Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

Sustainability Assessment of Concrete Masonry Blocks Incorporating Waste Materials

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Abstract. The depletion of natural fine aggregates and the growing accumulation of industrial and construction wastes pose serious challenges to sustainable development in the construction sector. This study evaluates the feasibility of producing sustainable concrete masonry blocks by partially and fully replacing river sand with five locally available alternatives: fly ash, quarry dust, lateritic waste, jarofix, and manufactured sand. Concrete mixes of 1:4:8 proportion were prepared with replacement levels of 0–100%, and their compressive strength, density, and water absorption were determined; masonry prisms were further tested to establish structural performance in accordance with IS and ASTM standards. All five optimised blocks satisfied the strength requirements for load-bearing masonry per IS 2185 (Part 1): 2005. Jarofix blocks at 30% replacement (JB03) achieved the highest block strength of 7.19 N/mm², a 38.8% improvement over the control, while fly ash (20%), quarry dust (30%), and manufactured sand (30%) blocks recorded improvements of 27.8%, 23.2%, and 16.2%, respectively. Masonry efficiency of the prisms ranged from 73.6% to 81.6%, comparable to conventional masonry. A quantitative environmental sustainability assessment based on material efficiency and embodied energy, aggregated through the simple additive weighting method, ranked the jarofix blocks highest (sustainability index = 1.0) against 0.489 for the control. The findings demonstrate that industrial by-products can be converted into structurally reliable, resource-efficient masonry units, offering a practical pathway for green construction while diverting substantial waste volumes from disposal.

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Received: 25th July, 2026 | Revised: 26th August, 2026 | Accepted: 30th August, 2026 | Available Online: 2nd September, 2026

(DOI): 10.70102/AEJ.2026.18.7s.1

1 Introduction

Construction activity exerts severe pressure on natural ecosystems and on the stability of sustainable habitats. Technology plays a crucial role in minimising the adverse environmental effects of construction. The principal long-term sustainability concerns in this industry are the depletion and subsequent over-exploitation of natural resources, the generation of solid waste, greenhouse gas emissions on a global scale, and pollution of the environment. The term sustainable construction was initially proposed to define the role of the construction industry in achieving sustainability, and several complementary definitions have since been advanced.

These definitions are directly relevant to the present study because together they establish the criteria against which any alternative building material must be judged. Kibert posits that, alongside traditional objectives such as cost-effectiveness, performance, and quality, sustainable construction should focus on minimising resource depletion, reducing environmental impact, and ensuring a healthy built environment [1]. Hussin et al. describe sustainable construction as an approach that balances the needs of people, the environment, and economic viability — the familiar three pillars of sustainability [2]. Yılmaz and Bakış extend this by requiring sustainable development principles to be integrated throughout the entire life cycle of a building, from inception to demolition [3], while assessment frameworks for building materials operationalise these pillars through measurable indicators and criteria [4]. Taken together, these definitions justify the two-fold structure of the present investigation: the candidate masonry blocks must first satisfy conventional technical requirements (strength, structural performance, and durability), and must then be evaluated against quantitative environmental indicators (resource efficiency and embodied energy). The sustainability assessment methodology adopted in Section 3 follows directly from this framework.

1.1 Construction practices – building blocks

India is the second largest producer of bricks in the world, with an annual output of 250–300 billion units, and demand is projected to nearly double to 750–1000 billion bricks annually over the next two decades [5]. Bricks made of laterite, mud, burnt clay, and concrete are the most common masonry units used on Indian construction sites. Excessive quarrying of good-grade lateritic blocks and rubble has resulted in the depletion of naturally fertile topsoil, the creation of deep and wide ponds, and the degradation of the natural environment. Clay mining for brick making further degrades natural ecosystems and consumes fertile paddy fields; the production of burnt clay bricks in India requires approximately 340 million tonnes of clay and excavates almost 5,000 acres of topsoil annually [5].

The annual consumption of coal and biomass fuels for firing bricks is estimated at 30–35 million tonnes and 10 million tonnes, respectively, and brick production in India emits about 66 million tonnes of CO_2 every year [5]. Concrete building blocks have therefore gained popularity over traditional units owing to their low cost, ease of transportation, and widespread availability. According to a market study by Transparency Market Research, the global market for concrete blocks and bricks is projected to grow from 1,837.48 billion units in 2016 to 2,769.24 billion units by the end of 2027 [6]. In Kerala, the Directorate of Economics and Statistics reported that the number of concrete block production units increased by 70%, from 2,795 units in 2011–12 to 4,754 units in 2015–16, producing 519.77 million blocks in 2015–16, of which 104.98 million originated from the Ernakulam district alone [7].

1.2 Need and novelty of the study

With the rising global emphasis on sustainable development, the construction sector is under intense pressure to adopt and promote green building practices. Considerable research effort worldwide has been directed at identifying sustainable alternatives to conventional construction materials; however, uptake remains poor owing to inadequate coordination among stakeholders, limited awareness, and the perception that sustainable options increase risk and cost. Sustainable material selection is further complicated by the multiplicity of environmental factors involved in evaluation and analysis, spanning technological, economic, and societal dimensions. A consistent and comprehensive assessment framework is therefore required to address the many facets of sustainability in building.

Concrete building blocks have recently overtaken clay bricks in Kerala's residential construction sector. However, data gathered from authorised testing centres in three districts of Kerala (Thiruvananthapuram, Ernakulam, and Palakkad) between 2016 and 2018 raise serious concerns regarding the quality of marketable blocks: the typical compressive strength of 3.6–3.9 N/mm² fell considerably short of the requirement for load-bearing masonry. The problem is aggravated by the scarcity of natural aggregates and the sharp increase in raw material prices, which have led to unhealthy competition among local producers. Although manufactured sand is widely available as a river sand substitute, local producers favour quarry dust on economic grounds, often without scientific understanding of the physical characteristics of these aggregates or their influence on workability and strength.

Several alternative fine aggregates are readily available in the region. Approximately 196 million tonnes of fly ash are generated annually in India, of which the construction sector utilises only a part while about one-third remains unutilised [8]. Jarofix,

a treated industrial waste of the zinc industry, has a cumulative stock in India of roughly 26 million tonnes with an annual output close to 5 million tonnes, and its indiscriminate disposal within industrial premises demands prompt action. India also generates about 15 million tonnes of construction and demolition waste annually, including lateritic waste from quarries and demolished structures.

The novelty of the present study lies in its combined technical–environmental evaluation: whereas previous investigations have examined individual substitute aggregates in structural concrete, no earlier work has comparatively assessed all five locally available alternatives — fly ash, quarry dust, lateritic waste, jarofix, and manufactured sand — as fine aggregate replacements (0–100%) in lean-mix (1:4:8) load-bearing concrete masonry blocks, verified their masonry-level structural performance through prism testing, and ranked the resulting blocks using a quantitative sustainability index. The specific knowledge gap addressed is thus the absence of a unified, quantitative basis on which local block producers can select among waste-derived fine aggregates. The objectives of the study are: (i) to characterise the alternative materials; (ii) to determine the optimum replacement level of each alternative through cube and block testing; (iii) to establish structural adequacy through masonry prism tests; and (iv) to compare the optimised blocks through an environmental sustainability index.

2 Literature review

Numerous waste materials — fly ash, ground granulated blast furnace slag, jarofix, quarry dust, silica fume, and waste gypsum, among others — have been successfully employed as cement substitutes, and a parallel body of research has examined alternative aggregates such as crumb rubber, crushed concrete, waste glass, slag, and marble waste. The review below focuses on the five materials selected for the present study, highlighting the findings that motivated their choice as fine aggregate replacements in masonry blocks.

Fly ash

Fly ash is a fine powder produced as a by-product of coal-fired power stations; ashes with $SiO_2 + Al_2O_3 + Fe_2O_3$ contents above 70% are classified as Class F under ASTM C618 and exhibit excellent pozzolanic properties. Concrete incorporating fly ash shows improved long-term performance, though with reduced early workability relative to conventional concrete. The finer fly ash particles produce a packing and filling effect that refines the microstructure of hardened concrete, which in turn yields superior strength characteristics. Reported benefits of fly ash incorporation include reduced permeability, lower heat of hydration, decreased chloride diffusivity and shrinkage cracking, and improved resistance to corrosion and chemical attack. Studies on M20–M30 concretes have shown that fly ash used as a partial fine aggregate replacement of up to 30%, without superplasticisers, exhibits enhanced strength characteristics — the direct motivation for its selection here.

Jarosite / jarofix

Jarosite is an industrial waste generated during the hydrometallurgical extraction of zinc; jarofix is produced by safely blending jarosite with appropriate quantities of lime and cement. Both find applications in soil stabilisation, embankment consolidation, building blocks and paving tiles, and pavement sub-grade layers. Sinha et al. established through mineralogical analysis that jarofix exhibits superior mechanical strength and durability compared with raw jarosite, and demonstrated the feasibility of jarofix in road embankments and of jarofix–soil–bottom ash combinations in pavement sub-grades [9]. Investigations of soil–jarofix mixtures at replacement levels up to 50% report improved long-term unconfined compressive strength, attributed to pozzolanic reaction, cation exchange, or the formation of strength-gaining compounds from the chemical constituents of jarofix. Asokan et al. confirmed the suitability of jarosite for building blocks and tiles, with jarosite–sand, jarosite–clay–fly ash, and jarosite–coal combustion residue composites showing improved compressive strength, higher density, and low water absorption [10]. Mymrin et al. similarly reported strength enhancement, attributing it to amorphous gel compounds formed during hydration [11]. In concrete, jarosite as an aggregate or partial cement substitute has yielded improved compressive strength, durability, and abrasion resistance, although workability decreases because jarosite has a higher specific surface area than cement; at 10% cement replacement, compressive strength (M40, 50.17 N/mm², w/c = 0.38) and water absorption comparable to control concrete have been reported. Utilisation of jarosite in precast paver blocks has also been demonstrated [12].

Quarry dust

Quarry dust (crushed stone dust) causes significant environmental harm owing to disposal difficulties, making its bulk utilisation attractive. Ilangovan et al. reported that quarry rock dust concrete exhibits 10–12% higher compressive and flexural strength for M20–M40 grades when superplasticisers are used, together with reduced permeability, comparable shrinkage strains, and satisfactory performance under sulphate and chloride exposure [13]. Manasseh found that even without superplasticisers, 100% replacement of river sand with crushed granite fines produced a compressive strength of 36.50 N/mm² for M35 concrete (w/c = 0.50), attributing the increase to the frictional resistance arising from the rough, angular texture of the crushed fines [14]. Across studies, the optimum replacement level varies from 10% to 60%

depending on concrete grade, aggregate properties, and the resulting workability.

Lateritic waste

Laterite soil occurs widely in tropical and subtropical regions, and an estimated 30% of the world's population still lives in laterite dwellings. Multiple studies have shown that laterite soil can partially replace fine aggregate in concrete with comparable strength and enhanced durability. Karra et al. demonstrated that partial replacement with laterite reduces workability because the clay and silt fractions retain more water than natural sand, effectively lowering the available water–cement ratio [15]. Udoeyo et al. found that the required strength could be achieved at replacement levels up to 40%, with strength declining at higher levels (M15, w/c = 0.56); they attributed the modest strength to the poor cementing ability of sesquioxides (Fe_2O_3 and Al_2O_3) binding quartz and granular kaolinite aggregates, which are inherently weaker than sand [16]. Strength gains at about 20% replacement have also been reported for M20 and M25 concretes.

Manufactured sand

Manufactured sand is an artificial fine aggregate produced by crushing larger rock, followed by grinding, screening, and washing. Studies across grades M20–M50 report that 60–100% replacement of river sand with manufactured sand yields concrete of comparable strength but reduced workability, with improved resistance to water permeability and chloride ion penetration, and better performance in acidic (5% H_2SO_4, 5% HCl) and sulphate (5% Na_2SO_4) environments. Good-quality manufactured sand — with fresh fracture surfaces, low fines contamination, angular particle shape, proper gradation, and a packing effect — contributes to superior strength and durability. Compressive strengths of 32.71 N/mm² (M20) and 63.56 N/mm² (M40, w/c = 0.40) at full replacement have been reported, with differences among studies attributable to source-dependent variations in the physical characteristics of the sand.

Recent studies and research gap

Recent investigations confirm strong potential for incorporating waste materials into concrete masonry blocks: composite industrial wastes have produced sustainable hollow blocks capable of replacing fired clay bricks [17]; demolition waste has been successfully integrated into block production [18]; and recycled concrete aggregates have yielded solid masonry blocks with acceptable engineering properties and improved sustainability [19]. Comprehensive reviews further document the physico-mechanical performance of masonry units incorporating municipal solid waste [20] and emphasise the circular use of recycled cement, concrete, and industrial by-products in construction [21, 22]. Nevertheless, these studies each address a single waste stream or block type, and none provides a comparative technical-plus-sustainability ranking of multiple locally available fine aggregate alternatives in lean-mix load-bearing masonry blocks. The present study fills this gap, providing block producers with a directly usable basis for material selection.

3 Materials and methods

3.1 Material characterisation

The materials used in this research were cement, fine aggregates (river sand, fly ash, quarry dust, lateritic waste, jarofix, and manufactured sand), and 10 mm graded coarse aggregate. Ordinary Portland cement of 43 grade conforming to IS 8112 (Malabar Cement brand) was used, with a specific gravity of 3.14, standard consistency of 34%, and a 28-day compressive strength of 43 N/mm². The coarse aggregate consisted of 10 mm crushed stone free of organic material and fines, with a specific gravity of 2.79, bulk density of 1,433 kg/m³, fineness modulus of 5.73, and crushing value of 29.65%. River sand served as the reference fine aggregate, alongside the five alternatives. Figure 1 shows the fine aggregates used in the study. The properties of the selected aggregates were determined in accordance with IS 2386-1963 and are summarised in Table 1.



Fig. 1. Fine aggregates used in the study.

Table 1. Properties of alternative fine aggregates.

Sl. No.	Property	Fly ash	Jarofix	Quarry dust	Lateritic waste	Manufactured sand
1	Specific gravity	2.503	2.86	2.758	2.63	2.795
2	Bulk density	0.70	0.675	0.949	1.038	1.613

	(g/cc)					
3	Porosity	0.72	0.764	0.656	0.605	0.423
4	Void ratio	2.568	3.243	1.907	1.532	0.733
5	Colour	Grey	Brick red	Grey	Brick red	Grey

3.2 Mix proportions, specimen preparation, and testing

A lean mix ratio of 1:4:8 (cement : fine aggregate : coarse aggregate) was adopted in accordance with the requirements for masonry concrete blocks in IS 2185 (Part 1): 2005, keeping environmental impact and production economics in view. Trial mixes at water–binder ratios of 0.45 and 0.48 showed reduced workability for all alternatives except manufactured sand; a uniform water–binder ratio of 0.50 was therefore adopted for all mixes to permit direct comparison. Concrete mixes were prepared with river sand replaced by each alternative at 0%, 10%, 20%, 30%, 40%, 50%, and 100% by mass; the mix designations are given in Table 2. For each mix, cube specimens of 150 mm × 150 mm × 150 mm were cast and water-cured, and compressive strength (IS 516), density (ASTM C140-03), and water absorption (IS 1237) were determined after the designated curing period. Three specimens were tested for each mix and age, and average values are reported.

Table 2. Mix designations (1:4:8 mix).

Replacement %	Fly ash	Quarry dust	Manufactured sand	Laterite waste	Jarofix
0	FC00	QC00	MC00	LC00	JC00
10	FC01	QC01	MC01	LC01	JC01
20	FC02	QC02	MC02	LC02	JC02
30	FC03	QC03	MC03	LC03	JC03
40	FC04	QC04	MC04	LC04	JC04
50	FC05	QC05	MC05	LC05	JC05
100	FC010	QC010	MC010	LC010	JC010

Solid concrete blocks of 400 mm × 200 mm × 150 mm were then produced from all mixes using hydraulic block-making machinery. The blocks were held in the production yard for 24 hours and subsequently water-cured by immersion in a curing tank (Fig. 3) for 28 or 90 days, with fresh water introduced at seven-day intervals. After curing, the blocks were removed, cleaned, and subjected to primary and secondary investigations. Block compressive strength was determined under a 2,000 kN capacity testing machine in accordance with IS 2185 (Part 1): 2005, with load applied progressively and continuously until failure.



Fig. 3. Curing of masonry blocks.

3.3 Masonry prism testing

Masonry prisms were constructed from the selected block specimens following IS 1905:1987, using a 1:6 cement mortar of 16 N/mm² compressive strength; capping used the same mortar as specified in IS 1905. The prisms were built to a height of 650 mm with a height-to-thickness ratio of 3.25 and a constant mortar joint thickness of 10 mm. All prisms were cured for 28 days under standard conditions and tested in a universal testing machine in accordance with ASTM C1314-11, with axial compressive load applied incrementally at 5 kN per step until failure; the ultimate load at breakage was recorded. Figure 4 illustrates the prism arrangement and test set-up. Masonry efficiency was calculated as the ratio of masonry strength to block strength, and the normalised compressive strength of masonry was obtained using a height-to-thickness correction factor of 1.09 as per ASTM C1314-11.

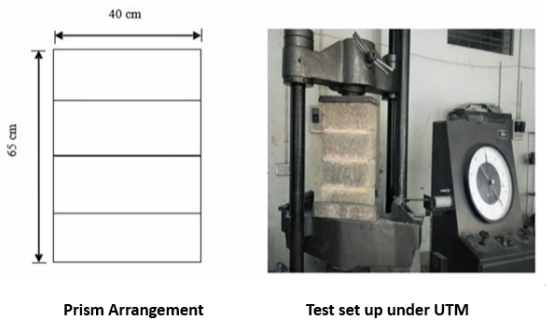


Fig. 4. Testing of the prism.

3.4 Sustainability assessment methodology

The environmental impact of the proposed blocks relative to conventional concrete blocks was assessed through sustainability indices computed by the simple additive weighting (SAW) method, a widely used multi-criteria decision-making technique in which normalised criterion scores are aggregated through criterion weights into a single index. Scores are normalised as:

$x_{ij} = a_{ij} / a_{j\,max}$ (criterion to be maximised)

$x_{ij} = a_{j\,min} / a_{ij}$ (criterion to be minimised)

where a_{ij} is the raw score of block i on criterion j. The sustainability index is then $SI = \Sigma\, x_{ij} \times w_j$, where w_j is the weight of criterion j and the summation extends over all criteria.

Environmental sustainability is generally measured through indicators of resource efficiency and environmental quality. Since the proposed blocks have not yet been deployed in service, the present comparison is necessarily restricted to the two quantifiable sub-criteria of the resource efficiency indicator: material efficiency and embodied energy. Material efficiency is quantified by the proportion of local waste, renewable, reusable, and recyclable materials substituting non-renewable materials; for the optimised blocks FB02 (20%), QB03 (30%), MB03 (30%), LB02 (20%), and JB03 (30%), the replacement percentage itself represents material efficiency, normalised against the maximum replacement of 30%. Embodied energy of each block was computed from the mix composition using published embodied energy coefficients of the constituent materials, with waste-derived aggregates assigned only their processing and transport energy. Material efficiency is treated as a criterion to be maximised and embodied energy as a criterion to be minimised. Because only these two criteria are evaluated and neither can be established as more consequential a priori, equal weights of 0.5 were assigned to each; this equal-weighting assumption is a recognised default in SAW when reliable preference information is unavailable, and its influence is noted in Section 4.4.

4 Results and discussion

4.1 Cube compressive strength

Table 3 and Figure 2 present the 28-day cube compressive strengths for all replacement levels. Every alternative except lateritic waste improved upon the control strength of 5.48 N/mm² over a broad range of replacement levels, with distinct optima: fly ash peaked at 20% (9.41 N/mm²), manufactured sand at 30% (8.84 N/mm²), quarry dust at 30% (9.15 N/mm²), and jarofix at 30% (11.00 N/mm²), while lateritic waste declined monotonically with replacement level.

Table 3. Compressive strength of cubes with different replacements (N/mm²).

% Replacement	Fly ash	M-sand	Quarry dust	Lateritic waste	Jarofix
0	5.48	5.48	5.48	5.48	5.48
10	8.43	7.22	7.72	5.26	9.00
20	9.41	8.00	8.67	5.04	10.05
30	8.13	8.84	9.15	4.83	11.00
40	6.90	7.75	7.94	4.67	10.18
50	6.06	6.62	6.44	4.47	9.55
100	4.06	5.93	5.13	4.03	7.72

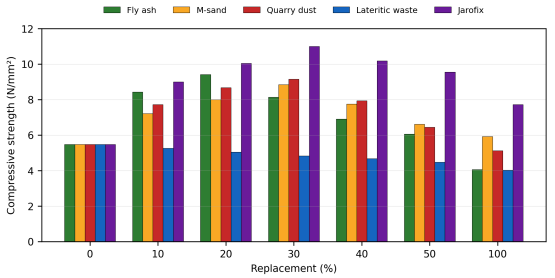


Fig. 2. Variations in compressive strength – 1:4:8 mix (cube specimens).

The observed trends are explained by the physical and chemical mechanisms of each material. In the fly ash mixes, the gain up to 20% replacement arises from the pozzolanic reaction of the Class F ash with the calcium hydroxide liberated during cement hydration, supplemented by the packing and filling effect of the fine spherical particles, which densifies the microstructure of the lean mix; beyond 20%, the dilution of reactive cement paste relative to the high ash volume reverses the gain. The jarofix mixes show the largest and most sustained improvement because the lime and cement used in jarofix stabilisation promote secondary pozzolanic reactions and the formation of amorphous gel compounds during hydration, consistent with the mechanism reported by Mymrin et al. [11]; even at 100% replacement, the jarofix mix (7.72 N/mm²) exceeds the control. Quarry dust and manufactured sand derive their improvement from mechanical rather than chemical action: the rough, angular texture of crushed particles increases inter-particle frictional resistance, and their graded fines improve particle packing, echoing the explanation advanced by Manasseh for crushed granite fines [14]. Lateritic waste, in contrast, weakens the matrix at all levels because its clay and silt fractions absorb mixing water — reducing the water available for cement hydration and workability, as observed by Karra et al. [15] — while its sesquioxide-bound kaolinitic aggregates are intrinsically weaker than quartz sand, as identified by Udoeyo et al. [16].

4.2 Masonry block strength

Table 4 presents the 28-day compressive strengths of the machine-made blocks. The block strengths follow the same ranking as the cube results, with optima at FB02 (6.62 N/mm²), QB03 (6.38 N/mm²), MB03 (6.02 N/mm²), LB02 (4.75 N/mm²), and JB03 (7.19 N/mm²) against 5.18 N/mm² for the control. All optimised blocks, including the laterite blocks, satisfy the minimum strength requirement for load-bearing masonry units in IS 2185 (Part 1): 2005. It is noteworthy that block strengths are systematically lower than the corresponding cube strengths, reflecting the leaner

compaction achievable in machine-made blocks and the size effect of the larger units.

Table 4. Compressive strength of masonry blocks at 28 days (1:4:8 mix, w/c = 0.50), MPa.

Mix	Strength	Mix	Strength	Mix	Strength	Mix	Strength	Mix	Strength
FB000	5.18	QB000	5.18	MB000	5.18	LB000	5.18	JB000	5.18
FB001	5.80	QB001	5.46	MB001	5.26	LB001	4.97	JB001	5.66
FB002	6.62	QB002	5.99	MB002	5.51	LB002	4.75	JB002	6.41
FB003	5.52	QB003	6.38	MB003	6.02	LB003	4.56	JB003	7.19
FB004	4.96	QB004	5.59	MB004	5.21	LB004	4.39	JB004	5.63
FB005	4.40	QB005	4.69	MB005	4.83	LB005	4.21	JB005	5.12
FB010	4.01	QB010	4.11	MB010	4.31	LB010	3.79	JB010	4.27

4.3 Masonry efficiency of prisms

Table 5 summarises the prism test results. Masonry efficiency ranged from 73.62% (laterite blocks) to 81.63% (control), with the fly ash (81.09%) and jarofix (81.45%) prisms essentially matching the control — indicating that the block–mortar interaction of the waste-derived units is as effective as that of conventional blocks. The jarofix prisms sustained the highest ultimate load (430.00 kN) and normalised masonry strength (5.859 MPa). Failure of all prisms occurred through vertical splitting cracks passing through blocks and mortar joints, the desirable failure pattern for masonry under axial compression, confirming satisfactory composite action. These efficiencies fall within the range commonly reported for solid concrete block masonry, establishing the structural feasibility of the proposed blocks.

Table 5. Masonry efficiency of prisms (400 × 200 × 650 mm).

Block masonry	Load (kN)	Masonry strength (MPa)	Correction factor	Normalised strength (MPa)	Block strength (MPa)	Masonry efficiency (%)
SB – Control	310.33	3.879	1.09	4.228	5.180	81.63
FB – Fly ash	394.00	4.925	1.09	5.368	6.620	81.09
MB – Manufactured sand	337.33	4.217	1.09	4.596	6.020	76.35
QB – Quarry dust	368.33	4.604	1.09	5.018	6.380	78.66
LB – Laterite waste	256.67	3.208	1.09	3.497	4.750	73.62
JB – Jarofix	430.00	5.375	1.09	5.859	7.193	81.45

4.4 Environmental sustainability assessment

Figure 5 shows the embodied energy of the optimised blocks, and Table 6 presents the computation of the sustainability indices; Figure 6 compares the resulting indices. All waste-incorporating blocks show lower embodied energy than the control (SB00, 12.66), with JB03 lowest at 12.38, because the waste-derived aggregates carry only processing and transport energy in place of the extraction energy of virgin aggregate. Combining the two normalised criteria at equal weights produces the ranking JB03 (1.00) > QB03 (0.996) > MB03 (0.993) > LB02 (0.830) > FB02 (0.829) > SB00 (0.489): every proposed block roughly doubles the sustainability index of the control, and the 30%-replacement blocks cluster at the top because material efficiency is normalised against the 30% maximum.

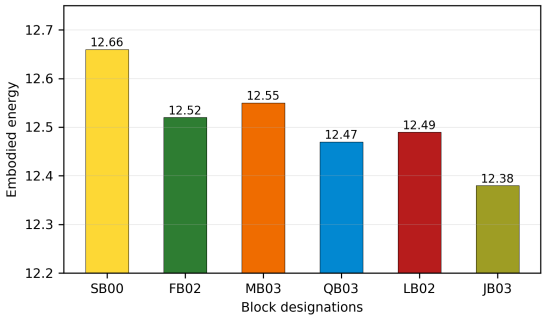


Fig. 5. Embodied energy of the proposed blocks.

Table 6. Sustainability index – environmental sustainability.

Indicator	FB02	QB03	MB03	LB02	JB03	SB00	Weight
Material efficiency (score)	0.20	0.30	0.30	0.20	0.30	0	0.5
Material efficiency (normalised)	0.67	1	1	0.67	1	0	–
Embodied energy (score)	12.52	12.47	12.55	12.49	12.38	12.66	0.5
Embodied energy (normalised)	0.989	0.993	0.986	0.991	1	0.978	–
Sustainability Index (Σ xij × wj)	0.829	0.996	0.993	0.830	1.000	0.489	

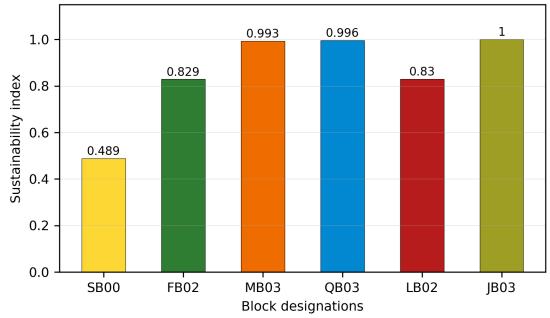


Fig. 6. Environmental sustainability – comparison of sustainability indices.

Given the uniformity of production practices across the proposed blocks, similar relative variations can be anticipated for the indicator 'environmental quality', and the remaining resource-efficiency criteria such as water efficiency and land adequacy can be evaluated in a comparable manner once field data become available. The highest index of the jarofix blocks should nevertheless not be read as a definitive measure of sustainability: because the blocks have not yet entered practice, the evaluation deliberately restricts itself to the quantifiable sub-criteria of material efficiency and embodied energy, uses a limited set of indicators, and adopts equal weighting. The indices therefore serve as a comparative indication of sustainability relative to the control blocks rather than an absolute rating, while the technological (strength and structural) evaluation is comprehensive since it rests directly on the experimental results.

4.5 Comparison with previous studies

The present findings align quantitatively with the literature while extending it to lean-mix masonry blocks. The 23.2% block strength gain at 30% quarry dust replacement is consistent with the 10–12% strength improvements reported by Ilangovan et al. for richer structural concretes [13] and with the strength retention at full replacement observed by Manasseh [14] — mirrored here by QC010 retaining 5.13 N/mm² at 100% replacement. The optimum of 20–30% for fly ash agrees with reports of enhanced strength up to 30% fine aggregate replacement in M20–M30 concretes. The jarofix result — a 38.8% improvement at 30% replacement, and strength above control even at 100% — parallels the improved compressive strength and density of jarosite composites reported by Asokan et al. [10] and the early strength acceleration observed when jarosite is blended in concrete. For laterite, the safe-use ceiling of about 20% replacement in blocks is more conservative than the 40% limit of Udoeyo et al. for M15 concrete [16], which is attributable to the leaner 1:4:8 mix providing less cement paste to compensate for the weak lateritic fines. These agreements confirm the reliability of the experimental programme, while the block-level and prism-level data constitute the new contribution.

5 Practical implications and engineering significance

The results carry direct significance for block producers and for waste management. First, all five optimised blocks meet the IS 2185 (Part 1): 2005 requirement for load-bearing masonry, so producers in regions facing river sand scarcity — such as Kerala, where marketed blocks have been found to average only 3.6–3.9 N/mm² — can adopt any locally abundant alternative at the identified optimum (fly ash 20%, quarry dust 30%, manufactured sand 30%, jarofix 30%, laterite ≤ 20%) and simultaneously raise product quality above the prevailing market level. Second, the strength optima occur at economically attractive replacement levels: a 30% substitution of river sand with quarry dust or jarofix reduces the most cost-volatile raw material input by nearly a third while increasing block strength by 23–39%. Third, bulk utilisation offers a meaningful waste-diversion pathway for the roughly one-third of Indian fly ash that currently remains unutilised, the ~5 million tonnes of jarofix generated annually, and the growing stream of construction and demolition waste. Finally, the masonry efficiencies of 73.6–81.6% demonstrate that no special mortar or workmanship provisions are needed: the blocks can enter conventional load-bearing masonry practice using standard 1:6 cement mortar and existing design rules, making adoption essentially cost-neutral for builders.

6 Conclusions

This study investigated the production of environmentally friendly concrete masonry blocks using commercially available and locally sourced alternatives to river sand — manufactured sand, fly ash, jarofix, quarry dust, and lateritic waste. The investigation proceeded in two stages: a semi-systematic literature review of sustainable building concepts and assessment systems, followed by an experimental programme on cube specimens, machine-made blocks, and masonry prisms, concluded by a quantitative sustainability assessment. The following conclusions are drawn:

(1) All five optimised blocks (FB02, QB03, MB03, JB03, and LB02) satisfy the strength requirements for load-bearing masonry units per IS 2185 (Part 1): 2005, and — except the laterite blocks — exhibit better strength, durability, water absorption, and initial rate of absorption than the control blocks (SB00).

(2) The lean 1:4:8 blocks achieved optimum strengths of 6.62 N/mm² for FB02 (+27.8%), 6.38 N/mm² for QB03 (+23.2%), 6.02 N/mm² for MB03 (+16.2%), and 7.19 N/mm² for JB03 (+38.8%, the highest). Strength improvement over the control extended up to 30% replacement for fly ash and up to 40% for manufactured sand, quarry dust, and jarofix. Laterite blocks were inferior to the control at all levels but remained suitable for load-bearing masonry up to 20% replacement.

(3) Masonry prisms built from the proposed blocks displayed desirable failure patterns and strength variations consistent with their block strengths; masonry efficiency ranged from 73.6% to 81.6%, comparable to control masonry, establishing the structural feasibility of the blocks.

(4) The environmental sustainability assessment, based on material efficiency and embodied energy aggregated by simple additive weighting, ranked the blocks JB03 > QB03 > MB03 > LB02 ≈ FB02 > SB00, with the jarofix blocks attaining the maximum index of 1.0 against 0.489 for the control. Within the stated limits of the assessment, waste-incorporating blocks approximately double the sustainability performance of conventional blocks.

Future work should extend the assessment to durability under aggressive exposure, field-scale production trials, life-cycle costing, and the remaining sustainability indicators once the blocks enter service.

Acknowledgment:

The authors would like to express their sincere gratitude to the organizers of the 2nd International Conference on Materials Innovation and Sustainable Infrastructure (ICMISI-2026), conducted by the Department of Civil Engineering, Vishnu Institute of Technology (Autonomous), Bhimavaram, Andhra Pradesh, India, held during April 1–2, 2026, for providing a valuable platform to present and discuss this research work. This paper is an extended version of the work originally presented at ICMISI-2026.

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