DOI - 10.68648/ijte-q-2026-49-03-004

Feasibility of Collaborative Robot-Assisted Wall Laying Using Interlocking Compressed Earth Blocks

Vishal Kumar Chaudhary
Ph.D. Scholar
Department of Civil and Environmental Engineering
IIT Patna
Assistant Professor
Dept. of Civil Engineering
Government Engineering College Khagaria
✉ vishal_2522ce09@iitp.ac.in

Hemant Kumar Prajapati
Senior Structural Engineer
Jacobs
✉ hkumar.hk5@gmail.com

ABSTRACT

Masonry laying remains one of the least mechanised construction trades, while the interlocking compressed earth block (ICEB) remains one of the least mechanised low-carbon walling materials at the placement stage. The paper argues the two problems solve each other: the properties masonry robotics has had to engineer at cost (mortarless assembly, self-aligning interlock geometry, dimensional uniformity and low unit mass) already exist in the ICEB, a unit codified by Indian Standards. A framework for a collaborative laying cell is proposed, comprising a block feed, a force-limited arm, two-camera perception and a wall-plan sequencer, with the mason retaining corners, openings, reinforcement and grouting. Four feasibility results follow from codal values and published measurements: a lead-in clearance of 6.9 mm absorbs the codal block tolerance (±2 mm) and demonstrated cell accuracy (2.90 mm), while course accumulation requires per-batch calibration of the effective block dimension; code-derived unit masses of 1.2–9.9 kg sit within 12–16 kg collaborative-arm payloads; and the laying rate reaches 70–130 blocks per hour with relocations amortised. Deployment is constrained by block supply and by the infill fraction of the wall, not by arm speed. The framework is analytical and awaits physical validation, for which success criteria are stated.

KEYWORDS *: Interlocking compressed earth block; Construction robotics; Dry-stack masonry; Sustainable construction.*

NOTATIONS

e_k : cell placement error (mm)

t_b : codal block tolerance (mm)

c_{li} : interlock lead-in clearance (mm)

Δ_N : end-of-course deviation over N blocks (mm)

t_{sys}, t_{ran} : systematic and random tolerance components (mm)

m : unit mass (kg)

ρ_d : dry density (kg/m³)

V : block volume (m³)

T_c : cycle time (s)

t_p, t_g, t_m, t_v : pick, gate, move and place components (s)

Q : throughput (blocks/h)

r_e : arm reach (m)

d : wall stand-off (m)

L_{st} : usable frontage per station (m).

INTRODUCTION

Construction productivity has grown by about one percent annually over two decades, against 2.8 percent for the world economy and 3.6 percent for manufacturing [1]. Masonry wall laying remains among the least mechanised site trades even as the industry, worth close to USD 10 trillion per annum, faces shortages of skilled workers [2], and its materials are carbon-intensive: reinforced cement concrete demands

1.69 times more energy than a compressed stabilised earth block system and emits 1.64 times more CO_2-equivalent than an interlocking-block system [3].

Interlocking compressed earth blocks (ICEBs) are an established low-cost, low-carbon walling technology for social housing, though build-quality variability and skill dependence limit wider use [4]. In India IS 1725:2023 fixes classes, sizes and tolerances for the stabilized soil block [5], and IS 17165:2020 gives manufacturing guidelines recognising manual, semi-automatic and fully automatic block-making machines [6]. Production of the unit is thus on an automation trajectory; placement is not.

Interlocking units with robotic laying are not themselves unexplored: research systems have adopted purpose-designed interlocking blocks, and simulation found modular construction with interlocking blocks and robotic handling gave the greatest productivity improvement of all scenarios tested [7]. The earth-block case is unexplored. A Scopus search (August 2026) returned 131 records for masonry robotics and 51 for interlocking compressed earth blocks, but only two at their intersection, neither addressing robotic placement of ICEBs, one being an agenda-setting paper that does not consider robotic unit assembly [8]. Since Scopus indexes neither patents nor industry literature, this evidences a gap in the research record rather than proving none exists. Robot-friendly interlocking units have so far been purpose-fabricated, whereas the ICEB is codified, soil-pressed and low-carbon.

The gap conceals a match: mortarless assembly, self-aligning interlock geometry, dimensional uniformity and robot-compatible mass are properties masonry robotics has repeatedly engineered at cost, and the ICEB possesses all four because its geometry was conceived so unskilled builders could lay accurate mortarless walls. The contributions are a matching of automation barriers to a codified earth-block unit, a framework for a collaborative laying cell, four feasibility results, and demonstrator requirements.

LITERATURE REVIEW

Robotic Masonry with Conventional Units

On-site bricklaying robotics dates to the mobile robot of Pritschow et al., which automated thin-bed mortar application, handled blocks up to 50 kg, and needed a device measuring block lengths to 1 mm accuracy solely to compensate unit tolerances [9]. Yu et al. verified a laying robot analytically, naming the inequality of construction materials as a principal obstacle [10], and Dakhli and Lafhaj designed one around the thin-joint method, which demands blocks rectified to 1 mm, with units weighing 17 kg [11]. Cooperative multi-robot systems have built scaffold-free masonry arches [12]. The SAM100 lays 2,000–3,000 bricks per day but still requires a human alongside to smooth the mortar before further bricks are placed, while the truck-mounted Hadrian X lays 1,000 bricks per hour fully automatically from a 3D CAD design, mortar or adhesive being delivered under pressure to its laying head [2]. An AR-guided relocatable cobot recently laid two 3 m walls of 138 wooden blocks each across 7 and 9 relocations, holding global deviations of up to 2.90 ± 2.05 mm at roughly 105 blocks per hour with speed capped at 120 mm/s [13]. The recurring cost drivers are mortar handling, unit tolerance, and unit mass driving machine scale.

Interlocking and Dry-Stack Robotic Assembly

Research has responded by redesigning the unit. Zhang et al. developed engineered interlocking blocks needing translation only, reduced surface contact giving better error tolerance while mortarless construction permits disassembly [14]. Loing et al. found topologically interlocking assemblies sensitive to production and assembly error, concluded tolerance accommodation is crucial, and proposed guiding protrusions aligned with the assembly direction [1]. Robotic dry-stacking of natural stones needs stability-based sequence planning, millimetric displacements being especially detrimental [15]. Simulation confirms the direction, the modular intervention alone cutting lead time by 46 percent [7]. The field converges on dry-stacked interlocking units but implements them as bespoke blocks.

Automation of Earthen Construction

Earthen construction is automated along wet and monolithic paths: extrusion 3D printing of earth is feasible once rheology is adjusted [16], cob printing has required bespoke extruder hardware [17], and robotic rammed earth transfers compaction to the robot [18], a route found environmentally superior to manual work

at 28 percent lower global warming potential [19]. An agenda-setting review, noting that about 30 percent of the world population lives or works in earth buildings, identifies digital production as the pathway yet does not consider robotic unit assembly [8]. The block-unit pathway, with processing completed upstream in the press and the robot only placing, remains unexamined.

Interlocking Compressed Earth Blocks

The ICEB knowledge base is mature. Sturm et al. characterised dry-stack ICEBs at a mean unit compressive strength of 2.34 MPa, modified triplet tests giving friction coefficient 0.73 and a non-zero initial shear strength of 0.035 MPa attributed to the interlock, the indentations breaking rather than slipping [20]. ICEB walls with grouted, reinforced cells reach ultimate lateral resistances of about 48–50 kN in a solid 1.8 m square specimen, falling to 13–15 kN when the wall width is halved, a capacity deriving from the reinforcement rather than the dry-stacked units [21]. The Float RAM press yields about 30 blocks per hour with three workers at unit masses of 6.4–6.8 kg [22], ultrasonic pulse velocity predicts properties of Indian hollow interlocking blocks to fair accuracy [23], and geometry-corrected strength protocols are established [24]. IS 1725:2023 fixes unit tolerance at ±2 mm, defines strength classes of 3.5–10.0 N/mm², requires dry density of at least 1750 kg/m³, and lists five modular sizes from 190 × 90 × 40 to 240 × 240 × 90 mm [5].

Human–Robot Collaboration and Perception

Safety analysis of construction robots distinguishes physical risks, attentional costs and psychological impacts [25]. Marker-less deep-network pose estimation requiring only an on-site camera system is demonstrated practice [26]. Acceptance research envisions robotic assistants performing the physically demanding repetitive work while construction personnel focus on the cognitive tasks needed to plan and supervise, and notes that job-security concerns may be alleviated where robotics is perceived as upgrading manual work to more value-added work [27].

METHODOLOGY

The study follows the analytical feasibility-verification approach established for masonry robotics [10], [12]: a framework is synthesised and checked by closed-form analyses whose every input is a codal value or published measurement, with no laboratory or field data generated. Inputs come from IS 1725:2023 [5], IS 17165:2020 [6], the relocatable cobot demonstration [13], and published ICEB production rates, masses and mechanics [20], [22], [23], at worst-case values. The application is bounded to single-storey load-bearing dwelling walls of one leaf, 140–240 mm thick, in modular interlocking units to IS 1725.

(a) Tolerance budget. A block is seated correctly if the placement error of the cell and the dimensional variation of the unit are absorbed by the interlock lead-in clearance:

$$e_k + 2t_b \le C_{li} \quad (1)$$

where e_k is the cell-level placement error, t_b the codal block tolerance and C_{li} the total lead-in clearance of the key–recess pair.

Dry-stack courses have no mortar joint in which to absorb drift, so unit tolerances accumulate along the course in a manner that depends on their origin. Blocks pressed in one mould share its dimension, so mould oversize or wear is a systematic bias accumulating linearly, whereas ejection, moisture and handling variation is random and accumulates as a square root. For N blocks laid to a datum the end-of-course deviation is

$$\Delta_N = N \cdot t_{sys} + t_{ran}\sqrt{N} \quad (2)$$

where t_{sys} and t_{ran} are the systematic and random components of the codal envelope. The systematic term dominates and, unlike the random term, is measurable and correctable.

(b) Payload. Unit mass is computed from codal geometry and density,

$$m = \rho_d \cdot V \quad (3)$$

and compared with collaborative-arm payload net of gripper mass.

(c) Cycle time and productivity. The per-block cycle is the sum of pick, grasp-and-gate, move, and place-and-verify components, giving hourly throughput:

$$T_c = t_p + t_g + t_m + t_v \quad (4)$$

$$Q = 3600 / T_c \quad (5)$$

(d) Workspace. The usable wall frontage per station of an arm of reach r_e standing off the wall by d is

$$L_{st} = 2\sqrt{(r_e^2 - d^2)} \quad (6)$$

The laying rate is reported both steady-state and effective with relocations amortised. Economic viability is discussed qualitatively rather than modelled, since cell prices and wage rates lack the traceability of the codal inputs. The claim defended is feasibility and unit suitability with demonstrator requirements, not measured performance, and is most sensitive to the systematic tolerance component governing Eq. (2).

PROPOSED FRAMEWORK

The Matching Argument

Table 1 aligns each documented barrier of masonry automation with the ICEB property that removes it. The correspondence is not coincidental: the ICEB was designed to make dry-stack walling foolproof for unskilled builders, and the same properties make it tractable for robots. The remedy proposed after tolerance failure, guiding protrusions aligned with the assembly direction [1], describes the ICEB key that already exists; and the interlock is not cosmetic, triplet tests showing the keys break rather than slip [20].

Table 1 Masonry-automation barriers and the ICEB properties that remove them

Documented barrier	ICEB property	Sources
Mortar dosing, spreading and cure control	Dry-stack assembly; no mortar in the process	[9], [7]
Placement precision borne by machine alone	Self-aligning key–recess lead-in; translation-only seating	[1], [14]
Unit dimensional variability (1 mm rectification demanded)	Press-moulded units; codal tolerance ±2 mm	[9], [11], [5]
Unit mass drives machine scale (17–50 kg in cited systems)	1.2–9.9 kg codal units within cobot payload	[9], [11], [22], [5]
In-place process burden (extrusion rheology; ramming energy)	All material processing upstream in the press	[16], [18], [6]
Wet-process cure-time coupling	Course rise limited only by robot cycle	[7], [16]
End-of-life demolition waste	Dry joints permit robotic disassembly and reuse	[14], [8]

Fig. 1 defines the geometry the analysis operates on: the key–recess pair, the chamfered lead-in funnelling an approaching block into position, and the clearance absorbing cell placement error and unit dimensional variation.

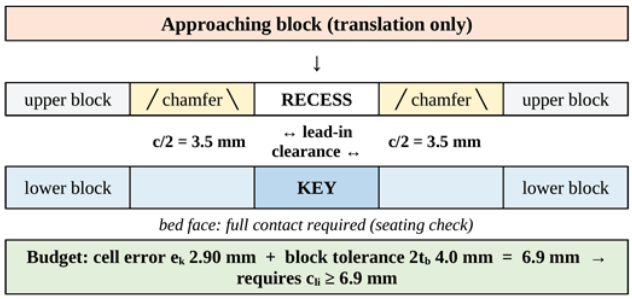


Fig. 1 Dimensioned section through a key–recess pair, showing the chamfered lead-in and the clearance budget of Eq. (1). Not to scale

Cell Architecture

Fig. 2 shows the cell. Blocks enter under three conditions rather than as free variables: produced from soil controlled to the 12–15 percent clay content IS 17165 identifies as optimum [6], since mix control upstream of the press determines how often the ±2 mm tolerance is met; cured to the requisite wet strength [6]; and laid in a stable moisture condition, since IS 1725 recognises linear expansion on saturation [5] and a mortarless wall has no joint to accommodate such movement.

Cured stock is presented at a fixed pick pose on a feed table. A collaborative arm of the 10–16 kg payload class, on a wheeled base relocated station-by-station by the mason [13], carries a force-limited parallel gripper whose wide flat jaws grasp only the plane faces, never the keys, respecting the green-strength handling

provision of IS 17165 [6]; the chipping tolerated by IS 1725 clause 5.2 is an acceptance concession for delivery handling [5], not a design allowance.

Perception is split between two viewpoints, since one fixed camera cannot serve both a close pick pose and millimetre-scale course geometry across a relocating cell. A wrist camera performs pose estimation at the pick point [26] with a defect gate applying IS 1725 clause 5.2 [5], optionally supplemented by ultrasonic pulse velocity [23]; a mast camera, re-registered at each station, verifies course level, plumb and bond and supplies the course-end position used to correct drift. Vision reports position, not bearing: a block on high points is geometrically correct but structurally deficient [1]. The cell therefore adds a seating check needing no extra hardware, since a force-limited arm senses contact: the height at which contact force develops is compared with that predicted from course datum and block dimension, a block seating high being lifted and re-placed.

A wall-plan sequencer converts the drawing into a course-by-course schedule. Because millimetric placement errors are especially detrimental in dry-stacked assemblies [15], each course is completed and verified before the next starts. It bounds the un-grouted lift height, since the wall is structurally incomplete until the mason grouts and reinforces the cells [21], so grouting is scheduled at intervals.

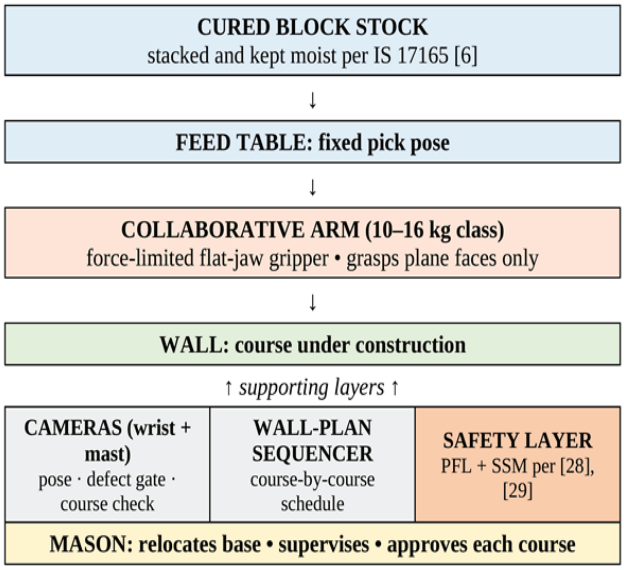


Fig. 2 Architecture of the collaborative ICEB laying cell

Operating Cycle

Fig. 3 gives the operating cycle, distinguishing the per-block loop (pick, gate, move, place and seat) from the per-course step of camera verification and mason approval. Rejected blocks leave at the gate, so the cell doubles as a quality filter on production.

Task Allocation

Table 2 states the human–robot split: the arm takes the repetitive, musculoskeletally punishing infill runs while the mason keeps every judgment task, including the reinforcement and grouting that give ICEB walls their ductile behaviour [21]. This is the division acceptance research envisions for construction robotics [27].

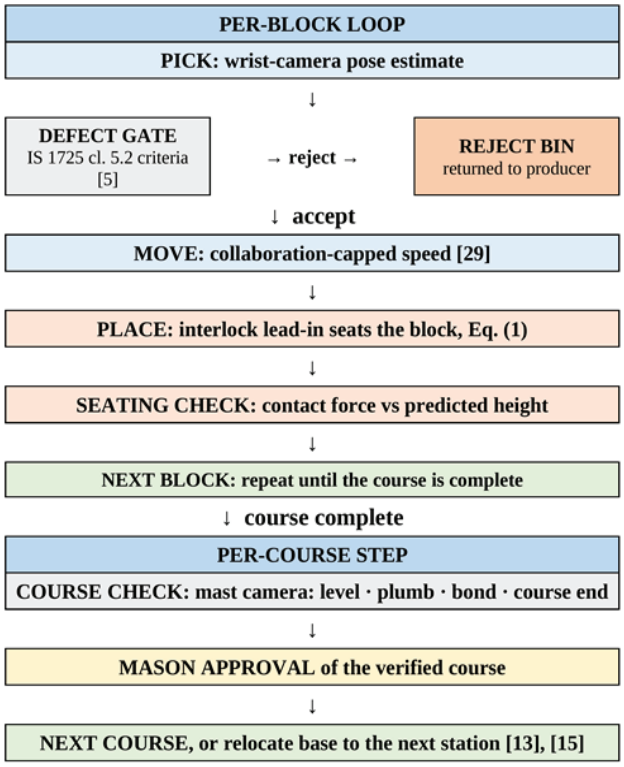


Fig. 3 Operating cycle: the per-block loop and the per-course verification step with mason approval

Table 2 Task allocation in the collaborative laying cell

Collaborative arm	Mason
Straight infill course laying	Setting out; first course on levelled bed
Per-block pick, gate, place	Corners, junctions, jambs and openings

Course geometry and seating checks	Reinforcement and cell grouting at scheduled intervals [21]
Repetitive lifting (up to 9.9 kg × hundreds)	Course approval; base relocation [13]
Halt on gate or check failure	Services, lintels, quality decisions

Safety as a Collaborative Application

The cell is designed as a collaborative application, the term used by ISO 10218-1:2025, which drops "collaborative robot" because only the application can be verified as collaborative [28]. The shared workspace uses power and force limiting with speed and separation monitoring at course approval, applying the biomechanical limits of ISO/TS 15066:2016, now in the ISO 10218:2025 series [29]: quasi-static limits of 140 N for hands and fingers, 160 N for the lower arm and wrist, 150 N for the upper arm and elbow. Hazards follow the construction-robotics taxonomy of physical risks, attentional costs and psychological impacts [25], met respectively by the force-limited grasp and capped speed, the pause at course approval, and the task split [27]. Grasp contact stress is capped below the IS 1725 strength class [5] per geometry-corrected protocols [24].

RESULTS AND DISCUSSION

Tolerance Budget

Table 3 evaluates Eq. (1) with worst-case inputs: the poorer demonstrated wall deviation, e_k = 2.90 mm [13], and the full codal tolerance t_b = ±2 mm [5]. The requirement is $c_{li} \geq 6.9$ mm, about 3.5 mm per side, a mould-design parameter rather than an exotic demand, since IS 1725 clause 7.1 permits shapes suited to construction needs through special mould attachments [5]. The binding term is cell-level registration across relocations, not arm repeatability, negligible at the ±0.05–0.1 mm typically specified for this class.

Course accumulation is the more demanding constraint, and the systematic term governs. Decomposing the ±2 mm envelope (t_{sys} = 0.5 mm with t_{ran} = 1.5 mm, or t_{sys} = 1.0 mm with t_{ran} = 1.0 mm), Eq. (2) gives end-of-course deviations of about 10–13 mm over ten blocks and 17–25 mm over twenty, three to seven times the 3.5 mm per-side clearance and beyond what any practical clearance absorbs uncorrected. Decisively, systematic bias is measurable: one calibration measurement per production batch establishes the effective block dimension, which the sequencer substitutes for the nominal value, removing the linear term and leaving a random residual of about 3–7 mm. The mast camera re-measures the realised course end each course, and the design reserves a closure block trimmed on site.

A trade-off must be acknowledged: the dry-joint shear capacity of [20] arises because the keys engage and break rather than slip, and widening the clearance to 3.5 mm per side introduces play in that load path, so whether the 0.035 MPa initial shear strength survives cannot be settled analytically. The clearance is a requirement to be validated for seating reliability and joint shear together.

Table 3 Tolerance budget for interlock seating, Eq. (1)

Quantity	Value	Basis
Cell placement error	2.90 mm	worst measured wall deviation [13]
Block dimensional tolerance	±2 mm	IS 1725:2023 cl. 7.3 [5]
Required lead-in clearance	≥ 6.9 mm total (≈3.5 mm/side)	Eq. (1), worst case
Design route	chamfered key–recess lead-in formed in mould	IS 1725 cl. 7.1, 7.4 [5]; [1], [14]

Unit Mass and Payload

Table 4 computes Eq. (3) between the codal minimum density of 1750 kg/m³ and a practical 1900 kg/m³, for solid units, hollow blocks [23] being lighter and the case therefore conservative. Computed as solid, the five codal modular sizes span 1.2 to 9.9 kg, the common 290 × 140 × 90 mm block giving 6.4–6.9 kg, which matches the measured 6.4–6.8 kg of production ICEBs [22]. A 2–3 kg gripper leaves 7–14 kg net across the 10–16 kg class, so a 12 kg arm carries the common unit at about 23 percent margin, while the heaviest modular size, 240 × 240 × 90 mm at up to 9.9 kg, requires a 16 kg arm, where the margin is 24 percent. Ordinary collaborative hardware therefore suffices across the codal range, against the 17 kg blocks of [11] and 50 kg units of [9] that pushed earlier systems to heavy machinery.

Table 4 Code-derived unit mass versus collaborative-arm payload

Block size (mm)	Volume (L)	Mass at 1750–1900 kg/m³ (kg)
290 × 90 × 90 [5]	2.35	4.1 – 4.5
290 × 140 × 90 [5]	3.65	6.4 – 6.9 (measured 6.4–6.8 [22])
305 × 143 × 100 [5]	4.36	7.6 – 8.3
240 × 240 × 90 [5]	5.18	9.1 – 9.9
Net arm capacity after a 2–3 kg gripper: 7–14 kg across the 10–16 kg class		

Cycle Time and Productivity

Table 5 assembles Eqs. (4)–(5) from conservative component times at capped speeds, giving 90–164 blocks per hour steady-state. Relocation must be added: Eq. (6) accommodates six to nine blocks per course and [13] averaged 15–20 blocks per relocation, so at an assumed two to three minutes each this amortises to 6–12 s per block, giving about 70–130 per hour effective, a band containing the realised 105 of [13]. The press rate of 30 blocks per hour in Table 5 is production, not laying, exposing the supply constraint, one cell consuming two to four presses; the mason figure of 400–500 units per day is fired brick [2] and context only.

Table 5 Cycle-time build-up and productivity comparison

Component / rate	Value	Basis
Pick + pose estimate	6–10 s	fixed pick pose, Fig. 2
Visual defect gate	4–8 s	camera criteria [5], [23]
Move to wall	8–14 s	capped collaborative speed [29]
Place + verify	4–8 s	interlock seating, Eq. (1)
Cycle → steady-state rate	22–40 s → 90–164 h^{-1}	Eqs. (4), (5)
Relocation amortised	6–12 s/block → 70–130 h^{-1}	15–20 blocks/ relocation [13]
Realised cobot rate	≈105 h^{-1}	138 blocks / ≈78 min incl. relocations [13]
Manual press output (production, not laying)	30 h^{-1} (3 workers)	[22]
Mason daily laying (fired brick; context only)	400–500 units	[2]

Workspace and Deployment

With reach 0.9–1.3 m and stand-off 0.35 m, Eq. (6) gives a usable frontage of 1.66–2.50 m per station, so a 10 m wall needs four to six stations, and courses above about 1.5 m need a lift axis, as platform geometry limited wall height in [13]. Economically the cell augments rather than replaces the crew, since Table 2 retains the mason and the feed table needs an attendant, confining the saving to the infill fraction. Near-term justification therefore rests on ergonomics, dimensional consistency and the documented shortage of construction workers [2], [27] rather than cost. The same trade is identified for robotic earthen construction, where operational and formwork savings are offset by capital and maintenance costs and precise quantification of market viability is left to further research, even though that route proved environmentally favourable [19]. Costing is deferred to the demonstrator.

How the Present Work Differs

Relative to prior investigators the distinction is efficiency through the unit rather than the machine. Commercial systems either retain a human to finish the mortar or deliver it under pressure through a purpose-built laying head [2]; thin-joint robots purchase tolerance with 1 mm rectified blocks [9], [11]; interlocking-assembly research purchases robot-friendliness with bespoke units [14]; wet earthen paths purchase automation with rheology control and in-place compaction [16], [17], [18]. This framework purchases none of these, adopting a codified unit whose ±2 mm tolerance, several-kilogram mass and load-bearing interlock are already standard [5], [20], [22]. Because that unit also showed the lowest lifecycle energy demand of the five systems compared

[3], and robotising earthen fabrication improves rather than erodes its environmental case [19], productivity and sustainability compound.

Implications for Skills and Technical Education

The reallocation in Table 2 changes what a mason does rather than displacing the mason, which carries a training requirement this journal's readership is placed to address. The retained tasks are the higher-skill portion of the trade; the transferred tasks are the repetitive lifting that causes musculoskeletal injury. Operating the cell adds competencies the masonry curriculum does not cover: reading a course plan against a digital wall model, performing the per-batch calibration on which Eq. (2) shows the system to depend, responding to gate and seating alarms, and working safely within a collaborative application [28], [29]. These suit a short add-on module in an ITI or diploma programme.

Limitations

The framework is analytical: no prototype has been built, and the evidence base leans heavily on one online-first source [13] whose demonstration used wooden blocks, so replicating it on production ICEBs is the first demonstrator task. The gripper is unproven against compressed-earth edge fragility, the mitigation being a flat-face force-limited grasp specified against geometry-corrected strength [24] with the gate rejecting damaged blocks [5]. Vertical reach beyond 1.5 m needs a lift axis, the feed table consumes labour, and the gain is bounded by the infill fraction. Durability against water, the reason IS 1725 caps absorption at 18 percent [5], remains a design responsibility, and adoption depends on the safety perceptions [25] and acceptance factors [27] documented for construction robotics.

A further caution concerns the codal tolerance itself: ±2 mm is a specification, not a measurement of what field presses deliver, and CEB production variability is appreciable, at a 24 percent coefficient of variation on unit strength [20]. The framework does not assume compliance so much as enforce it, since the gate rejects non-conforming blocks; but a cell fed by an uncontrolled press would reject heavily, making the rejection rate the decisive operating variable this analysis cannot predict and a demonstrator must measure.

CONCLUSIONS

The ICEB, conceived so that unskilled builders could dry-stack accurate walls, proves to be the masonry unit whose properties best match the documented failure modes of masonry robotics: every recurring barrier of bricklaying automation is removed by a property the unit already possesses. A lead-in clearance of 6.9 mm absorbs the codal tolerance and demonstrated cell accuracy at block level as ordinary mould design, but course-level accumulation is dominated by systematic mould bias and is tractable only with per-batch calibration, which the analysis establishes as a precondition. Code-derived masses suit ordinary collaborative arms, and an effective rate of 70–130 blocks per hour makes block supply rather than arm speed the binding constraint. Future work is a demonstrator: an instrumented mould realising the lead-in, grasp-and-place trials on production blocks, and a pilot wall with the gate and seating check in the loop. It confirms feasibility if placement error stays within the derived clearance over a course, the seating check detects nine in ten mis-seated blocks, rejection stays below one in ten, and the rate reaches 70 blocks per hour.

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