

Article

Thermal Mass–Ventilation Interaction in Naturally Ventilated School Classrooms: A Building Performance Simulation Study Evaluated Against Field Measurements in South East Nigeria

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Abstract

Field measurements undertaken in six paired primary school classrooms in Anambra State, Nigeria, previously demonstrated that interlocking compressed earth block (ICEB) classrooms maintained significantly lower occupied-hour temperatures than adjacent sandcrete block (SCB) classrooms. This study applies DesignBuilder/EnergyPlus simulation, evaluated against field measurements, to investigate the physical mechanisms underlying this observed thermal advantage and to explore seasonal performance beyond the period accessible through field monitoring. Simulation models were developed using literature-derived thermophysical properties and validated against field measurements collected at Awkuzu Primary School on 2 July 2024. Model accuracy was assessed using ASHRAE Guideline 14 metrics. The ICEB model achieved NMBE of -6.4% and CV(RMSE) of 6.8% , satisfying both recommended thresholds. The SCB model achieved CV(RMSE) of 15.6% , while NMBE of -14.0% marginally exceeded the recommended threshold because of conservative TMYx boundary conditions. Results indicate that the superior wet-season performance of ICEB classrooms is attributable to the interaction between high thermal mass ($\mu = 0.31$; $\varphi = 9.1$ h) and continuous cross-ventilation. Parametric crossover simulations demonstrated that ventilation was the dominant cooling mechanism, while ICEB wall thermal mass provided an additional independent thermal benefit of approximately 0.31 °C. This material contribution is secondary in magnitude to the ventilation effect and is not presented as a standalone practical advantage. Dry-season simulations suggested a possible reversal of performance under near-calm harmattan conditions; however, the magnitude and direction of this effect remain uncertain because of EPW boundary-condition limitations. The findings suggest that classroom thermal performance depends on the interaction between envelope thermal mass and ventilation configuration rather than material properties alone and highlight the potential importance of controllable ventilation in naturally ventilated educational buildings in tropical climates.



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1. Introduction

Naturally ventilated educational buildings in tropical climates depend primarily on passive architectural strategies to maintain acceptable indoor thermal conditions. Building envelope properties and ventilation configurations jointly determine thermal performance,

yet the interaction between these two variables has received limited attention in sub-Saharan African school buildings [1,2]. Studies focusing on Nigerian classrooms have consistently reported elevated indoor temperatures and thermal discomfort under conventional sandcrete block (SCB) construction, which remains the dominant walling material across West Africa [1,2].

Field measurements conducted across six primary schools in Anambra State, Nigeria, confirmed that interlocking compressed earth block (ICEB) classrooms maintained lower indoor temperatures than co-located SCB classrooms during occupied periods, yielding a mean temperature reduction of $2.03\text{ }^{\circ}\text{C}$ ($t = 6.83$, $p < 0.01$, $d = 2.79$). However, empirical field observations are temporally bounded: they capture wet-season conditions only and cannot characterise classroom thermal behaviour across the full annual climatic cycle, which includes a thermally demanding dry-season harmattan period (November–March) [3].

The broader literature situates this investigation within three convergent research streams. First, the favourable thermophysical characteristics of earth-based walling materials in Nigerian and West African contexts are well documented [4–6]. Comparative studies in Burkina Faso found that stabilised compressed earth block masonry produced more stable indoor thermal conditions than conventional cementitious construction [7], and calibrated EnergyPlus modelling showed that, while baseline discomfort hours were comparable between compressed earth block and cement-block test buildings, the compressed earth block envelope became measurably more comfortable once passive optimisation measures were applied—an advantage attributed to its higher thermal inertia [8]. Second, thermal mass–ventilation interaction studies establish that the passive cooling benefit of high-mass construction is contingent on ventilation regime [9,10]: high thermal mass benefits occupants when coupled with controlled nocturnal purging but may be detrimental when coupled with continuous uncontrolled ventilation during periods of elevated overnight temperatures. Third, the adaptive thermal comfort framework validated for Nigerian primary school children by Munonye and Ji [1] provides the evaluative basis for interpreting simulation outputs.

Against this background, no prior study has combined EnergyPlus simulation with field-measured ICEB–SCB paired classroom data to investigate seasonal performance reversal in a West African climate. Crucially, this study evaluates the two classroom systems as constructed: SCB classrooms incorporate operable casement windows; ICEB classrooms incorporate permanent screen walls providing continuous, uncontrolled ventilation. The simulation therefore examines the interaction between wall thermal mass and ventilation configuration—the real-world performance system—rather than material properties in isolation.

The objectives of this study are (1) to apply a DesignBuilder/EnergyPlus simulation model against field-measured indoor temperatures, (2) to quantify the dynamic thermal properties of each wall system, (3) to examine seasonal behaviour through simulation of peak dry-season conditions, and (4) to assess temperature sensitivity to increased classroom occupancy. Airport- and typical-year-derived EPW files are known to deviate substantially from locally monitored conditions [11]; this study extends that concern by providing evidence that the resulting boundary-condition uncertainty propagates non-uniformly across construction types in a West African classroom simulation context.

2. Materials and Methods

2.1. Building Geometry and Environmental Context

A classroom model was developed in DesignBuilder version 7.3 (DesignBuilder Software Ltd., Stroud, Gloucestershire, UK), acting as a graphical interface for the EnergyPlus simulation engine (U.S. Department of Energy, Washington, DC, USA) [12]. Saif et al. [13]

applied the same software combination to a school classroom study validated against field data in a comparable hot climate. Shrestha and Rijal [14] similarly validated a DesignBuilder classroom model against field measurements in naturally ventilated school buildings in Nepal. The classroom was modelled as a single thermal zone: 7.5 m $\times$ 6.5 m floor area; 3.0 m internal height; 1.0 m front overhang and a further 2.0 m front verandah; 1.0 m rear overhang; adiabatic side walls representing shared-wall terrace conditions; front wall facing north (0°). Roof construction—corrugated aluminium sheets supported on timber purlins with fibre-cement ceiling boards—was held constant across both construction types. (Figure 1 illustrates the classroom geometry).

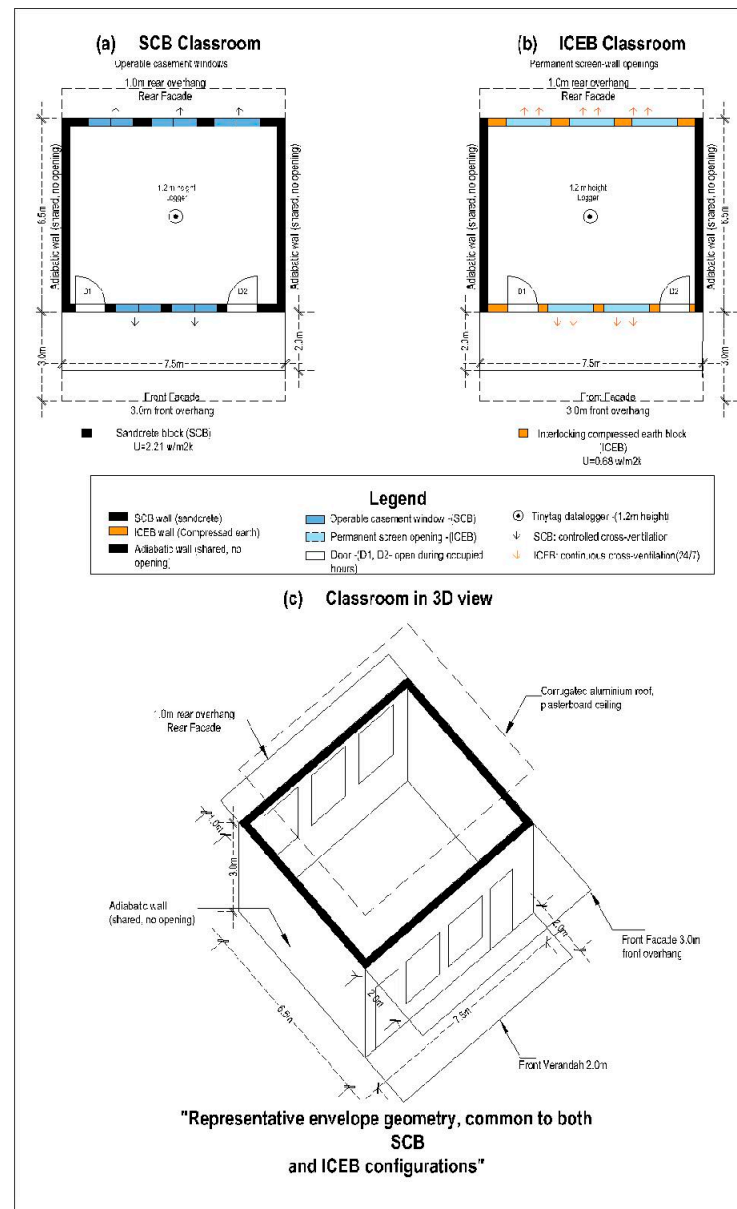


Figure 1. Classroom geometry. (a) SCB classroom: sandcrete block walls ($U = 2.21 \text{ W/m}^2\text{K}$; $\phi = 4.2 \text{ h}$; $\mu = 0.58$) with operable casement windows on front and rear facades. (b) ICEB classroom: interlocking compressed earth block walls ($U = 0.68 \text{ W/m}^2\text{K}$; $\phi = 9.1 \text{ h}$; $\mu = 0.31$) with permanent screen-wall openings providing continuous cross-ventilation. (c) Three-dimensional axonometric view of the representative classroom envelope, common to both configurations. Both classrooms: 7.5 m $\times$ 6.5 m floor area, 3.0 m internal height, corrugated aluminium roof with plasterboard ceiling, 1.0 m front overhang with a further 2.0 m front verandah, and 1.0 m rear overhang. Side walls modelled as adiabatic (shared-wall terrace condition). Source: Authors.

Weather data were assigned using the Owerri Airport EPW file: NGA_IM_Owerri.AP.6 52016_TMYx.2011–2025 (Sam Mbakwe International Airport, WMO 652016; ASHRAE Climate Zone 1A; Köppen Af), sourced from the Climate.OneBuilding repository [15]. No Anambra-specific EPW file exists; therefore, the Owerri EPW was selected as the nearest available WMO weather station and the most representative available weather file for the study area. The implications and limitations of this boundary-condition assumption are assessed in Section 3.1.

2.2. Wall Construction and Thermophysical Properties

Two walling systems were modelled against a constant roof and floor assembly. SCB: 225 mm hollow sandcrete block with 12mm cement plaster on each face. ICEB: 220 mm monolithic stabilised compressed earth block, unrendered. Thermophysical properties were derived from published Nigerian material characterisation studies [4,5,16] and are presented in Table 1.

Table 1. Thermophysical properties and dynamic thermal characteristics of the modelled wall assemblies. Sources: Bakam et al. [4]; Morel et al. [16]; Etuk et al. [5]; Kontoleon and Eumorfopoulou [10]. Decrement factor (μ) and thermal time lag (ϕ) values are derived from the thermophysical property literature and are consistent with ISO 13786 [17] methodology for periodic heat flow through multilayer assemblies. They are not presented as author calculations.

Property	SCB Wall (225 mm Hollow + Render)	ICEB Wall (220 mm Monolithic)
Thermal Conductivity (W/m·K)	1.10–1.30	0.48
Density (kg/m ³)	1600	1950
Specific Heat Capacity (J/kg·K)	840	1000
Wall U-value (W/m ² K)	2.21	0.68
Thermal Mass Index (kJ/m ² K)	≈820	≈1640
Decrement Factor (μ)	0.58	0.31
Thermal Time Lag (ϕ , hours)	4.2	9.1

2.3. Ventilation Configuration

Ventilation was modelled using the EnergyPlus AirflowNetwork (AFN) method, computing dynamic air movement from wind pressure coefficients, EPW wind data, and thermal buoyancy. The two systems differ fundamentally in their as-built configuration. SCB Classrooms: Operable metal casement windows on front and rear façades; 50% operable free area fraction when fully open; occupancy-driven schedule (08:00–14:00 weekdays); both front doors fully open 08:00–14:00; background infiltration 0.50 ACH.

Mean occupied ventilation rate: 20.6 ACH (peak 22.2 ACH) under wet-season conditions. ICEB Classrooms: Permanent screen-wall openings on a 24 × 7 always-open schedule; both front doors fully open 08:00–14:00; background infiltration 0.50 ACH. Mean occupied ventilation rate: 31.2 ACH under wet-season conditions and approximately 0.10 ACH under dry-season near-calm harmattan conditions. The following AirflowNetwork (AFN) input parameters were applied: discharge coefficient $C_d = 0.6$ (standard value for sharp-edged openings per EnergyPlus Engineering Reference); wind pressure coefficients set to ‘Calculated’ within DesignBuilder based on the building’s low-rise form, aspect ratio, and surface exposure. Opening dimensions: SCB—front façade 5.4 m² total glazing area, 50% operable free area; rear façade 3.6 m², 50% operable. ICEB screen walls modelled with equivalent continuous opening area consistent with field observation. No field airspeed measurements were collected; this is acknowledged as a limitation (Section 4.5).

2.4. Occupancy and Internal Gains

Internal heat gains were derived from ASHRAE Standard 55 metabolic rates for seated schoolchildren (75 W/person sensible heat) [18]. Two occupancy scenarios were simulated: standard (22 pupils + 1 teacher; 0.47 persons/m²) and overcrowded (35 pupils + 1 teacher; 0.72 persons/m²).

2.5. Simulation Protocol and Validation Metrics

Simulation outputs were validated against field-measured Tinytag indoor air temperatures at Awkuzu Primary School (2 July 2024, 10:00–14:00 LST) following ASHRAE Guideline 14 [19] and the validation framework of Coakley et al. [20] and Saif et al. [13]. Envelope thermal properties were held fixed at literature-derived values throughout; no parameters were adjusted post hoc to improve statistical fit. Field study design: six paired primary school sites in Anambra State were selected on the basis of construction type, comparable floor area (42–48 m²), comparable orientation, and maximum 50 m proximity between paired classrooms to minimise microclimate differences. Sensors: Tinytag Plus 2 (TGP-4017) and Tinytag Ultra 2 (TGU-4500) data loggers (Gemini Data Loggers Ltd., Chichester, West Sussex, UK), manufacturer-specified accuracy ±0.5 °C positioned at 1.2 m above finished floor level in accordance with ISO 7726 [21]. Loggers synchronised to a common time reference with maximum deviation ±1 min. The Standardised Morning Ventilation Protocol (SMVP) was applied across all six sites to eliminate prior thermal history as a confounding variable. Reference loggers were positioned on the teacher’s desk at 1.2 m height: SCB classroom, Tinytag Plus 2 (TGP-4017); ICEB classroom, Tinytag Ultra 2 (TGU-4500). Model accuracy was assessed using the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and Normalised Mean Bias Error (NMBE), calculated per ASHRAE Guideline 14 [19], where M^- is the mean of measured values, M_i is the measured value at interval i , and S_i is the simulated value at interval i . Validation statistics were calculated using four hourly matching points (11:00–14:00 LST), corresponding to the field-measurement and simulation comparison period. ASHRAE Guideline 14 stipulates acceptance thresholds of $|NMBE| \leq 10\%$ and $CV(RMSE) \leq 30\%$ for hourly data.

3. Results

3.1. EPW Boundary Condition Assessment

Before presenting simulation results, the representativeness of the Owerri Airport TMYx EPW requires systematic assessment. Four interacting factors determine the direction and magnitude of EPW bias, summarised in Table 2.

Table 2. EPW boundary condition factors, bias direction, and effect on the simulated ICEB–SCB dry-season differential.

Factor	Mechanism	Bias Direction	Effect on Dry-Season Differential
1. TMYx statistical smoothing	Represents long-term mean; underrepresents anomalously warm July 2024 (El Niño; elevated Atlantic SST)	Cool bias—both types equally	Understates absolute temperatures; limited differential effect
2. Station-to-site gap (22 km)	Awkuzu ~45–50 m lower elevation; Anambra lowland clay soils retain more moisture	Awkuzu ~0.3–0.5 °C warmer than airport	Understates both; similar differential effect

Table 2. Cont.

Factor	Mechanism	Bias Direction	Effect on Dry-Season Differential
3. Green airport ET cooling	Airport on low grass in Ngor Okpala LGA; evapotranspiration may produce cooler nocturnal station temps than surrounding rural landscape	Uncertain: may invert standard warm-airport assumption	May suppress ICEB nocturnal discharge—may overstate ICEB dry-season penalty
4. Differential nocturnal sensitivity	ICEB $\phi = 9.1$ h: daytime interior governed by prior night's boundary. SCB $\phi = 4.2$ h: governed primarily by same-day conditions	Amplifies nocturnal biases disproportionately on ICEB	Direction of differential uncertainty compounds—indeterminate

Net conclusion: the 0.16 °C dry-season ICEB disadvantage is uncertain in both magnitude and direction. The wet-season field-measured advantage of 2.03 °C ($n = 6$, $p < 0.01$) remains the more reliable basis for design conclusions.

3.2. Model Application Results: Wet Season (2 July 2024)

Validation statistics were computed per ASHRAE Guideline 14 against Tinytag field measurements at Awkuzu (2 July 2024, $n = 4$ hourly matching points, 11:00–14:00 LST). The ICEB model meets both thresholds: NMBE -6.4% (within $\pm 10\%$); CV(RMSE) 6.8% (within 30%). The SCB model CV(RMSE) (15.6%) is within threshold; SCB NMBE (-14.0%) marginally exceeds the $\pm 10\%$ limit. This exceedance is attributable to the EPW boundary condition: ERA5 reanalysis data [22] for 2 July 2024 confirms outdoor temperatures approximately 5.3 °C above the TMYx statistical mean during the measurement window, suppressing simulated temperatures relative to field-measured values. No envelope parameters were adjusted to improve the fit; the simulation is a direct projection of literature-derived material properties under EPW boundary conditions (Table 3, Figure 2).

Table 3. Model application results: Awkuzu Primary School, 2 July 2024 (11:00–14:00 LST). NMBE and CV(RMSE) calculated per ASHRAE Guideline 14 using four hourly matching points. The ICEB model satisfied both recommended thresholds (NMBE = -6.4% ; CV(RMSE) = 6.8%). The SCB model satisfied the CV(RMSE) threshold (15.6%) but marginally exceeded the recommended NMBE threshold (-14.0%). The exceedance is attributed to conservative TMYx boundary conditions during the anomalously warm July 2024 measurement period rather than envelope parameterisation error.

Metric	SCB Measured	SCB Simulated	ICEB Measured	ICEB Simulated
Mean indoor air temp. (°C)	29.51	25.80	27.11	25.41
Peak indoor air temp. (°C)	32.60	26.05	27.70	25.68
Underprediction (°C)	—	3.71	—	1.70
NMBE (%)	n/a	-14.0	n/a	-6.4
CV(RMSE) (%)	n/a	15.6	n/a	6.8
Simulated ICEB–SCB mean differential (°C)	—	—	0.39 (ICEB cooler)	—

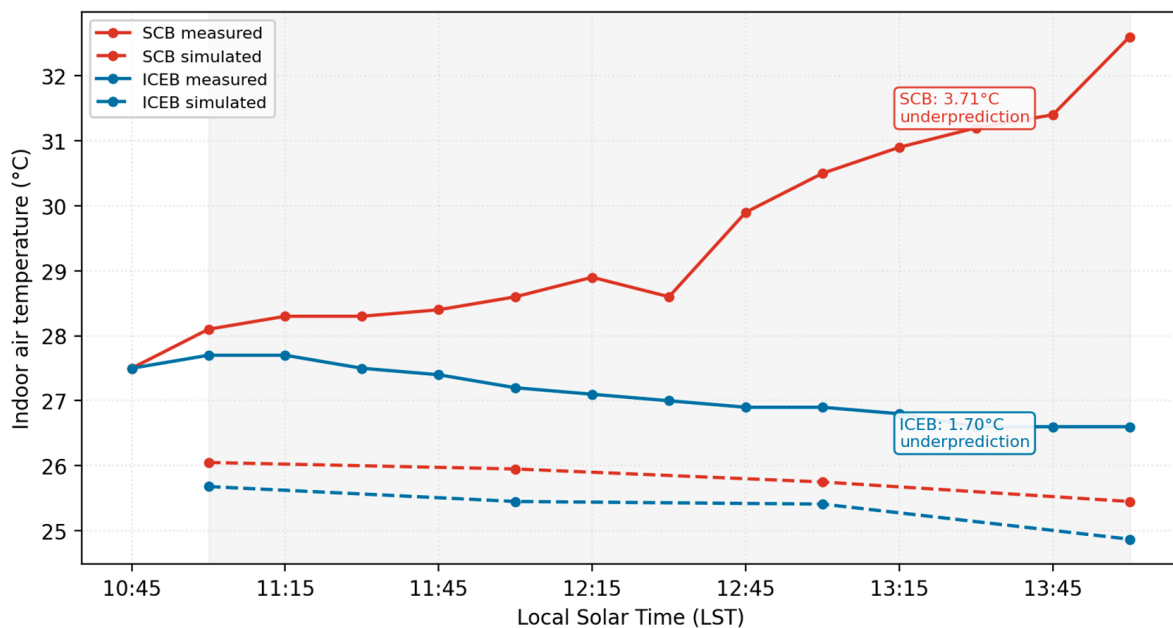


Figure 2. Measured vs. simulated indoor air temperature, Awkuzu Primary School, 2 July 2024. Validation window 11:00–14:00 LST ($n = 4$ hourly points, ASHRAE Guideline 14). Solid lines: field-measured (15 min resolution); dashed lines: simulated (hourly). Source: Authors.

3.3. Wet-Season Physical Mechanism

The simulation confirms the physical mechanism underlying the field measurements. The ICEB wall's thermal time lag ($\phi = 9.1$ h) means heat absorbed during morning solar exposure does not reach the classroom interior until approximately 19:00–20:00, well after school hours. The low decrement factor ($\mu = 0.31$) attenuates this heat to less than one-third of the outdoor swing amplitude. The SCB wall ($\mu = 0.58$; $\phi = 4.2$ h) transmits more than half the outdoor swing within the occupied period. Figure 3 illustrates the diurnal thermal behaviour of both wall assemblies.

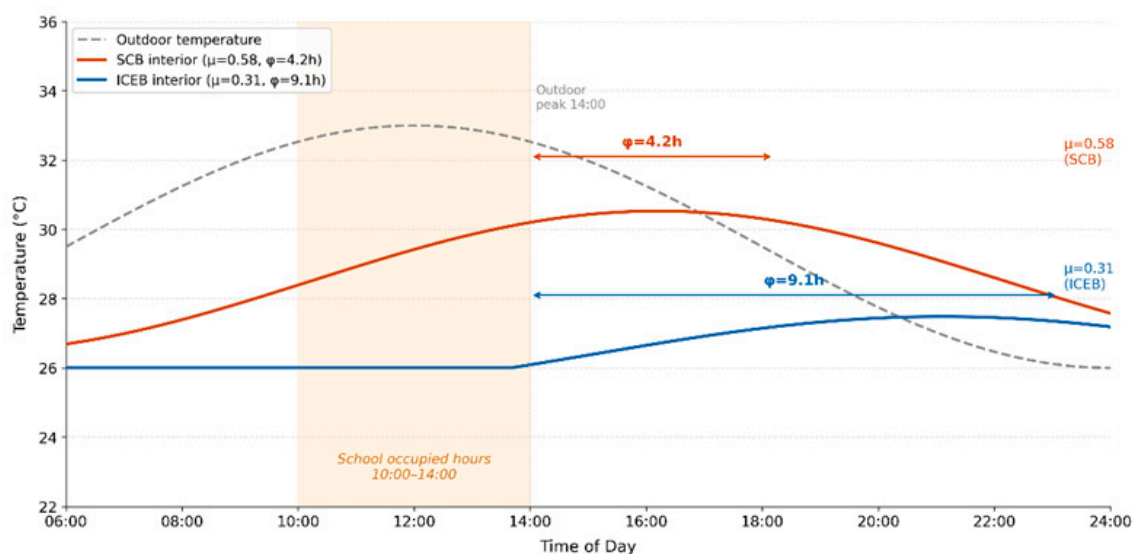


Figure 3. Diurnal thermal lag and decrement factor for ICEB and SCB wall assemblies under typical wet-season conditions. Outdoor temperature (grey dashed) peaks at 14:00. SCB interior (red) peaks at 18:12 ($\phi = 4.2$ h; $\mu = 0.58$). ICEB interior (blue) peaks at 23:06 ($\phi = 9.1$ h; $\mu = 0.31$). Orange shading: school occupied hours (10:00–14:00). Source: Authors.

3.4. Dry-Season Stress Test: Peak Harmattan (15 February 2024)

Models were run for 15 February 2024 representing peak dry-season harmattan conditions: outdoor temperatures above 30 °C, intense solar radiation, low relative humidity, and near-calm wind. These are simulation-only projections; no dry-season field data were available. EPW boundary condition uncertainty (Table 2) summarised in Table 4.

Table 4. Peak dry-season simulation results: Awkuzu Primary School, 15 February 2024 (10:00–14:00 LST). Simulation-only projections. Near-calm harmattan winds produce ACH collapse in ICEB screen-wall classrooms. Wet:dry performance ratio approximately 1:13 in favour of ICEB. EPW boundary condition uncertainty applies (Table 2).

Metric	Outdoor (EPW)	SCB Simulated	ICEB Simulated
Mean temp., 10:00–14:00 (°C)	32.52	—	—
Mean simulated indoor temp. (°C)	—	33.42	32.96
Peak simulated indoor temp. (°C)	—	33.85	33.88
Time of peak	—	13:00	13:00
ICEB vs. SCB mean (°C)	—	—	ICEB warmer by 0.16
ICEB vs. SCB peak (°C)	—	—	ICEB warmer by 0.03
Mean ACH, 10:00–14:00	—	0.68	0.10
Occupancy penalty (22→35 pupils)	—	Negligible	Negligible

Both classroom types exceeded the adaptive comfort threshold of 30.5 °C during all occupied hours of the simulated dry-season period, indicating that neither construction system alone can ensure thermal comfort under extreme seasonal conditions.

3.5. Parametric Isolation: Material Effect vs. Ventilation Effect

To separate the independent contributions of wall thermal mass and ventilation configuration, two crossover simulations were conducted for 2 July 2024 (Table 5). Crossover A applied ICEB wall thermophysical properties ($k = 0.48 \text{ W/m}\cdot\text{K}$; $\rho = 1950 \text{ kg/m}^3$; $C_p = 1000 \text{ J/kg}\cdot\text{K}$) with the SCB casement window configuration (open 08:00–14:00). Crossover B applied SCB wall thermophysical properties with the ICEB permanent screen-wall configuration (always open). Crossover A produced a mean operative temperature of 31.86–6.06 °C above the as-built ICEB baseline (25.41 °C) and 6.06 °C above the as-built SCB baseline (25.80 °C). This suggests that high thermal mass alone does not deliver cooling benefit in the absence of adequate ventilation; the ICEB system's performance is contingent on the screen-wall ventilation configuration. Crossover B produced 25.72–0.08 °C below the as-built SCB baseline, but 0.31 °C above the as-built ICEB baseline. This 0.31 °C differential represents the independent thermal contribution of ICEB wall material under identical ventilation conditions: when both systems are given equivalent screen-wall ventilation, ICEB remains cooler. The combined evidence indicates that the ICEB system's thermal advantage is a product of the material–ventilation interaction: ventilation is the primary cooling driver, and ICEB wall thermal mass provides an independent supplementary benefit of 0.31 °C that should be read as a simulation-internal comparison pending field validation of the underlying AirflowNetwork assumptions (Section 4.5). The material effect is secondary to, and substantially smaller than, the ventilation effect and should not be read as a standalone justification for material substitution.

Table 5. Parametric isolation results: mean operative temperature (10:00–14:00 LST), Awkuzu Primary School, 2 July 2024. Variants A and B isolate the independent contributions of wall thermal mass and ventilation configuration to the observed ICEB–SCB temperature differential. All other model parameters (geometry, roof, occupancy, EPW file) held constant.

Building Configuration	Wall Material	Ventilation Schedule	Mean Op. Temp 10:00–14:00 (°C)	Diff. vs. SCB Baseline (°C)
Base SCB (as built)	Sandcrete (low mass)	Casement: open 08:00–14:00	25.80	—
Crossover A: ICEB walls + SCB windows	ICEB (high mass)	Casement: open 08:00–14:00	31.86	+6.06
Crossover B: SCB walls + ICEB screen wall	Sandcrete (low mass)	Screen wall: always open	25.72	−0.08
Base ICEB (as built)	ICEB (high mass)	Screen wall: always open	25.41	−0.39

4. Discussion

4.1. Thermal Mass–Ventilation Interaction: Seasonal Contingency

The findings demonstrate that the thermal performance relationship between ICEB and SCB classrooms is contingent on the interaction between wall material, ventilation regime, and seasonal climate. Under wet-season conditions with prevailing south-westerly winds and moderate diurnal swings (4–6 K), ICEB’s high thermal mass ($\mu = 0.31$; $\varphi = 9.1$ h) coupled with adequate cross-ventilation produces the 2.03 °C temperature advantage confirmed by field measurement across six sites. Under dry-season harmattan conditions with near-calm winds, ICEB’s permanent screen-wall ventilation collapses to 0.10 ACH, eliminating nocturnal purging capacity. The marginal 0.16 °C mean dry-season penalty is small relative to the wet-season advantage by a ratio of approximately 1:13.

4.2. Simulation Validity and EPW Boundary Conditions

Relative humidity analysis from supplementary RH-capable loggers (26 July 2024) confirmed that indoor relative humidity closely tracked the outdoor boundary condition (approximately 79%) in both classroom types, with no statistically significant inter-type difference. The thermal comfort advantage observed in ICEB classrooms was therefore primarily attributable to dry-bulb temperature reduction rather than differential moisture buffering.

The systematic underprediction of measured indoor temperatures (SCB: 3.71 °C; ICEB: 1.70 °C) is primarily attributable to TMYx statistical smoothing rather than model error. The TMYx EPW represents the long-term climatic mean, whereas the July 2024 measurement period was anomalously warm due to El Niño forcing. Under typical-year conditions, both simulated systems produce lower indoor temperatures than those measured in July 2024, confirming the simulation’s role as a conservative projection of typical-year behaviour.

The differential underprediction (SCB: 3.71 °C versus ICEB: 1.70 °C) reveals a deeper issue: the Owerri Airport TMYx EPW introduces non-uniform boundary condition uncertainty across construction types. This finding has broader implications for building performance simulation in sub-Saharan Africa. High-thermal-mass simulations require particular attention to nocturnal boundary condition representativeness, and airport EPW files should not be assumed to introduce uniform bias across construction types.

4.3. Design Implications: Controllable Ventilation

The finding identifies controllable ventilation as the critical design variable for year-round performance. ICEB classrooms with operable louvres or closable panels within the screen-wall system would allow restriction of hot air ingress during dry-season occupied hours while enabling nocturnal purging when outdoor temperatures fall sufficiently. This

preserves the wet-season advantage while reducing the dry-season vulnerability. The wet-season field evidence is robust ($n = 6$, $p < 0.01$), whereas the dry-season simulation is directional only and remains subject to EPW boundary condition uncertainty. The AirflowNetwork-derived ACH values underlying this recommendation have not been validated against measured airspeed, ACH, or tracer-gas data; the recommendation is presented as a hypothesis supported by simulation evidence, requiring experimental confirmation before field implementation.

4.4. Adaptive Comfort Evaluation

Evaluating the outputs against the adaptive comfort framework of Munonye and Ji [1], which builds on the adaptive model of de Dear and Brager [23], (neutral temperature 28.1 °C for enclosed classrooms; comfort range 25.8–30.5 °C), the wet-season field-measured ICEB mean temperature (26.4 °C) falls within the 80% acceptability range. The SCB mean (28.5 °C) approaches the upper boundary. Under dry-season conditions, both simulated systems approach or marginally exceed the upper comfort boundary, consistent with the known severity of harmattan conditions in naturally ventilated tropical classrooms.

4.5. Limitations

Several limitations are acknowledged. First, the SCB NMBE marginally exceeds the ASHRAE Guideline $14 \pm 10\%$ threshold due to TMYx boundary condition conservatism; therefore, the simulation should be interpreted as a directional projection rather than a fully validated replica of field conditions. Second, the model was applied at a single site (Awkuzu), and variations in construction quality and microclimate across the six monitored schools are not captured. Third, the 10:00–14:00 analysis window excludes nocturnal conditions, which are the primary driver of ICEB daytime performance. Fourth, the absence of field airspeed measurements prevents AirflowNetwork validation against measured airflow rates; consequently, the mechanistic claim that ventilation is the dominant cooling mechanism (Section 3.5) should be read as consistent with the parametric simulation rather than as independently confirmed by field-measured airflow data. Fifth, the floor construction was modelled as a 150 mm concrete slab with a 25 mm cement/sand screed finish, consistent across both models and with Nigerian public primary school construction standards. Sixth, dry-season field monitoring, site-specific microclimate logging, and multi-site validation remain the highest priorities for future work; the present single-site, single-day wet-season validation constrains the strength of the dry-season and mechanistic conclusions and should be read accordingly.

5. Conclusions

This study applied DesignBuilder/EnergyPlus simulation to evaluate the dynamic thermal behaviour of ICEB and SCB classroom systems in naturally ventilated primary schools in South East Nigeria. The key findings are as follows:

- Wet-season performance: ICEB classrooms demonstrated a clear thermal advantage. Field measurements show a mean temperature reduction of 2.03 °C compared to SCB classrooms. This effect is consistent across six schools and is supported by simulation results, which reproduce both the direction and the underlying physical mechanism.
- Model evaluation: The ICEB simulation meets ASHRAE Guideline 14 validation criteria (NMBE = −6.4%; CV(RMSE) = 6.8%). The SCB model satisfies the CV(RMSE) threshold but marginally exceeds the recommended NMBE limit. This deviation is attributed to conservative TMYx boundary conditions rather than errors in envelope parameterisation. The directional thermal advantage of ICEB is correctly reproduced without post hoc model calibration.

- Dry-season performance: Simulations suggest that continuous screen-wall ventilation reduces nocturnal heat dissipation under near-calm harmattan conditions. As a result, ICEB classrooms show a marginal simulated temperature increase of 0.16 °C compared to SCB classrooms. This effect is small relative to the wet-season benefit and remains uncertain, in both magnitude and direction, due to EPW boundary condition limitations; it has not been validated against dry-season field measurements.
- EPW boundary condition sensitivity: The results indicate that airport-derived TMYx weather files introduce non-uniform uncertainty across construction systems. High-thermal-mass buildings are particularly sensitive to nocturnal boundary conditions, meaning that EPW data can influence simulation outcomes differently for ICEB and SCB systems.
- Design implications: The findings are consistent with controllable ventilation as a beneficial design intervention. Integrating operable louvres or adjustable panels into ICEB screen-wall systems may allow improved seasonal control, preserving the wet-season cooling advantage while reducing dry-season overheating risk. This recommendation follows from parametric simulation evidence and has not been tested experimentally.
- Future work: Further research should prioritise dry-season field monitoring; site-specific microclimate measurement; multi-site validation across the six monitored schools; field-measured airspeed/ACH data to validate AirflowNetwork assumptions; full annual simulation validation; and experimental testing of controllable ventilation retrofits.
- Overall, classroom thermal performance is determined by the interaction between material properties and ventilation strategy rather than material properties alone. These results provide preliminary design guidance for naturally ventilated school buildings in tropical climates, subject to the limitations identified in this study.

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Informed Consent Statement: Informed consent was obtained from parents or guardians of all pupil participants. All participants are anonymised in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available at this time as they form part of an ongoing PhD thesis.

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