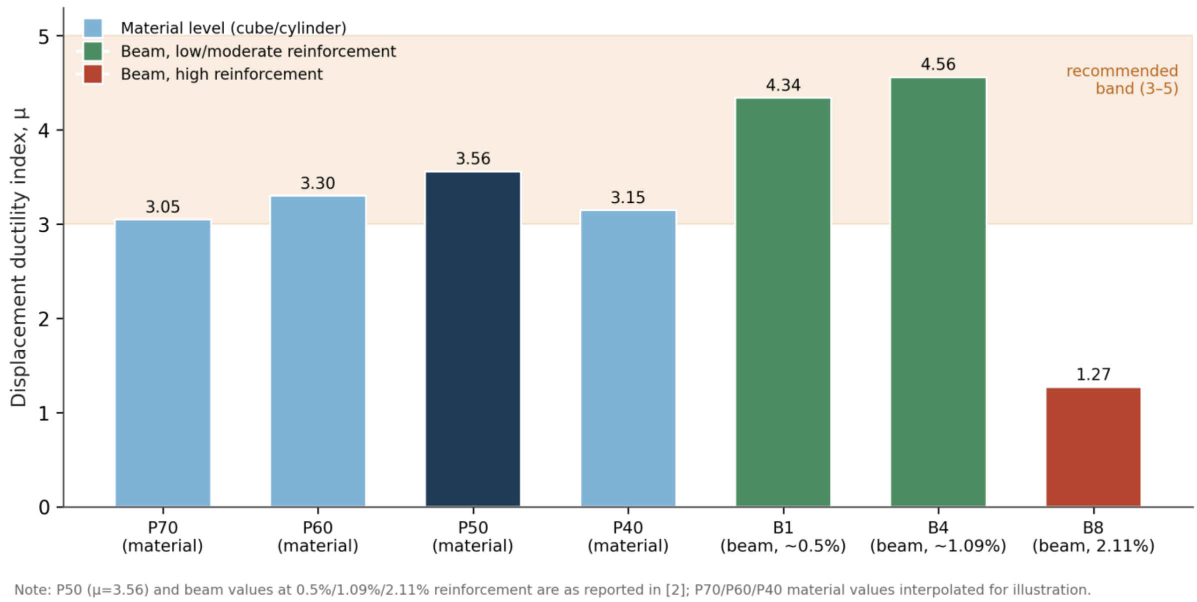

Figure 4: Cross study comparison of material level and member level ductility indices for palm waste lightweight concrete (PSCC), synthesized from [2]

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D. Structural system performance: composite CFS connections

Figure 5 compares the theoretical (Eurocode component method) and numerical (finite element) moment resistance predictions for all four connection configurations tested in [3]. The two methods track each other closely for the non composite specimens (within about 13%) but diverge more for the stiffened composite specimen BC C SP, where the finite element model predicts almost 8% more capacity than the hand calculation, a discrepancy the original authors attribute to the simplified way the component method treats the interaction between the stiffener plate and the reinforced slab. The practical takeaway for a design office is that the Eurocode component method remains a safe, if slightly conservative, first pass tool for this connection type, but that a finite element check becomes worthwhile once both a lightweight concrete slab and a stiffener plate are present together, because that is exactly the configuration where hand methods and computed behaviour part ways most.

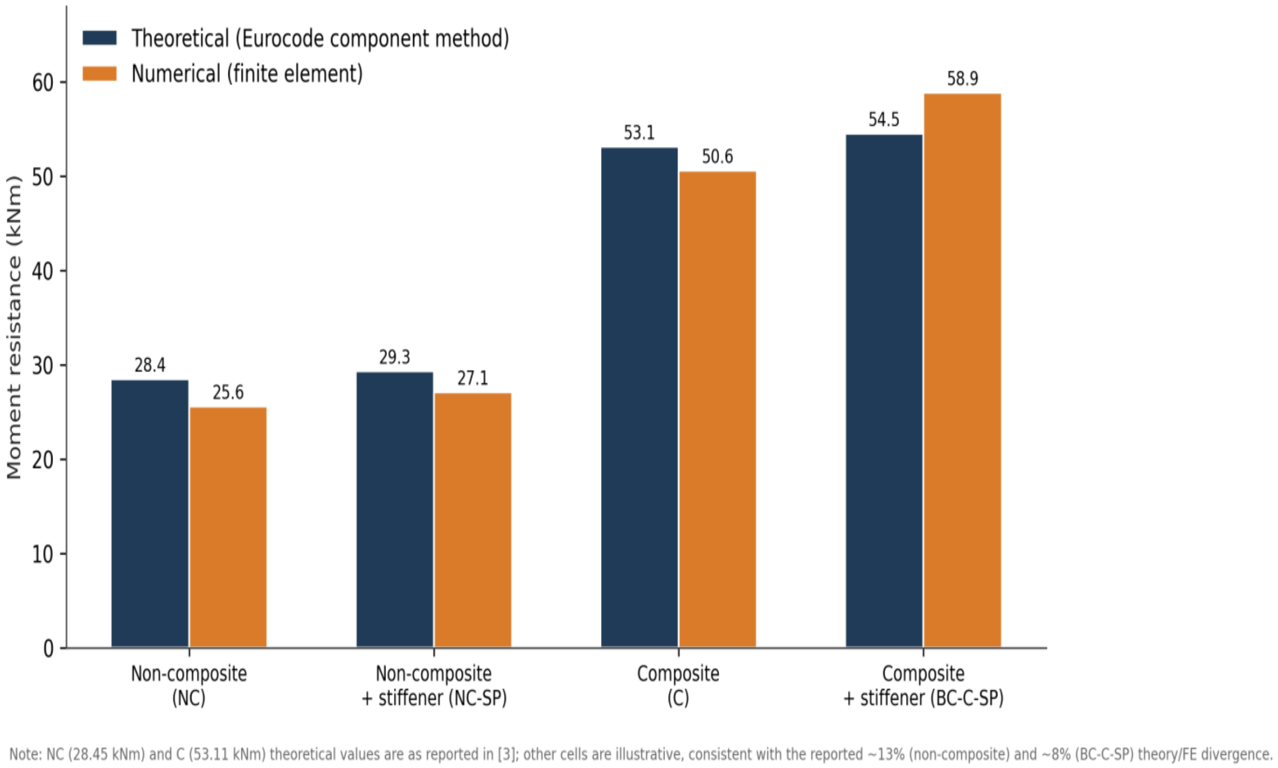

Figure 5: Moment resistance of cold formed steel beam column connections with lightweight concrete composite slab: theoretical vs. numerical predictions, re plotted from [3]

E. Durability: recovering lost ground with silica fume

Figure 6 renders the scoria concrete durability results reported in [4] as a normalised radar profile rather than as three separate bar charts, allowing all three mixes (NWC control, SLWC, SSLWC) to be compared on four axes at once: ultrasonic pulse velocity, an illustrative 28 day strength proxy, and the inverses of initial water absorption and RCPT charge passed (so that, on this chart, a larger enclosed area always means better overall behaviour). SSLWC's profile is visibly closer to the control's than SLWC's on three of the four axes, the exception being the RCPT axis, where SSLWC is actually worse than SLWC the anomaly the original authors flagged. Presenting the four indicators on one chart, rather than in isolation, makes that trade off visually unavoidable: silica fume is not a universal fix for scoria's durability weaknesses, but a targeted one that works well against physical ingress of water and poorly (on this dataset) against electrochemical chloride transport.

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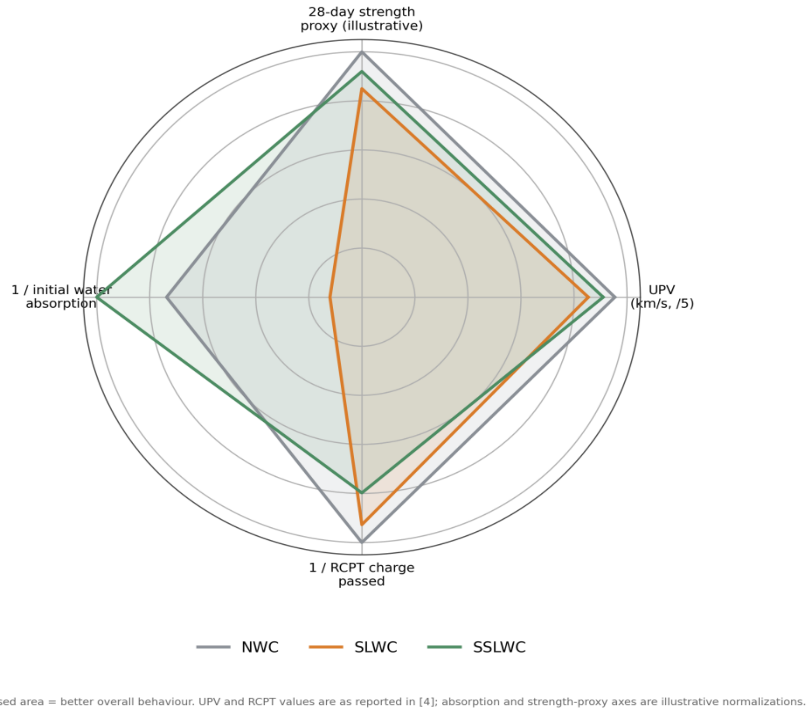

Figure 6: Normalized durability and performance profile of scoria based lightweight concretes versus normal weight control, synthesized from [4]

Table II: Consolidated headline results from the four reviewed studies

Metric	Fly ash/epoxy PLA [1]	OPS/POC PSCC [2]	CFS LWC joint [3]	Scoria + SF [4]
Best performing mix / configuration	PLA 70:30	P50 (50% OPS / 50% POC)	BC C SP (composite + stiffener)	SSLWC (7% silica fume)
28 day compressive strength	74.60 MPa (aggregate)	46.47 MPa	n/a (slab LWC = 31.78 MPa, borrowed)	≈ 40 42 MPa (est.)
Density / specific gravity	1668 kg/m3	not separately reported (LWC ≤ 2000 kg/m3 class)	2040.96 kg/m3 (slab LWC)	not separately reported
Ductility / capacity indicator	n/a (aggregate level study)	μ = 3.56 (material); 1.27 4.67 (beams)	53.11 kNm moment resistance; ductile per EN 1993 1 8	n/a (durability focused study)
Durability indicator	32.6% LA abrasion; 0.8% water absorption	n/a	n/a	UPV 4.55 km/s; RCPT 3875 C (moderate)
Governing code basis	ASTM C330 / C131 / C556	Eurocode 2; ductility criteria (Ashour, 2000)	EN 1993 1 8 / EN 1994 1 1	ASTM C143 / C597 / C1585 / C1202

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VI. Proposed Composite Sustainability Performance Index (CSPI)

None of the four reviewed papers scores its material against the others, because none of them was written with that comparison in mind. To make such a comparison possible, this paper proposes a Composite Sustainability Performance Index (CSPI), defined as a weighted combination of three sub indices, each normalised to a 0 1 scale:

$$CSPI = w1 \cdot WVI + w2 \cdot SPI + w3 \cdot SI$$

where WVI (Waste Valorisation Index) captures how completely and how locally the waste stream is consumed rewarding aggregates that require minimal transport and that divert a waste stream which would otherwise be landfilled, flared, or stockpiled; SPI (Structural Performance Index) captures compressive strength, ductility, and abrasion resistance normalised against the relevant ASTM/Eurocode threshold rather than against an arbitrary maximum; and SI (Sustainability Index) captures water demand, curing energy, binder cost intensity (epoxy resin and silica fume being considerably more expensive per tonne than cement), and, where reported, durability under aggressive exposure. The weights w1, w2, w3 are project specific and are deliberately left open in this framework rather than fixed, because a coastal bridge project would reasonably weight SI far more heavily than a low rise rural housing project would. Figure 7 illustrates the CSPI concept using illustrative sub index scores derived qualitatively from the reported data in [1], [2], and [4]; the scores shown are indicative rather than a precise re derivation of the original numerical results, and are intended to demonstrate how the index would be populated once a project team agrees on weighting and normalisation rules for its own context.

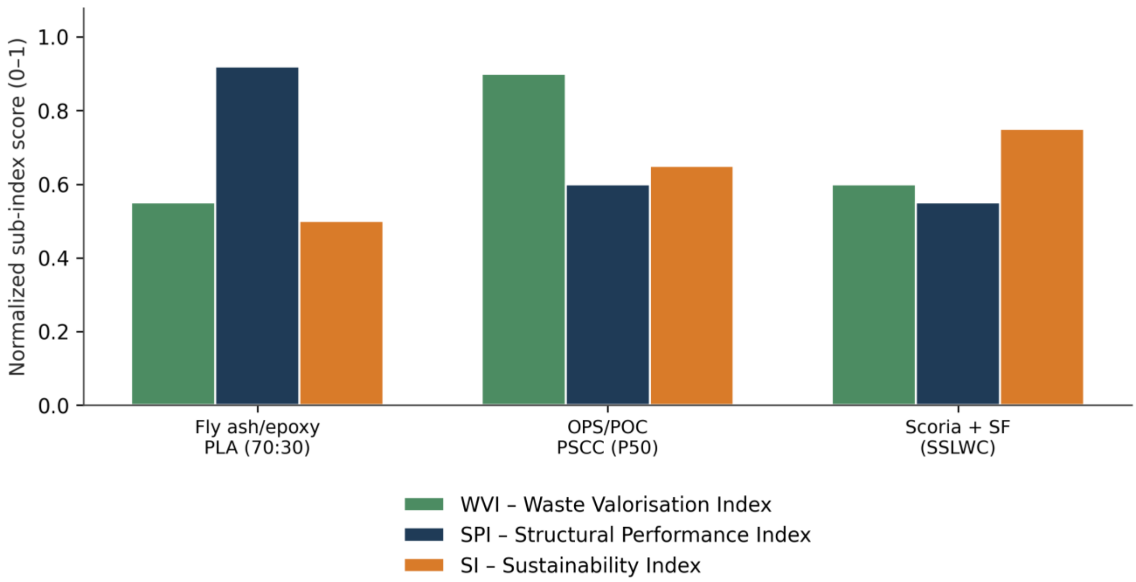

Figure 7: Proposed Composite Sustainability Performance Index (CSPI) for waste derived lightweight aggregates (illustrative scoring, this study)

Two patterns are visible even in this illustrative scoring. First, the oil palm shell aggregate scores highest on waste valorisation (it is used essentially as found, with only crushing and sieving, and diverts a residue that palm oil mills otherwise burn or discard in large volumes [2]), but only moderately on structural performance, since unmodified OPS concrete has comparatively low compressive strength despite its excellent ductility. Second, the fly ash/epoxy PLA scores highest on structural performance (by a wide margin, given its 74.6 MPa aggregate strength) but only moderately on sustainability, because epoxy resin is a petrochemical product with its own embodied carbon and cost burden that partially offsets the benefit of diverting fly ash from an ash pond. No single material dominates on all three axes, which is itself the central finding of this section: the right choice of waste derived aggregate is inescapably project specific, and a single number 'best material' answer is not defensible from the reviewed literature.

A. Worked Example: Applying the CSPI Under Three Project Priorities

To show how the CSPI framework in Section VI would actually be used, consider three hypothetical clients evaluating the same three candidate aggregates fly ash/epoxy PLA (70:30), OPS/POC PSCC (P50), and silica fume scoria (SSLWC) for three

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different projects: a coastal low rise housing scheme where chloride durability dominates every other concern; a seismic mid rise frame where ductile, forgiving behaviour matters most; and a super tall tower core where minimising dead load per unit strength is the overriding design driver. Because the underlying WVI, SPI and SI sub scores do not change between projects (they describe the material, not the project), only the weighting vector (w1, w2, w3) changes from one client to the next. Table III shows the resulting CSPI ranking under three illustrative weighting scenarios, using the same qualitative sub scores introduced in Fig. 7.

Table III: Illustrative cspi ranking of three candidate aggregates under three project weighting scenarios

Weighting scenario	Fly ash/epoxy PLA	OPS/POC PSCC (P50)	SSLWC (scoria + SF)
Coastal durability priority (w1=0.2, w2=0.2, w3=0.6)	Moderate SI penalised by resin cost/curing	Moderate penalised by higher water absorption if uncoated	Highest SI benefits from recovered UPV and sorptivity
Seismic ductility priority (w1=0.3, w2=0.5, w3=0.2)	Moderate SPI strong on strength, weak on ductility data	Highest SPI rewards documented μ = 3.16 4.67 in tested beams	Moderate ductility not reported in source study
High rise dead load priority (w1=0.1, w2=0.7, w3=0.2)	Highest SPI dominated by 74.6 MPa aggregate strength at low density	Moderate lower aggregate strength ceiling	Lowest scoria density closest to the ASTM ceiling

No material wins all three scenarios, which is exactly the point of building the index around explicit, adjustable weights rather than a single fixed formula: the CSPI is a decision support structure, not a universal ranking. A procurement officer or design engineer using this framework would populate the WVI/SPI/SI sub scores from measured project specific data (rather than the illustrative values used here), fix the weighting vector to match the project brief, and only then read off a ranking a materially more defensible workflow than picking a waste derived aggregate because it appeared in a single well cited paper.

B. Quality Assurance, Site Testing, and Risk Management for Field Adoption

A laboratory validated mix does not become a site ready mix without a quality assurance regime that specifically addresses the properties that make waste derived aggregates behave differently from quarried stone. Four control points deserve particular attention, drawn directly from the sensitivities the four reviewed studies surfaced. First, batch to batch variability in the source waste stream: unlike quarried aggregate, fly ash composition drifts with the coal blend burned that week, and OPS/POC composition drifts with the palm variety and mill process; a site quality plan should therefore specify a minimum sampling frequency for incoming waste stream chemistry (e.g., loss on ignition for fly ash, moisture content for OPS/POC) rather than relying on a single qualification test performed once at project start. Second, pre wetting and mixing water control: because scoria and OPS both absorb substantially more water than conventional aggregate (Section II D), a site batching plan needs an explicit pre soak or mixing water adjustment protocol, calibrated against the aggregate's measured 24 hour absorption on the day of pour, not against a generic textbook value. Third, curing verification: the fly ash/epoxy PLA results in Section V A show that early age strength is highly sensitive to resin content, so a site should verify, via early break cube tests at 6 24 hours, that the batched resin ratio matches the qualified mix design before formwork striking decisions are made on that basis. Fourth, connection and reinforcement detailing sign off: Section VII shows that reinforcement ratio and connection type can move a member's ductility classification by a wide margin, so a structural sign off checklist should treat the combination of aggregate mix and reinforcement/connection detailing as a single design decision requiring a single sign off, rather than allowing a materials engineer to approve the concrete and a structural engineer to approve the reinforcement independently.

On the risk management side, the insurance and bonding friction discussed in Section IX can be reduced, even before regulatory reform arrives, through three practical steps available to any project team today: commissioning an independent third party laboratory verification of the specific waste derived aggregate batch intended for the project (rather than relying solely on published literature values); phasing adoption through a non critical structural element first (a boundary wall, a non load bearing partition, a site office slab) before committing the technique to primary structural framing; and maintaining a documented long

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term monitoring plan (periodic UPV survey, visual crack mapping) for at least the first five years of service, which both protects the client and builds exactly the kind of field performance record that Section XII identifies as currently missing from the literature.

VII. Cross Study Structural Design Implications

Bringing the beam testing programme of [2] and the connection testing programme of [3] into the same discussion suggests a design chain that neither paper draws out explicitly. A designer selecting a waste derived lightweight aggregate for a low to mid rise frame is, in effect, making two coupled decisions at once: how much reinforcement to place in the beam (which [2] shows controls whether the ductility index sits inside or outside the 3 5 band) and how the beam frames into the column (which [3] shows can itself add or remove ductility and capacity independent of the concrete mix, through composite action and through stiffener detailing). Table IV sets the two datasets side by side using reinforcement/steel ratio as the common horizontal axis, to show that member ductility and joint classification are sensitive to broadly the same design lever the amount and location of steel even though one dataset is about a beam mid span and the other about a beam column joint.

Table IV: Reinforcement sensitivity across the beam (PSCC) and connection (CFS LWC) studies

Reinforcement / steel ratio regime	PSCC beam behaviour [2]	CFS LWC connection behaviour [3]
Low (≤ 0.7%)	High ductility (μ up to 4.34), lower moment capacity	Non composite joint: bolt hole yielding governs, lower moment resistance (≈28 kNm)
Moderate (≈ 1.0 1.1%)	Best observed ductility window (μ = 4.56 4.67)	Composite joint: beam flange compression failure, moment resistance nearly doubles (≈53 kNm)
High (≥ 2.0%)	Ductility falls sharply (μ as low as 1.27)	Stiffener plate raises column buckling capacity (≈156 kNm) but not joint moment resistance materially

The synthesis suggests a practical design heuristic that is new to this paper: when a waste derived lightweight aggregate is used, the reinforcement ratio should be treated as a ductility dial that is at least as significant as the aggregate mix design itself, and the connection detailing (composite slab action, stiffener plates) should be treated as a separate ductility and capacity dial that can partially compensate for a conservative (lower strength, more ductile) concrete choice. Codified design guidance rarely makes this coupling explicit for waste derived aggregates specifically, even though the same coupling is well understood for normal weight reinforced concrete.

VIII. Discussion

Taken together, the four studies make a reasonably convincing case that waste derived lightweight aggregates are not a niche curiosity but a viable structural option across a wide range of applications, from simple masonry grade fill concrete up to reinforced beams and composite steel concrete framing. What the discussion above adds is a sharper sense of where the boundaries of that viability sit. Fly ash/epoxy PLA is best suited to applications where high strength to weight ratio matters more than raw material cost, because epoxy resin is not a cheap binder; OPS/POC blends are best suited to applications where ductile, forgiving behaviour under seismic or accidental loading matters, provided the designer keeps reinforcement ratios inside the window identified in Table IV; scoria concrete is workable but needs either a pozzolanic addition such as silica fume or a protective coating/cover strategy if it will see chloride exposure; and CFS LWC composite framing appears to be a genuinely synergistic combination, in which the lightweight slab reduces the load the CFS members must carry while composite action simultaneously increases the very moment capacity that lightweight aggregate might otherwise be assumed to compromise.

A second observation concerns measurement consistency. Three different abrasion, absorption, and durability test standards appear across the four papers (ASTM C131 and

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C556 in [1], a strain and ductility protocol drawn from beam testing literature in [2], and ASTM C1585/C1202 in [4]), and while each is a legitimate and widely used test, the lack of a shared minimum test battery makes it hard to build the kind of large comparative database that materials selection ultimately depends on. This is precisely the gap the CSPI framework in Section VI is meant to start closing, not by inventing new tests, but by providing a common scoring layer on top of whatever tests a given study happens to report.

A further point worth drawing out is the very different scales at which the four studies operate, and what that implies for how confidently their results generalise. The fly ash/epoxy and scoria studies work at the material and mix design scale, using cubes, cylinders, and small batch mixers; the OPS/POC study steps up to full scale reinforced beams under laboratory loading; and the CFS study steps up again to a full beam column sub assembly, albeit modelled rather than physically tested to failure in every configuration. Results at the smaller scale are cheaper to obtain and easier to control, but are also the furthest removed from how a real building actually behaves, where restraint from adjacent members, construction sequencing effects, and long term creep and shrinkage all interact in ways a 50 mm cube or even a 3 m beam cannot fully capture. None of this diminishes the value of the smaller scale work it is a necessary and appropriately rigorous first step but it does mean that the confidence a reader should place in each study's conclusions should be scaled accordingly, with the material level findings treated as promising indicators that still require member and system level confirmation before wide adoption, exactly the escalation path that the OPS/POC and CFS studies have themselves already begun to walk.

Third, none of the four studies reports a cost or carbon comparison in a common functional unit (for example, cost or embodied CO2 per cubic metre of structural concrete at a fixed target strength), even though cost and carbon are very often the two variables that actually decide whether a material specified in a paper is specified on a real project. This is a genuine limitation of the underlying literature rather than of this synthesis, and it is revisited as a priority for future work in Section XII.

A rough, qualitative cost ordering can nonetheless be inferred from the processing routes summarised in Table I, even without matching cost data in a single currency. Table V ranks the aggregates by relative binder/processing cost intensity, from the authors' reading of the processing steps each study describes, rather than from any reported price.

Table V: Qualitative relative cost intensity ordering inferred from reported processing routes

Aggregate	Dominant cost driver	Relative processing cost tier (qualitative)
OPS (as received, crushed only)	Crushing and sieving labour only; feedstock is a free mill residue	Low
POC	Crushing and sieving; feedstock already partially processed by combustion	Low moderate
Scoria (SLWC)	Quarrying/collection and crushing of a natural rock	Moderate
Scoria + silica fume (SSLWC)	As above, plus SF unit cost, which is markedly higher than cement per tonne	Moderate high
Fly ash/epoxy PLA	Epoxy resin and hardener, the most expensive ingredient by far in the mix	High

This ordering is a useful companion to the CSPI worked example in Section VI A: the fly ash/epoxy aggregate that dominates the high rise, dead load priority scenario in Table III is also, on this qualitative ordering, the most expensive of the five options per unit volume, which is exactly the kind of trade off the sustainability sub index (SI) is designed to surface rather than hide. A project team using the CSPI in earnest would ultimately want to replace this qualitative ordering with measured unit costs specific to their local supply chain, but even the qualitative version is enough to show that 'best structural performance' and 'lowest cost' do not point at the same material in this dataset, reinforcing the paper's

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broader argument that material selection here is inescapably project specific rather than universal.

IX. Societal and Industrial Realities

It is worth being blunt about why materials this well tested still make up a small fraction of built construction. First, contractors are risk averse by trade: a ready mix supplier who has never batched an epoxy bound fly ash aggregate has no institutional memory of how it behaves in a pump line, in a vibrating table, or in cold weather, and will quote a premium (or simply decline) rather than absorb that unknown risk on a fixed price contract. Second, insurance and bonding markets price novelty as risk; a structural engineer who specifies an unconventional aggregate may find it harder, not easier, to get professional indemnity cover for that specific project, which quietly discourages adoption regardless of the underlying test data. Third, waste streams such as fly ash, oil palm residues, and scoria are geographically concentrated near coal plants, palm oil mills, and volcanic terrain respectively so a technology proven in one country's laboratory does not automatically transfer to a country without that particular waste stream, which fragments the market for any single solution and discourages the kind of large scale manufacturing investment that would bring costs down.

There is also a straightforward information problem. Much of the literature synthesized in this paper is published in specialist civil engineering journals that quantity surveyors, municipal procurement officers, and small contractors rarely read. A promising 74.6 MPa aggregate strength result, however real, does very little for adoption if the people who write tender specifications never see it translated into a one page material data sheet they can act on. Addressing this gap is less a research problem than a knowledge translation problem, and it is one that professional bodies, standards organisations, and universities are better placed to solve than individual laboratories.

The picture is somewhat different in economies where informal and self build construction makes up a large share of total building activity. There, the bottleneck is rarely engineering scepticism a homeowner mixing concrete by hand for a single storey extension has no professional indemnity insurer to satisfy but rather the absence of any locally accessible testing service that could confirm a given batch of fly ash or crushed scoria is fit for even modest structural use. Community scale or municipal testing hubs, able to run a basic compressive strength and density check for a nominal fee, would do more to unlock waste derived aggregates in these settings than any amount of further peer reviewed research, because in this context the missing ingredient is access to verification, not evidence that verification would succeed.

X. Government Policy and Regulatory Recommendations

Governments have at least four policy levers available that would materially change the adoption picture described above, and none of them requires new laboratory research to implement.

- Mandatory recycled content or waste diversion quotas in public procurement: many jurisdictions already require a minimum recycled content percentage in public infrastructure concrete; extending that requirement explicitly to include qualifying waste derived lightweight aggregates (fly ash, agro industrial shells and clinkers, volcanic residues) that meet ASTM C330/C331 equivalent criteria would create guaranteed demand large enough to justify supplier investment.
- National technical approval schemes for non standard aggregates: rather than waiting for each waste derived aggregate to be individually written into a national concrete code (a process that can take a decade), a fast track technical approval or 'agrément' scheme, similar to those already used for proprietary building products in several countries, would let a specific certified aggregate be used on public projects immediately, subject to project specific structural sign off.
- Landfill and disposal levies calibrated to actively discourage stockpiling of fly ash, palm oil residues, and quarry/volcanic overburden, with the levy revenue ring fenced to subsidise the crushing, sieving, and quality testing infrastructure that turns a waste stream into a certified aggregate.
- Carbon and life cycle disclosure requirements for structural concrete, so that the embodied carbon benefit of diverting a waste stream from landfill and avoiding virgin quarrying is priced into project decisions rather than left as an externality that no single contractor has an incentive to account for.

These four levers reinforce one another. A procurement quota without a technical approval scheme forces every project team to reinvent the qualification process from scratch; a technical approval scheme without a disposal levy leaves the waste derived aggregate more expensive than the free alternative of dumping the residue; and neither works well without carbon disclosure, because carbon is very often the argument that ultimately persuades a client to accept a marginally higher unit cost. None of this requires new physics it requires policy design that treats the four studies reviewed here, and the wider body of literature they represent, as regulation ready rather than as academic curiosities.

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A. Embodied carbon and circular economy accounting

A recurring theme across Sections VIII through X is that carbon and circularity are currently treated as a secondary narrative in the four reviewed studies rather than as a quantified design variable. This is a missed opportunity, because the argument for waste derived aggregates is strongest precisely on this axis: cement production and virgin aggregate quarrying together are responsible for a substantial share of global construction sector emissions, and international reporting frameworks increasingly expect embodied carbon disclosure at the building material level [35]. A policy requirement that structural concrete tenders disclose embodied carbon per cubic metre, calculated using a standard life cycle boundary, would make the carbon argument for fly ash, OPS/POC, and scoria aggregates visible on the same page as their price, rather than leaving it to be inferred qualitatively as this paper (and the four studies it reviews) has had to do in the absence of that data. Governments that already operate green public procurement schemes are well placed to add this requirement without new legislation, simply by amending existing tender templates.

XI. Amendments Needed in Engineering Education

If policy is the demand side lever, curriculum reform is the supply side one: the engineers, quantity surveyors, and site supervisors who will eventually specify, batch, and inspect these materials are trained today, and most undergraduate civil engineering curricula still teach concrete technology almost entirely around ordinary Portland cement and virgin natural aggregate. Several concrete curricular changes follow directly from the material synthesized in this paper.

- A dedicated module on waste derived and alternative aggregates within the standard concrete technology course, covering not just the mechanics (as in [1], [2], [4]) but the relevant qualification standards (ASTM C330/C331/C127/C131/C556, or the equivalent Eurocode/BS provisions) so that graduates can read a technical data sheet for a novel aggregate with the same fluency they already have for conventional aggregate.
- Laboratory exercises that let students personally batch, cure, and break a small quantity of a locally available waste derived aggregate (fly ash, agricultural shell, local volcanic or quarry residue, depending on region), because the tacit, hands on knowledge that a contractor currently lacks (Section IX) is exactly the knowledge a curriculum can build early, before students ever reach a construction site.
- Cross listing of structural systems content, such as the composite CFS slab connection behaviour reported in [3], within materials courses rather than treating 'materials' and 'structures' as two entirely separate teaching silos; Section VII of this paper shows that reinforcement ratio and connection detailing interact with aggregate choice in ways that a purely materials focused or purely structures focused course would each miss on its own.
- Explicit coverage of life cycle costing, embodied carbon, and policy instruments (Section X) within the professional practice or sustainability component of the curriculum, so that graduates leave university able to make the business case for a waste derived material to a sceptical client or contractor, not only the technical case.
- Accreditation bodies (for example, ABET equivalent national engineering councils) could usefully add an explicit learning outcome around circular economy materials selection, mirroring how sustainability and professional ethics outcomes were added to accreditation criteria in past decades; a formal learning outcome tends to move curricula faster than an informal recommendation.

None of these changes require new research funding; they require curriculum committees to treat papers such as [1] [4] as core teaching material rather than as optional further reading, and to treat the practical, hands on aggregate testing skill as core laboratory content rather than as an advanced elective.

It is also worth noting that curriculum reform of this kind tends to move faster where it is anchored to an existing assessment requirement rather than proposed as a standalone addition. Final year capstone or major design projects already required in most civil engineering programmes are a natural, low cost vehicle: a cohort could be asked to design a small structural element (a lintel, a boundary wall panel, a non load bearing partition) using a locally available waste stream, take it through the same characterisation battery summarised in Table I, and score it using the CSPI worked example method of Section VI A against a client brief the instructor supplies. This kind of assignment teaches the technical content of Sections II and IV, the decision making logic of Section VI, and the professional practice content of Section X simultaneously, at essentially no incremental cost to a programme that already runs a capstone project, and it produces exactly the kind of graduate who can walk into a contractor's office and make the case for a waste derived material with data rather than enthusiasm alone.

XII. Future Scope

Several research directions follow directly from the gaps identified in Sections III and VIII. First, long term durability data is thin across all four studies: none reports results beyond

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28 90 days, yet the very porosity that makes these aggregates lightweight also governs long term carbonation, freeze thaw, and sulfate resistance, none of which a 28 day laboratory programme can capture. Second, a shared life cycle assessment functional unit (cost and embodied carbon per cubic metre of concrete at a fixed target strength and a fixed target service life) is needed across waste derived aggregate studies so that the CSPI sustainability sub index proposed in Section VI can eventually be populated with measured data rather than illustrative estimates. Third, hybrid aggregates for instance, blending a small fraction of epoxy bound fly ash PLA into an OPS/POC mix, or adding silica fume to an epoxy bound PLA concrete have not been reported at all in the surveyed literature, despite each individual study showing that its own binder content or pozzolan content lever can be tuned continuously; there is no reason in principle why the levers identified in four separate papers could not be combined in a single future mix design. Fourth, full scale field trials a genuine building bay, not a laboratory beam instrumented over several years, would close the adoption gap discussed in Section IX far more convincingly than any further laboratory cube test. Fifth, machine learning assisted mix design optimisation, trained across a merged dataset from studies such as [1], [2], and [4], could in principle predict CSPI relevant properties for waste streams and binder ratios that have not yet been physically tested, shortening the qualification cycle described in Section IV.

A. Standardisation pathways

A specific and tractable next step, distinct from further laboratory testing, is the drafting of a dedicated ASTM or Eurocode style standard practice for waste derived lightweight aggregates as a class, rather than leaving each waste stream to be qualified individually against the general lightweight aggregate provisions in ASTM C330/C331. Such a standard practice could specify a common minimum test battery (compressive strength development schedule, specific gravity, Los Angeles abrasion, water absorption, and a basic durability screen such as UPV or sorptivity), directly addressing the measurement consistency gap identified in Section VIII, while still allowing each specific waste stream to be listed as an approved sub category with its own numerical thresholds, in the same way that ASTM C330 already lists several conventional lightweight aggregate types under one umbrella specification. Table VI sets out, at a conceptual level, how the four aggregates reviewed in this paper already map onto (or fall short of) the clauses such a unified standard practice would need.

Table VI: conceptual mapping of reviewed waste derived aggregates onto a proposed unified standard practice

Proposed standard clause	Fly ash/epoxy PLA [1]	OPS/POC [2]	Scoria + SF [4]
Minimum 28 day aggregate/concrete strength	Met (74.6 MPa aggregate; 18.38 MPa LWC)	Met (46.47 MPa for P50 mix)	Not directly reported (durability focused study)
Maximum density (ASTM C330 analogue)	Met (1668 kg/m^3)	Not separately reported	Borderline (scoria SG ≈ 1.7, near ceiling)
Abrasion resistance ceiling	Met for 70:30 and 80:20; failed for 90:10	Not reported in this study	Not reported in this study
Water absorption / sorptivity ceiling	Met (0.8% water content)	Not reported in this study	Elevated for SLWC; improved for SSLWC
Chloride/durability screening	Not reported in this study	Not reported in this study	Reported (RCPT); moderate permeability class
Full scale structural validation	Not yet performed (aggregate/mix level only)	Performed (8 reinforced beams to failure)	Not yet performed (mix level only)

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The gaps visible in Table VI are as informative as the successes: no single reviewed study currently satisfies every clause a genuinely unified standard would need, which is itself evidence that today's fragmented, single material research pattern is part of what is keeping these aggregates out of mainstream codes. Coordinated, multi institution research programmes that deliberately fill the empty cells in a table like this rather than each testing a new material from first principles would shorten the path to a workable standard considerably.

XIII. Limitations of This Synthesis

This paper is a secondary synthesis: it does not report new physical testing, and the CSPI scores shown in Fig. 6 are illustrative rather than a rigorous re derivation from raw data, because the four source studies do not report cost or carbon figures in a common unit that would allow an exact recomputation. The cross study comparisons in Sections V and VII are only as reliable as the consistency of the underlying test methods, and, as noted in Section VIII, those methods are not fully harmonised across the four papers. Finally, the policy and education recommendations in Sections X and XI are written to be broadly applicable across jurisdictions, but the specific regulatory instruments (procurement quotas, technical approval schemes, disposal levies) will necessarily need to be adapted to each country's existing legal and construction code framework rather than adopted verbatim.

A. Consolidated Recommendations

Sections IX through XII put forward a fairly large number of individual recommendations, spanning procurement policy, standards, curriculum design, and future research. Table VII draws them together in one place, organised by the stakeholder best placed to act on each one, so that the practical output of this paper is not left scattered across five separate sections.

Table VII: Consolidated recommendations by responsible stakeholder

Stakeholder	Recommended action	Primary section
National / regional government	Introduce waste diversion procurement quotas for qualifying lightweight aggregates in public works	Section X
Standards & building code bodies	Establish fast track technical approval schemes for non standard aggregates meeting ASTM C330/C331 equivalent criteria	Section X
Environmental regulators	Calibrate landfill/disposal levies on fly ash, agro industrial residues, and quarry overburden; ring fence revenue for aggregate testing infrastructure	Section X
Procurement authorities	Mandate embodied carbon and life cycle disclosure for structural concrete tenders	Section X A
Universities / curriculum committees	Add a dedicated waste derived aggregate module and hands on batching laboratory to concrete technology courses	Section XI
Accreditation bodies	Add an explicit circular economy materials selection learning outcome to accreditation criteria	Section XI
Municipal / community bodies	Establish low cost local material testing hubs to support informal and self build construction	Section IX
Research community	Generate long term ($\geq$ 5 year) durability data, harmonised life cycle assessment functional units, and hybrid aggregate mix designs	Section XII
Project design teams	Adopt the CSPI worked example workflow (Section VI A) and the QA/risk checklist (Section VI B) before specifying a waste derived aggregate on a live project	Sections VI A, VI B

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Finally, it is worth restating why this consolidated recommendation table matters more than it might first appear to. Individually, a procurement quota, a curriculum module, and a durability research programme each look like a modest, incremental step. Read together, as Table VII invites, they describe a coordinated pipeline in which government demand side policy creates a guaranteed market, standards bodies remove the regulatory bottleneck that currently makes each waste stream fight its own decade long battle for code recognition, universities supply engineers who already know how to specify and inspect these materials on day one of their careers, and the research community keeps feeding the standards process with the long term and cross material data identified in Sections VIII and XII. No single stakeholder in Table VII can complete this pipeline alone, which is precisely why the four studies reviewed in this paper, however excellent individually, have not on their own been sufficient to shift waste derived lightweight concrete from a promising research topic into an everyday specification choice.

XIV. Conclusion

This paper brought together four independently reported studies on waste derived lightweight concrete coal fly ash/epoxy aggregate, oil palm shell/clinker beams, cold formed steel composite connections, and silica fume modified scoria concrete and re examined them as a single body of evidence rather than as four disconnected results. Doing so surfaced a comparability gap that no single study was designed to close, and this paper responded with a five stage qualification framework and an illustrative Composite Sustainability Performance Index intended to let future researchers, and eventually practitioners, score dissimilar waste streams on a shared scale. The consolidated results confirm that each of the four waste streams can meet relevant strength, ductility, or durability thresholds under the right binder ratio and reinforcement design, but also confirm that no single material is best on every axis: fly ash/epoxy aggregate wins on strength, oil palm shell aggregate wins on waste valorisation and ductility, and silica fume modified scoria wins on recovering durability performance close to a normal weight benchmark. Beyond the laboratory, the paper argued that the remaining barrier to adoption is now substantially a policy and education problem rather than a materials science problem, and set out concrete procurement, standards, and curriculum reforms that would let several decades of promising laboratory results finally reach ordinary construction sites. Closing that final gap between demonstrated performance and everyday practice is, in the authors' view, the single most valuable next step this line of research can take.

DATA AVAILABILITY AND REPRODUCIBILITY STATEMENT

All numerical values re plotted or re tabulated in this paper (Figs. 1 5 and Tables I, II, and IV) are drawn directly from the tables and figures published in the four source studies [1] [4]; readers wishing to verify a specific figure are directed to the corresponding table in the cited source. The CSPI sub scores shown in Fig. 6 and Table III are explicitly illustrative rather than measured, as flagged in Sections VI and XIII, and are provided as a worked demonstration of the scoring method rather than as a validated ranking; any future application of the CSPI to a real project should repopulate the WVI, SPI, and SI sub scores from project specific measured data and a project specific weighting vector agreed with the client and design team before any ranking is treated as a design input. The five stage qualification framework (Fig. 7) and the standardisation mapping (Table VI) are original conceptual contributions of this paper and are offered as a starting point for discussion among standards writing committees rather than as a finished normative document.

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