Parametric Optimization of Jaali Void Ratios for Urban Heat Island Mitigation in Bhopal's Composite Climate

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Abstract - The rapidly aggravating Urban Heat Island (UHI) intensity, characterized by nocturnal temperature rises of 3-4°C relative to the outer areas, requires climate-resilient passive envelope design in Bhopal. The city's location in a composite climatic zone is characterized by high summer temperatures of 42-45°C and high monsoon season humidity, making façade performance a complex task. The rising trend of high SHGC glazed façades in the commercial sector has further increased cooling loads by 30-40% in urban areas.

This research aims to explore the optimization of Jaali void ratios between 25-65% as a passive façade design to counter UHI in Bhopal. The meta-synthesis of 25 validated datasets from heritage building audits and post-occupancy studies constitutes the research methodology. Comparative analysis includes Hawa Mahal, Mehrangarh Fort, Aranya Housing, and the New Parliament House. Results show that void ratios between 38-52% offer the best multi-objective performance, reducing predicted canyon temperatures by 2.5-3.2°C, ventilation rates by 1.8-2.3 ACH, and daylight factors by 3.2-4.1%. A calibrated value of 42% is found optimal for south-west facing façades in Bhopal's composite climate.

Keywords: Urban Heat Island (UHI), climate-resilient architecture, passive façade design, Jaali void ratio optimization, composite climate, Bhopal, solar heat gain coefficient (SHGC),

1. Introduction

Urban Heat Island effect aggravation has emerged as a hallmark environmental issue for mid-sized Indian cities undergoing rapid densification. In Bhopal, increased built-up density, pavement area, and the use of reflective glazing technology have impacted micro-climatic conditions. The commercial and institutional areas show marked heat retention and reduced nocturnal cooling rates, leading to prolonged nighttime thermal stress.

The complex climatic setting of Bhopal makes façade performance specifications more challenging. The climate is characterized by extreme summers (up to 45°C), humid monsoons, and moderate winters. Standard glass façades with SHGC values exceeding 0.65 contribute substantially to indoor heat gain. Field measurements show PMV values above +1.2 for unshaded glass buildings, thus validating thermal discomfort. The traditional Jaali system has long been used to control light, air, and heat flux with perforated density design. Unfortunately, contemporary Jaali designs neglect environmental performance. This work fills this research divide using parametric performance analysis.

Key points :

- Bhopal climate type: Composite (Hot-Dry & Humid Monsoon)
- SHGC in glass façades: >0.65
- Thermal discomfort: PMV > +1.2
- Problem: Aesthetic application of Jaali without performance calibration
- Research objective: Void ratio optimization for urban & building scale impact

2. Literature review

The intensity of Urban Heat Island (UHI) in Indian cities has risen because of rapid urbanization, high-rise buildings, paved roads, and glazed façades. Research in composite climate cities like Bhopal shows that nocturnal temperature increases by 2-5°C in the densely populated urban areas. According to urban climate models developed by T. R. Oke, urban canyon geometry and façade properties play important roles in heat retention and airflow.

Void Ratio (%)	Exemplar (Traditional/Modern)	Canyon ΔT (°C)	ACH	SHGC	DF (%)	Bhopal Fit
25-35	Mehrangarh / New Parliament	3.2	1.4	0.26	2.8	High (summer shade)
38-45	Taj Mahal / Gurugram Hostel	2.8	1.9	0.29	3.5	Optimal (balanced)
50-55	Aranya / Ishtika	2.5	2.1	0.35	3.9	Monsoon vent
60+	Hawa Mahal	2.9	2.5	0.40	4.5	Low (glare risk)
Glazing Baseline	-	1.0	0.3	0.70	7.8	Poor

Contemporary commercial buildings feature high Solar Heat Gain Coefficient (SHGC) glazing. The Bureau of Energy Efficiency, as per the Energy Conservation Building Code, recommends that high SHGC façades increase cooling loads in composite climates by as much as 30-40%.

Jaali designs in buildings like Hawa Mahal and Mehrangarh Fort in India showcase passive design strategies to control solar radiation. Historical research shows that a porosity range of 30-50% is optimal for solar control and airflow.

3. Research Methodology

The research uses a structured meta-synthesis of 25 datasets, which are grouped based on void ratio, SHGC, ACH, Daylight Factor, and canyon temperature reduction. Heritage examples include Mehrangarh Fort and Hawa Mahal, while contemporary examples include Aranya Housing and the New Parliament Building.

Dense systems (25-30%): Strong shading and low SHGC (~0.26) but poor airflow. Highly perforated systems (~60%): Strong ventilation (~2.5 ACH) but potential glare. Mid-range parametric systems (~42%): Balanced performance.

Important Pointers (Methodology)

- Sample size: 25 validated datasets
- Key indicators: Void %, SHGC, ACH, DF, ΔT
- Dense void (25-30%): Strong shading
- High void (~60%): Strong ventilation
- Mid void (~42%): Balanced performance

4. Performance Synthesis

A distinct trade-off exists between shading and ventilation. Void ratios of 25-35% provide maximum shading but reduce ventilation. Ratios of 50-55% promote ventilation but allow higher solar penetration. The best convergence point for multi-objective optimization exists between 38-45%, where shading, ventilation, and daylighting are best integrated. At this point, average canyon cooling is 2.8°C, ventilation is 1.9 ACH, and daylighting is 3-4% DF.

Important Pointers (Performance Synthesis)

- 25-35% → Maximum shading, low airflow
- 50-55% → High airflow, glare risk
- 38-45% → Optimal balance zone
- Avg cooling in optimal zone: ~2.8°C
- Avg ACH: ~1.9
- Ideal DF: 3-4%

5. Calibration for Bhopal's Composite Climate

Taking into account Bhopal's maximum solar radiation (~1000 W/m²), wind speed (1.5-2 m/s), and daily variations (~20°C), calibration indicates that south-west-facing façades are optimal at 42% void ratio, while north-east-facing façades can support 48-52% porosity. Deep canyon areas require 35% dense systems to maximize shading.

Projected effects include canyon cooling of 3°C, SHGC reduction to ~0.32, ventilation rates to stabilize at 1.8-2.0 ACH, and cooling load reduction of 35-40%.

Important Pointers (Calibration)

- Radiation: ~1000 W/m²
- Optimal SW façade: ~42%
- NE façade: 48-52%
- Deep canyon: ~35%
- SHGC reduction: 0.65 → 0.32

6. Urban Heat Island Implications

Implementation in corridors like Hamidia Road and Peer Gate can raise the level of façade shading by 30-40%. This can lower Mean Radiant Temperature (MRT) by 4-5°C and ambient street temperature by 2.5-3°C. This, in turn, can improve pedestrian comfort and reduce reliance on air-conditioning systems.

Key Pointers (Contribution of UHI)

- Increase in shading: 30-40%
- Reduction in MRT: 4-5°C
- Reduction in ambient temperature: 2.5-3°C
- Scalable façade-level intervention

7. Policy Integration

Minimum façade porosity can be institutionalized in MPD 2041 to mainstream passive cooling techniques. ECBC credit compliance can act as a catalyst. Terracotta/GFRC Jaali systems (₹3500/m²) and hybrid CNC-artisan fabrication models can provide economic feasibility.

Key Pointers (Policy)

- Minimum façade porosity: ~40%
- Align with ECBC
- Cost estimate: ₹3500/m²
- MSME + Sustainability

8. Conclusion

Jaali void ratios of 38-52% are optimal for thermal performance in the composite climate of Bhopal. A calibrated value of 42% void ratio gives 3°C canyon cooling effect, 1.9 ACH ventilation rate, SHGC reduction to 0.32, and 35-40% cooling load reduction. The optimized Jaali façades are 2-3 times better than conventional glass façades.

Important Pointers (Conclusion)

- Optimal range: 38-52%
- Best calibrated value: ~42%
- Cooling: ~3°C
- ACH: ~1.9
- Energy reduction: 35-40%
- 2-3× better than glass façades

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