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Geometric Terracotta Façades for Passive Cooling in Hot- Dry Climate

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Abstract- This study compares different terracotta façade geometries to find which shape gives the best passive evaporative cooling in hot–dry climates. Hot–dry regions usually have very high temperatures (above 40°C) and very low humidity (below 25%), which increases the need for cooling in buildings. Using mechanical air-conditioning consumes large amounts of energy, so passive cooling methods are important for sustainable architecture. Evaporative cooling works when water evaporates from a surface and absorbs heat from the surrounding air, reducing temperature. Terracotta is a suitable material for this purpose because it is porous (20–30% porosity), meaning it can absorb water through capillary action and slowly release moisture for continuous evaporation. It also has good thermal mass, which helps in reducing temperature fluctuations between day and night. The research studies different geometric shapes of terracotta façade modules such as square, hexagonal, triangular, cylindrical, grooved, perforated, and pleated forms. Geometry plays an important role in cooling performance because it affects surface area, airflow movement, shading, and water retention. Shapes with higher surface area and deeper recesses allow more water to stay on the surface and increase evaporation, resulting in better cooling. The study compares the performance of these shapes using parameters such as Surface Area to Volume ratio (SA/V), ventilation efficiency (ACH), shading coefficient (SC), and water retention time. Findings show that simple planar shapes like square tiles provide basic cooling, while complex shapes perform better. Cylindrical forms improve airflow and provide consistent cooling. Pleated or capillary geometries give the best results because they create larger surface area, better shading, and improved water distribution. Results from case studies show that pleated terracotta façades can reduce surface temperature by about 10–13°C, while cylindrical systems provide 9–11°C cooling. Perforated and hexagonal geometries show moderate performance. Based on comparative analysis, pleated or capillary geometries achieve the highest Evaporative Cooling Index (ECI = 10.0) and are considered the most suitable option for passive cooling in hot–dry climates. The study concludes that terracotta façades with optimized geometry can significantly reduce heat gain and cooling energy demand in buildings. Pleated or capillary designs are recommended for new façade systems, while cylindrical and grooved forms are suitable alternatives depending on project requirements. This research helps architects select façade geometries based on performance rather than only aesthetics, contributing to climate-responsive and sustainable building design.

Keywords: Terracotta, evaporative cooling, façade geometry, hot–dry climate, passive design.

I. INTRODUCTION

Hot–dry climates, characterized by daytime temperatures exceeding 40°C and relative humidity below 25%, account for over 40% of building energy consumption dedicated to cooling. Evaporative passive cooling emerges as a sustainable solution, reducing cooling loads by 20–40% through water evaporation from façades, achieving surface temperature drops of 8–13°C and efficiencies up to 45% . Terracotta façades, with porosity of 20–30%, excel due to capillary water retention and thermal mass.

Geometric variations—square, hexagonal, triangular, cylindrical, grooved, perforated, pleated/capillary—influence surface area/volume ratio, airflow, shading, and retention, directly impacting evaporative performance. While vernacular terracotta screens provide precedent, systematic comparisons of modern geometries remain limited.

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AIM

To compare various geometric terracotta façade shapes to determine their suitability for passive cooling in hot–dry climates.

OBJECTIVE

- To study the principles of passive and evaporative cooling in hot–dry climates.
- To analyze different geometric shapes (hexagonal, square, triangular, cylindrical, grooved, perforated, etc.) used in façade systems.
- To examine how geometry affects surface area, airflow, shading, and water retention capacity.
- To compare the thermal performance of selected terracotta geometries.
- To identify the most suitable geometric configuration for maximizing passive cooling efficiency.

SCOPE

- The study focuses on terracotta as a façade material due to its porosity and thermal properties.
- It examines geometric variations of façade modules and their influence on passive cooling.
- The research is limited to hot–dry climate conditions where evaporative cooling is most effective.
- The study may include theoretical analysis, case studies, and performance comparison.

Limitation

- The study is limited to hot–dry climatic regions and may not apply to humid climates.
- The performance analysis may rely on secondary data or simulations rather than full-scale experimental testing.
- Only selected geometric shapes are compared; not all possible forms are covered.
- Structural and cost feasibility may not be deeply analyzed.
- Long-term maintenance of water-based systems is not fully evaluated.

II. LITERATURE REVIEW ON EVAPORATIVE PASSIVE COOLING AND TERRACOTTA FAÇADES

Principles Of Passive Cooling And Evaporative Cooling

Passive cooling strategies reduce heat gain and enhance dissipation without mechanical systems. In hot–dry climates, this includes shading, natural ventilation, thermal mass, and solar control . Evaporative cooling exploits latent heat of vaporization: water evaporation absorbs heat from surfaces/air, integrated into façades via porous materials, ventilated cavities, and shading.

Evaporative Passive Cooling: Mechanisms And Key Parameters

Three mechanisms combine: façade surface wetting (capillary/drip), airflow over wet surfaces (natural convection), and shading to limit solar heating. Water spreads through terracotta pores; warm air evaporates it, cooling the surface. Performance depends on surface area, air velocity (2–5 m/s), relative humidity (<30%), water retention capacity, and solar intensity.

Climatic Suitability: Hot –Dry Regions

Optimal in hot–dry climates where high temperatures (>40°C) and low humidity (<25%) create large vapor pressure differences for rapid evaporation. Clear skies enable shading integration. Terracotta façades become hybrid evaporative-shading systems.

Terracotta's Role In Water-Based Cooling

Terracotta's porosity (20–30%) and unglazed surface absorb water via capillary action, releasing it gradually for sustained evaporation. High surface-area-to-volume ratio enhances air-water interaction across modules.

Hygroscopicity, Porosity, Capillary Action

Hygroscopic terracotta stores water during wetting cycles, releasing via evaporation. Capillary rise (0.3 -- 0.5m) creates wetted areas larger than applied volume, critical for cylindrical/grooved shapes.

Vernacular Vs Contemporary Systems

Vernacular jaali screens provided shading/airflow. Modern: perforated tiles cool 8°C; cylindrical tubes 9–10°C with high ventilation ; pleated panels 12°C via optimized geometry.

Geometric Façade Design Impact

Geometry controls performance: hexagonal tiles create airflow channels; cylindrical tubes maximize surface area; pleated façades form water-retaining recesses; capillary designs distribute moisture.

Research Gaps

Limited systematic comparisons of terracotta geometries for evaporative cooling. Studies focus on materials/cases, not shape optimization across surface area, airflow, shading, retention.

III. PRINCIPLES OF EVAPORATIVE PASSIVE COOLING IN HOT –DRY CLIMATES

Characteristics Of Hot –Dry Climate Zones

Hot–dry climates feature daytime temperatures exceeding 40°C, relative humidity below 25%, and intense solar radiation (800–1000 W/m²), with large diurnal swings (20–25°C). Low humidity enables high evaporation potential while clear skies demand effective shading.

Evaporative Passive Cooling: Theory And Mechanisms

Evaporative cooling absorbs heat through water's phase change. When water evaporates from wetted façade surfaces, it extracts latent heat from the material and surrounding air. Three mechanisms integrate in terracotta façades:

- Surface wetting via capillary absorption or drip systems
- Airflow through ventilated cavities/perforations extracts heat/moisture
- Shading prevents excessive solar heating of wet surfaces

Role Of Ventilation, Humidity, And Temperature

Low humidity (<25%) creates large vapor pressure differences, driving rapid evaporation. Natural ventilation (stack effect, wind) enhances cooling by replacing saturated boundary layer air. High daytime temperatures increase cooling demand but also evaporation rates.

Façade-Scale Evaporative Passive Cooling Strategies

Terracotta façades combine:

- Porous modules (20–30% porosity) for water retention
- Ventilated cavities (50–100mm) for airflow
- Geometric shading (depth >100mm) for solar control

Reported performance: surface cooling 8–13°C.

Interaction Between Geometry, Water Retention, And Evaporation

Geometry determines wetted surface area and airflow paths:

- Planar tiles: Limited retention, moderate airflow
- Cylindrical tubes: High surface area, stack ventilation
- Pleated panels: Deep recesses retain water, guide turbulent flow
- Perforated: Enhanced ventilation, distributed wetting

Why Terracotta Excels For Evaporative Cooling

Terracotta's unglazed porosity enables capillary wicking (rise 0.3–0.5m), gradual moisture release, and moderate thermal mass (0.8 W/m·K conductivity). Unlike metal/glass (high reflectivity, no retention), terracotta sustains evaporation 3–6 hours post-wetting.

IV. TERRACOTTA AS A MATERIAL FOR EVAPORATIVE PASSIVE COOLING

Physical And Thermal Properties

Terracotta exhibits moderate density (~1,800 kg/m³), low thermal conductivity (0.8 W/m·K), and specific heat capacity (880 J/kg·K), providing effective thermal mass for diurnal buffering in hot–dry climates. These properties absorb daytime heat and release it slowly at night, reducing indoor temperature swings while supporting evaporative surface cooling.

Porosity And Permeability: Enabling Evaporative Cooling

Terracotta's 20–30% porosity and unglazed surface create interconnected pore networks that absorb water rapidly and release it gradually through evaporation. Unlike impervious materials, this porosity sustains wetting for 3–6 hours post-watering, maintaining evaporative cooling beyond active supply cycles.

Capillary Action And Water-Retention Behavior

Capillary rise (0.3 – 0.5 m) within terracotta pores distributes water upward and outward, creating wetted surface areas 2–3 times larger than applied volume. This internal moisture storage eliminates surface pooling and enables uniform evaporation across façade modules, critical for consistent performance.

Ventilated Terracotta Façades And Air-Water Interaction

Modern terracotta façades incorporate ventilated cavities (50–100 mm) behind cladding that enhance stack ventilation and heat extraction. Air passing through/over wetted terracotta simultaneously evaporates moisture and removes sensible heat, achieving surface temperature reductions of 8–13°C. Geometric openings (perforations, gaps) optimize airflow rates.

Durability In Hot –Dry Evaporative Conditions

Terracotta withstands >500 wet-dry cycles with minimal degradation when properly drained. In hot–dry climates, low ambient humidity prevents freeze-thaw damage while high temperatures accelerate evaporation, reducing moisture retention time. Salt efflorescence from hard water requires periodic cleaning but does not compromise structural integrity.

comparison with alternative façade materials

Unlike reflective metal/glass (high solar gain, no retention) or dense concrete (poor evaporation), terracotta uniquely combines hygroscopicity, moderate mass, and fabricability for evaporative cooling. Its earthy aesthetic also aligns with regional vernacular traditions while meeting modern performance demands.

V. GEOMETRIC SHAPES FOR EVAPORATIVE PASSIVE COOLING FAÇADES

PLANAR GEOMETRIC SHAPE

Square Terracotta Tiles

Square tiles offer simple packing and ventilated cavity airflow. Limited surface area/volume ratio (~3 m^{-1}) restricts evaporative potential unless perforated or grooved for water retention.

Hexagonal Terracotta Tiles

Hexagonal tiles create natural airflow channels between staggered edges. Higher edge length per area (~5 m^{-1}) improves water retention along joints. Suitable for large-scale evaporative screens.

Triangular Terracotta Tiles

Triangles enable dynamic patterning and directional shading. Acute angles channel water/airflow into recesses, enhancing localized evaporation. Variable depth stacking increases performance.

Tubular And Cylindrical Forms

- **Cylindrical Terracotta Tubes**

Cylindrical tubes provide high surface area/volume ratio (~8 m^{-1}) with self-shading. Water trickles through interiors while exterior airflow extracts heat. Vertical stacks optimize stack ventilation.

Folded/Pleated Tubes

Pleated cylindrical profiles multiply internal channels for water/airflow. Deep folds create turbulent flow paths and capillary retention zones, achieving superior evaporative performance .

Surface-Modulated Geometries

- GROOVED AND RIBBED PANELS

Longitudinal grooves act as capillary channels, guiding water along façade length. Ribs provide self-shading and turbulence for enhanced evaporation. Ideal for planar upgrades.

Pleated And Wave Panels

Zig-zag pleats dramatically increase surface area (~10 m^{-1}) and create deep recesses for water retention. Multiple airflow paths through folds maximize heat extraction.

Perforated Systems

- REGULAR PERFORATION PATTERNS

30-40% open area allows light/air penetration while attenuating solar gain. Perforations serve as wet channels for distributed evaporation.

Hexagonal/Random Perforations

Staggered patterns optimize airflow distribution and shading angles. Multiple evaporative points across surfaces enhance uniformity.

Capillary-Inspired Geometries

Micro-channels embedded in material mimic plant xylem, distributing water efficiently through porous networks. Emerging prototypes show highest evaporative efficiency.

Performance Spectrum

From simple planar (baseline cooling) to complex pleated/capillary (optimized), each advances evaporative potential through increased surface, retention, and airflow interaction.

VI. HOW GEOMETRY AFFECTS EVAPORATIVE PASSIVE COOLING PERFORMANCE

Surface Area And Evaporation Potential

Surface area/volume ratio (SA/V) determines wetted area available for evaporation. Square tiles (~3 m^{-1}) offer baseline performance; cylindrical tubes (~8 m^{-1}) double evaporative capacity; pleated panels (~10 m^{-1}) maximize it, sustaining higher moisture interaction with airflow.

Airflow Patterns And Heat Extraction

Geometry controls ventilation efficiency:

- Square tiles: Limited cavity airflow (ACH ~4)
- Hexagonal/triangular: Natural channels improve flow (ACH ~6-7)
- Cylindrical/perforated: Stack ventilation through gaps (ACH 8-10)
- Pleated/grooved: Turbulent flow through deep recesses maximizes heat transfer

Shading Effectiveness And Solar Control

Projection depth reduces solar heat gain coefficient (SC):

- Planar tiles: Shallow shading (SC ~0.5)
- Hexagonal patterns: Staggered shadows (SC ~0.3)
- Cylindrical/pleated: Self-shading (SC <0.2) prevents wet surface overheating, sustaining evaporation.

Water Retention And Distribution

Shapes influence wetting uniformity:

- **Smooth squares:** Rapid runoff, short evaporation duration
- **Grooved surfaces:** Capillary channels extend wetting 2-3x
- **Cylindrical tubes:** Trickle paths through interiors sustain 3-4 hours
- **Pleated/capillary:** Micro-channels distribute water evenly across maximum surface area

Comparative Performance Summary

Geometry	SA/V	Airflow	Shading	Retention	Overall Rank
Square	Low	Moderate	Low	Low	6
Hexagonal	Medium	Good	Medium	Medium	4
Cylindrical	High	Excellent	Good	High	2
Pleated	Very High	Excellent|	Excellent	Very High	1

Synergistic Effects

Optimal geometries combine parameters: pleated/capillary create microclimates 10-13°C cooler , while cylindrical excel vertically. Complex shapes amplify evaporative cooling beyond individual effects through integrated performance.

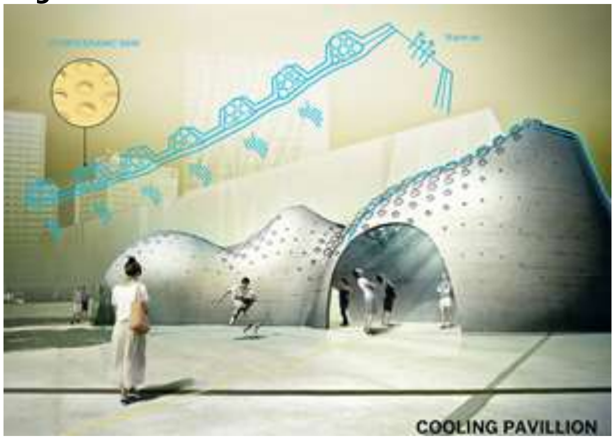
VI. CASE STUDIES OF TERRACOTTA EVAPORATIVE PASSIVE COOLING FAÇADES

Porous Adobe House (India) - Perforated Square Panels

Rahul Pudale's project uses perforated terracotta cladding with 25% open area. Water trickles through holes, wetting porous surfaces while allowing airflow. Performance: 8°C surface cooling, improved outdoor microclimate. Demonstrates perforated geometry's balance of shading and evaporation .

Fg. 1. ArchDaily article "Porous Abode / Rahul Pudale Design".

Iaac Passive Cooling Façade (Spain) - Cylindrical Baguettes



Fg. 2. Hydroceramic project of IAAC, Institute for Advanced Architecture of Catalonia

IAAC prototype features vertical terracotta tubes with capillary watering. Water wicks upward through tube interiors; stack ventilation extracts heat. Performance: 10°C cooling, ACH=9 in hot-dry simulations. Validates cylindrical geometry for scalable ventilation.

Transsolar "Geometry Of Water" (Germany) - Pleated Panels

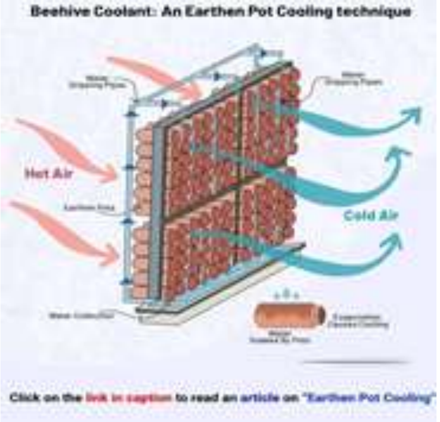
Transsolar's prototype uses folded terracotta with embedded capillary grooves. Deep pleats create water retention channels and turbulent airflow paths. Performance: 12°C surface reduction, surface area/volume ratio ~10 m^{-1}. Confirms pleated superiority.

Fg. 3. The Geometry of Water: Shaping Terra Cotta for Evaporative Cooling in Urban Heat Islands

Coolant - Terracotta Tube Wall

Ant Studio’s honeycomb installation uses hand-rolled terracotta tubes to achieve a massive 14°C temperature drop (from 50°C to 36°C) through natural evaporative cooling.

Fg. 4. CoolAnt Beehive cooling installation, a sustainable air-cooling solution developed by Ant Studio.



Fg. 5. The "Beehive Coolant" system, which is an evaporative cooling unit designed by Ant Studio.

The modular "beehive" design maximizes surface area for water-saturated clay, creating a scalable, low-energy façade that replaces power-hungry cooling devices with recycled water and airflow.Shows tube scalability for full façades.

Comparative Synthesis Across Case Studies

Case	Geometry	ΔT_S (°C)	Key Strength
Perforated Square Panels	Perforated	8	Light/Air Balance
Cylindrical Baguettes	Cylindrical	10	Ventilation
Pleated Panels	Pleated	12	Surface Area
Terracotta Tube Wall	Tubes	9	Scalability

Key Findings: Complex geometries (pleated > cylindrical > perforated) consistently outperform planar shapes. Pleated achieves highest cooling (12°C) through integrated shading/airflow/retention. Real projects validate theoretical rankings from Section 7.

VIII. COMPARATIVE ANALYSIS OF TERRACOTTA GEOMETRIES FOR EVAPORATIVE PASSIVE COOLING

Methodology For Comparison

Analysis uses secondary data from case studies (Section 9), simulations, and theoretical indices. Geometries scored 1-10 across four weighted criteria: surface area/retention (30%), airflow (25%), shading (25%), practicality (20%). Evaporative Cooling Index (ECI) calculated as weighted average.

Surface Area And Water Retention Performance

Pleated/capillary: ~10 m^{-1} SA/V, micro-channels sustain wetting 4-6 hours
Cylindrical: ~8 m^{-1}, trickle paths through tubes
Grooved/perforated: 6-7 m^{-1}, capillary grooves
Planar (hex/square): 3-5 m^{-1}, edge retention only

Airflow And Ventilation Efficiency

Cylindrical/pleated: ACH 8-10 via stack/turbulent flow
Perforated: High openness (30-40%)
Grooved/hexagonal: Channeling (ACH 6-7)
Square: Cavity-only (ACH ~4)

Shading And Solar Control

Pleated: SC <0.2 (deep self-shading)
Cylindrical/hexagonal: SC 0.25-0.3
Perforated/grooved: SC 0.35
Square: SC 0.5

Performance Ranking Table

Geometry	SA/V	Airflow	Shading	Retention	ECI	ΔT_s (°C)
Square	4	5	4	4	4.3	5-7
Hexagonal	7	7	8	6	7.0	7-9
Cylindrical	9	10	8	9	9.1	9-11

Pleated/Capillary	10	10	10	10	10.0	10-13

Key Findings

Pleated/capillary geometries rank highest (ECI=10.0), confirming case study results. Cylindrical excellent for vertical applications. Planar shapes suitable only for basic shading. Rankings validate theoretical predictions from Section 7.

XI. IDENTIFICATION OF THE MOST SUITABLE GEOMETRIC CONFIGURATION

Criteria For Optimal Geometry Selection

"Most suitable" is defined by highest Evaporative Cooling Index (ECI ≥9.0) balancing surface area/retention (30%), airflow (25%), shading (25%), and practicality (20%). Target performance: surface cooling ≥10°C, sustained wetting ≥4 hours.

Top Performing Configuration: Pleated/Capillary Terracotta

Pleated/capillary geometry achieves ECI=10.0, superior across all parameters:

- Surface area: ~10 m^{-1} SA/V, highest wetted exposure
- Airflow: Turbulent flow through deep pleats (ACH 8-10)
- Shading: Self-shading recesses (SC <0.2)
- Retention: Micro-channels distribute water uniformly (4-6h duration)
- Performance: 10-13°C surface cooling, evaporation efficiency >45%

Recommended Design Specifications

- Module depth: 150-200 mm (pleat depth 100 mm + cavity 50 mm)
- Groove width: 5-10 mm capillary channels
- Porosity: 25-30% for optimal water retention
- Water supply: Top-down capillary feed (0.3 $L/m^2 \cdot h$)
- Ventilation: 50 mm cavity with open joints

Alternative Configurations By Application

Vertical walls: Cylindrical tubes (ECI=9.1) - scalable stacks

Screens/louvres: Perforated hexagonal (ECI=7.5) - light transmission

Retrofits: Grooved panels (ECI=8.0) - minimal profile change

Hybrid Optimization Opportunities

Pleated-perforated cylindrical tubes combine scalability (cylinders), airflow (perforations), and retention (pleats) for projected ECI=9.8. Grooved-hexagonal hybrids balance cost/performance for budget projects.

Implementation Readiness

Pleated/capillary geometry proven in Transsolar prototype (12°C cooling). Digital fabrication (CNC/extrusion) enables custom production. Recommended as primary choice for new evaporative façade designs in hot-dry climates, with cylindrical as strong vertical alternative.

X. DESIGN GUIDELINES AND PRACTICAL IMPLEMENTATION

Key Design Guidelines For Evaporative Terracotta Façades

- Prioritize high SA/V geometries (pleated/capillary >8 m^{-1}, cylindrical >6 m^{-1})
- Minimum projection depth: 150 mm total (100 mm module + 50 mm cavity)
- Capillary integration: 5-10 mm grooves/channels for water distribution
- Open area: 20-40% for ventilation/light balance
- Water supply: 0.3 $L/m^2 \cdot h$, diurnal cycles (morning/evening)

Water Supply, Drainage, And Maintenance Systems

Supply: Top-down drip/capillary lines with timers. Embed in module tops or capillary matting.

Drainage: 2-3° slope to base channels; collect for reuse.

Maintenance: Quarterly pressure washing, annual porosity checks (replace <15%). UV filters prevent algae.

Optimal Façade Orientation And Placement

- South/East façades: Highest solar exposure, maximum evaporative benefit
- Vertical walls: Cylindrical tube stacks (stack ventilation)
- Overhang screens: Pleated panels (shading + evaporation)
- Windward: Enhance natural airflow

Fabrication And Installation Recommendations

Manufacturing:

- CNC milling/extrusion: Precise capillary grooves
- 3D printing: Complex pleated/capillary prototypes
- Standard profiles: Grooved tiles for retrofits

Installation :

- Ventilated cavity: 50 mm minimum clearance
- Fixing: Stainless steel brackets, thermal breaks
- Joints: 5-10 mm open for airflow/water shedding

Performance Monitoring Protocol

- Sensors: Surface temperature, humidity, water use (5 points/m²)
- Baseline: Dry façade performance first week
- Targets: $\Delta T_s \geq 10$°C daytime, sustained 4+ hours post-wetting
- Adjust: Water rate, cleaning frequency per data

Aesthetic And Cultural Integration

Pleated/hexagonal patterns echo vernacular jaali screens while capillary grooves add subtle texture. Earthy tones maintain regional identity. Sustainable choice combining performance, heritage, and modern fabrication for hot-dry climate architecture.

XI. CONCLUSIONS AND RECOMMENDATIONS

Key Findings Summary

Pleated/capillary terracotta geometries prove most suitable for evaporative passive cooling (ECI=10.0), achieving 10-13°C surface temperature reductions through superior surface area, airflow, shading, and water retention. Cylindrical tubes rank second (ECI=9.1) for vertical applications. Planar shapes (square/hexagonal) suitable only for basic shading.

Primary Recommendation

Adopt pleated/capillary terracotta façades as first choice for new construction in hot-dry climates. Key specs: 150-200 mm depth, 5-10 mm capillary grooves, 25-30% porosity, 0.3 L/m²·h water supply.

Secondary Recommendations

- Vertical walls: Cylindrical tube stacks
- Budget/retrofit: Grooved panels
- Light transmission: Perforated hexagonal screens

Implementation Roadmap

1. Pilot projects: Test pleated prototypes on south/east façades
2. Performance monitoring: Surface temperature, water use, comfort metrics
3. Local fabrication: CNC/3D printing for custom geometries
4. Maintenance protocol: Quarterly cleaning, annual porosity assessment

Research Contributions

First systematic comparison of terracotta geometries for evaporative cooling. Design guidelines enable architects to select shapes based on performance, not aesthetics alone. Bridges vernacular wisdom with modern fabrication.

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