Top floors of low-rise modern residences in Kolkata: preliminary exploration towards a sustainable solution

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Kolkata is a leading metro city in India with a tropical hot and humid climate. Old buildings in the city had climate-responsive architectural design and elements. However, the modern low-rise residential buildings are not provided with proper thermal insulation on roofs and walls, spatial planning and ventilating elements for which inhabitants at the top floors suffer from unbearable indoor environment during summer. Moreover, often rainwater percolates through the roofs after some years. For relief, many inhabitants install air-conditioners in their rooms and repair the roofs recurrently. This raises the demand for energy and contributes to urban heat island effect and unsustainable environment in the city. A research funded by the University Grants Commission, Government of India, was taken up to do fieldwork, survey and documentation of the actual situation along with the literature study for formulating an architectural solution to attain comfortable, energy-efficient and environmentally sustainable indoor condition at the top floors of low-rise residences.

Keywords: Indoor environment, low-rise residences, sustainable solution, top floors.

Introduction

KOLKATA, situated on the east bank of River Hooghly in West Bengal is a linear city that grew since about 260 years. It is the most important city of eastern India. The Kolkata Municipal Corporation (henceforth, KMC) area is comprised of 185 sq. km with 41 wards and has a population of 4,486,679 according to the Census of India 2011 (ref. 1). The scale of urban development in the municipal area as well as in the metropolitan boundary of the city has been huge since the latter half of 1990s till date. A recent survey explored that from April 2005 to March 2013, the KMC sanctioned 29,394 residential buildings for construction in its area and about 95% of these buildings are five storeys or less in height[2]. In the adjoining municipalities like New Town Kolkata Development Authority (NTKDA) at Rajarhat, the floor–area ratio allowed for the proposed buildings is large and subsequently most of them are high-rise buildings.

Kolkata has a tropical hot and humid climate in which maximum temperature in summer (March–May) goes up to 41°C and relative humidity rises up to around 90%. Thus, felt temperature (combining air temperature and relative humidity to determine human-perceived equivalent temperature) remaining very high brings discomfort to people in the city. Annual average rainfall in the city is about 1651 mm and about 80% of that occurs in the monsoon period (early June to September)[3].

Since the later part of the 20th century, architectural design of buildings, especially the block-of-flats, did not consider the climatic factors and comfort condition of the interiors. With the surge in the development of residential buildings during the last two decades, the owners, builders and developers did not provide proper insulation on roofs or walls, for which the inhabitants of the top floors in low-rise (up to four stories) modern residences experience tremendous discomfort in the indoor environments during summer. Heat is transmitted from the roof to the top floor and keeps it hotter than normal. Moreover, there is contribution from urban heat island, dust dome and air pollution in the city. The roofs also become damaged from leakage of rainwater after few monsoons. Some people install air conditioners to get relief from the heat. Installation of air-conditioners and recurring roof repairs increase maintenance cost and energy consumption contributing to pollution and unsustainable environment.

Funded by the University Grants Commission, Government of India, this study was undertaken during 2011–2014 to explore through field surveys and literature analysis the problems in the top floors of low-rise modern residences and to find appropriate solutions with architectural planning and suitable materials and techniques for energy conservation and environmental sustainability.

Research findings

During summer seasons of 2012–2014, about 60 low-rise old and modern residential buildings mostly in various parts of Kolkata and a few in the adjoining Howrah city were surveyed and documented (Table 1) using necessary

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Table 1. Chart showing number and type of buildings surveyed

Type of building	No. of buildings	Age of building (years)	Modern/old	Location
Modern with no roof insulation	20	2–15	Modern	North Howrah, South Kolkata
Modern with screed concrete insulation and IPS flooring on roof	14	4–20	Modern	North Howrah, South Kolkata
Modern with screed concrete insulation and mosaic top finish on roof	6	5–20	Modern	South Kolkata
Modern with brick flat or on edge insulation on roof	2	15–25	Modern	North and South Kolkata
Modern with inverted earthen pot and screed concrete insulation on roof	3	5–10	Modern	North Howrah, East Kolkata
Modern with lime terracing on roof	5	10–35	Modern	North and South Kolkata
Old with lime terracing on roof	10	More than 100	Old	North, East and South Kolkata

Figure 1. Centrally oriented courtyard in an old building.

Figure 2. Louvered timber windows of an old building.

equipment like data logger for recording air temperature and humidity, infrared thermometer for measuring surface temperatures of the roof and corresponding ceiling, anemometer for measuring the quality of airflow in the rooms on the top floors as well as those in the floors below. A study has also been done on materials and methods of construction of old and modern buildings in the city.

The study has revealed that old buildings were constructed in load-bearing wall system with thick brick walls (about 500–550 mm) with lime–sand–surki (brick dust) mortar. These buildings have a courtyard in the centre with running verandah along its periphery (Figure 1); shading systems like verandah, porches and cornices; louvered timber windows (Figure 2), and some internal doors; ventilators, roof treatment with lime terracing (Figure 3); higher room height, i.e. about 3600 mm or more, etc.[4]. Floors were constructed with lime concrete sandwiched between two layers of burnt clay tiles placed on a structural system of timber beams and rafters (Figure 3) and later on iron beams (rolled steel joists) and iron T-rafters. Some buildings have marble finish on the floor. A layer of 100–125 mm thick lime terracing was laid on the roof as insulating material. In some cases, inverted earthen pots were used over the basic roof with a layer of lime terracing all over it to ensure more thermal comfort in the top floor. The indoor environment quality of the top floor of these buildings is acceptable.

The modern technology of construction of low-rise residential buildings includes framed structure with reinforced cement concrete (RCC), thin external brick walls (200–250 mm), steel, aluminium or UPVC framed windows with sheet glass panes, solid core-type flush doors, no ventilator and flat RCC roofs without lime terracing layer (Figure 3) or thermal insulation on top[4]. Because of skyrocketing land price and cost of construction, flats for common people are made of smaller built-up areas and not considering indoor comfort condition. Apartments with two bed rooms, a hall and a kitchen (termed as 2 BHK flats) mostly have floor (covered) area of 550–750 sq. ft and 3 BHK apartments about 850–1050 sq. ft, where the rooms are very small and without any proper scope of cross ventilation. In 17 apartments out of 50 modern buildings surveyed, one bedroom in each apartment had only one window and that too in the leeward side. Average sizes of the bedrooms were 2850 mm × 3000 mm and 3000 mm × 3600 mm. Floor-to-floor height of these buildings was about 2950 mm. A flat oriented in the northwest direction is bad in terms of natural ventilation and heat loss. To maintain privacy in a closely packed neighbourhood as well as to prevent mosquito infestation and burglary, many windows of flats are kept closed, especially at night leading to no provision for natural ventilation. With afternoon temperature reaching about 40°C and the surface temperature of concrete rooftop rising up to about 67°C in summer, the heat gain from roofs and walls by conduction and radiation, no exhaust through ventilators, closing or curtaining of some windows, the ceiling fan blasting hot air from the overheated ceiling – altogether create an intolerable indoor environment at the top floors. Roofs often get damaged after the monsoon season, resulting in leakage of rainwater.

Many buildings constructed about 30–40 years ago with jhama-khoa (brickbats) as coarse aggregate in RCC roof have their roofs damaged because of rainwater leakage and moisture retention by porous jhama-khoa resulting in rusting of reinforcement bars. Chunks of concrete fall down from the ceiling (Figure 4) of such affected roofs posing danger to the inhabitants and requiring immediate repair. Repair work is generally done by laying a layer of 50–63 mm average thick screed concrete with Indian Patent Stone (IPS) or mosaic top finish. To deal with the problem of extreme heat and rainwater penetration in the top floors, people erect a steel-framed shed of colour-coated galvanized iron sheets over the roof for thermal comfort as well as to stop rainwater penetration (Figure 5).

Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation'[5]. The variables that affect heat dissipation from the body producing thermal comfort are: (a) environmental – which includes air temperature, air movement, humidity and radiation; (b) personal – which includes metabolic rate, clothing, state of health and acclimatization; and (c) contributing factors – which include food and drink, body shape, subcutaneous fat, age and gender[6]. Air temperature is considered the dominant environmental factor as it determines convective heat dissipation. Air movement accelerates convection and increases evaporation from the skin resulting in physiological cooling effect[6]. High humidity restricts evaporation from the skin for which, evaporative cooling will be neither effective nor desirable as it would increase the humidity. Low humidity leads to drying out of mucous membranes and the skin resulting discomfort[6]. All the top floors of 50 modern buildings surveyed had higher indoor air temperature and felt temperature than their corresponding bottom floors @ 2–7°C during afternoon (14 : 00–17 : 00) and @ 2–4°C early morning (01 : 00–03 : 00; Tables 2 and 3) and all through the day and night (Figure 6). It is classified that in the Indian condition, a felt temperature above 33°C is hot (above very warm category) and unbearable[7]. During 14 : 00–17 : 00 h in summer, the felt temperature in the top floors is found to be between 39°C and 56.5°C, which is in the very hot to extremely hot category, and during 01 : 00–03 : 00 h it is between 36.5°C and 42.9°C, being in the uncomfortable range.

The felt temperature in floors below the top floor is also uncomfortable but could be managed using fans during summer. Other important findings include:

- At night, indoor temperature in the top floor is found to be more than the outdoor temperature, the difference being about 3–4°C (Figure 7). There is difference in humidity as well.

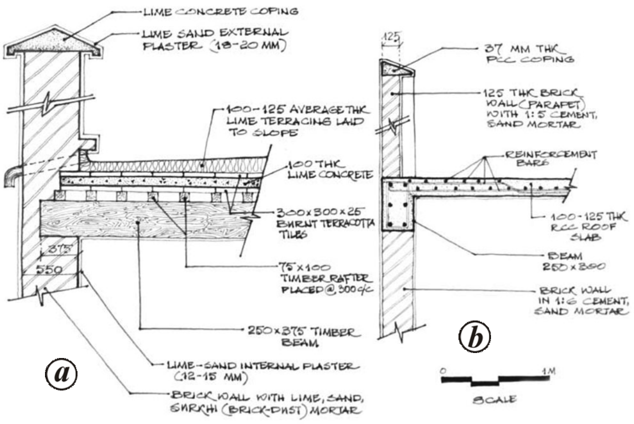

Figure 3. Sections of roofs of old (***a***) and new (***b***) buildings.

Figure 4. Damaged ceiling of a new building due to rainwater leakage.

Figure 5. Low-rise buildings with GI-sheds over the roof.

Table 2. Indoor temperature in the top and bottom floors during 14 : 00–17 : 00 h

House no.	Average temperature (°C) in the top floor	Average RH (%) in the top floor	Average felt temperature (°C) in the top floor	Average temperature (°C) in the bottom floor	Average RH (%) in the bottom floor	Average felt temperature (°C) in the bottom floor
1	36.1	42.5	39.9	33.9	50.2	37.8
2	40.1	40.5	48.5	32.6	51.4	35.5
3	34.9	48.2	39.4	32.9	54.1	36.9
4	36.6	70.5	56.3	34.1	78.7	51.2
5	35.7	72.5	54.0	33.3	80.6	49.0
6	36.8	40.2	40.5	33.6	43.6	35.3
7	34.6	56.4	41.8	31.5	67.3	37.6
8	37.3	45.8	44.1	34.5	53.3	40.3
9	40.9	27.5	43.5	33.4	54.2	38.0

Table 3. Indoor temperature in the top and bottom floors during 01 : 00–03 : 00 h

House no.	Average temperature (°C) in the top floor	Average RH (%) in the top floor	Average felt temperature (°C) in the top floor	Average temperature (°C) in the bottom floor	Average RH (%) in the bottom floor	Average felt temperature (°C) in the bottom floor
1	33.5	61.5	40.9	31.2	55.7	33.8
2	34.4	57.5	41.8	32.9	60.3	38.9
3	33.2	58.2	38.9	31.5	55.2	34.3
4	34.4	56.4	41.3	30.4	54.2	32.0
5	32.5	55.8	36.5	30.1	58.2	32.2
6	33.7	56.5	39.6	31.5	57.2	34.8
7	32.9	60.2	38.9	30.2	62.2	33.2
8	32.2	62.4	37.8	29.9	64.2	33.0
9	34.1	62.2	42.9	33.5	60.4	40.5

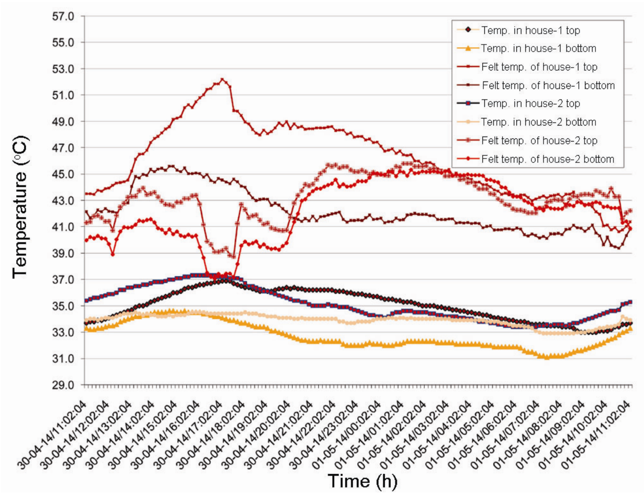

Figure 6. Temperature graph of top and bottom floors of a couple of two-storied houses during April–May 2014.

- A room with better natural cross ventilation is cooler than one with less ventilation in the top floor of the same building (Figure 7).
- The surface temperature of the roof is more than that of the corresponding ceiling during 6 : 30 am to 6 : 30 pm, and less during 6 : 30 pm to 6 : 30 am of the next day (Figure 8).
- The indoor thermal condition in the top floor of a two-storied building with terrazzo mosaic tiles over RCC roof slab and that of a building with RCC roof slab only showed no major difference on the same day and at the same time.
- Thermal condition in the top floor of a three-storied building with lime terracing insulation on the roof and natural cross ventilation in the interior rooms showed better comfort conditions than that of the top floor of a two-storied building with RCC roof and no thermal insulation on top[4] (Figure 9).
- Roof insulation with lime terracing is most effective for thermal insulation; inverted terracotta pots with plain cement concrete (PCC) top finish over RCC roof are quite effective; however, the result is not uniform and satisfactory in all the rooms on the top floor; cement mosaic and screed concrete finish are least effective for thermal insulation but quite effective for rainwater proofing; and only RCC roof is least effective for thermal insulation and rainwater proofing (Figure 10). (Figure 10 demonstrates the temperature graph during April 2014, of the top floors of six buildings with different roof treatments – type A is of a 120-year-old house with traditional lime concrete roof over timber beams and rafters and lime terracing insulation on top; type B is of a 40-year-old house with lime terracing insulation on top of the RCC roof slab; type C is of a new house with inverted terracotta pots with PCC top finish over RCC roof slab; type D is of a new house with cement mosaic finish over RCC roof slab; type E is of a 30-year-old house with screed concrete finish over RCC roof slab; and type F is of a new house without any treatment over RCC roof slab.)

- Windows with glass panes or timber but no louvers, if closed for any reason, do not allow ventilation at all and make the interior uncomfortable.
- External walls of smaller thickness (200 mm) have low thermal mass and add to the heating problem.
- A shed of colour-coated galvanized iron sheets with iron-structure over the roof minimizes the indoor temperature of the rooms of the top floor and stops rainwater penetration.

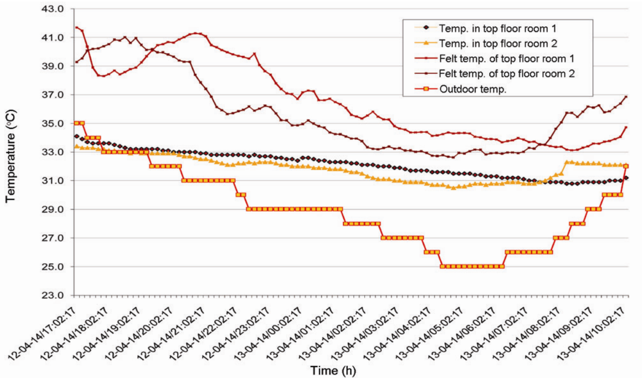

Figure 7. Night-time temperature graph of two rooms on the top floor of a building with 62 mm screed concrete over an RCC roof slab in April 2014; the room with better ventilation shows lower temperatures.

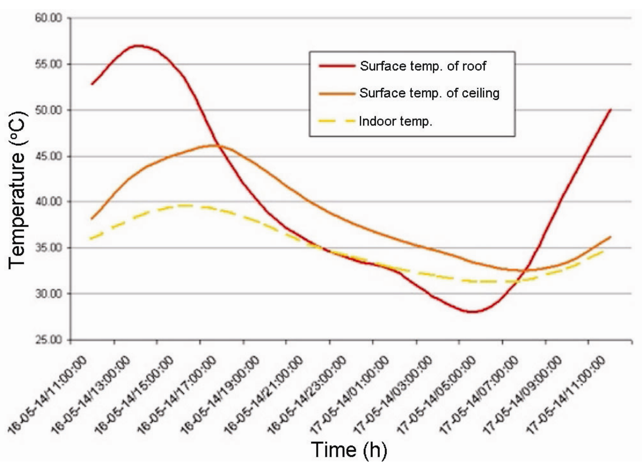

Figure 8. Temperature graph of roof and corresponding ceiling surfaces of top floor of a two-storied residence in May 2014.

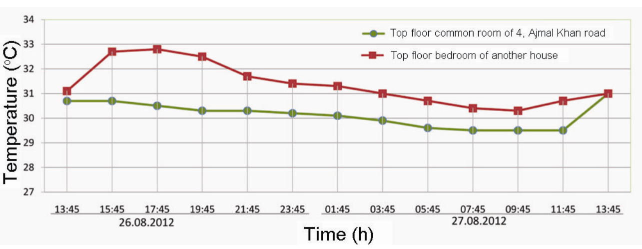

Figure 9. A comparison of temperatures of the top floors of two houses, one with roof insulation and good ventilation in the floor and the other without them; Survey done in 2012.

- Hot air expelled by air-conditioner of one apartment is sucked by the adjacent apartment making cooling load high.
- Top floors of old and traditional residential buildings are more comfortable than those of modern residential buildings.
- Residents in the top floors of modern houses surveyed were ready to accept a cost-effective solution to mitigate this problem.

Proposal for improving the indoor condition at the top floor

We would like to suggest some measures that can be taken up to improve the comfort condition of the top floors of residences. A top floor is essentially surrounded by the building envelope. Many studies have taken place on these elements – recent ones are with the help of simulation tools. EnergyPlus[8] developed by the US Department of Energy simulated following interventions along with detailed weather data and found that if taken care of properly, they give good results[9].

- Ventilation: reflective internal blinds, external window shutters, reflective cooling, window curtains, deep overhangs, ventilation only when outside air is cooler.
- Internal and external wall insulation.
- Roof insulation, cool roof.

Cross ventilation

Cross ventilation takes place when air moves spontaneously across a space from positive pressure zone on the windward side to negative pressure zone on the leeward side. In hot humid climate it brings comfort through evaporative cooling, especially when the air flows in the occupied zone of 2 m from the floor and covers maximum area of the room. A room with only one opening (however big it is) or bigger windward opening to 'catch more air' is ineffective for cross ventilation. On the same principle

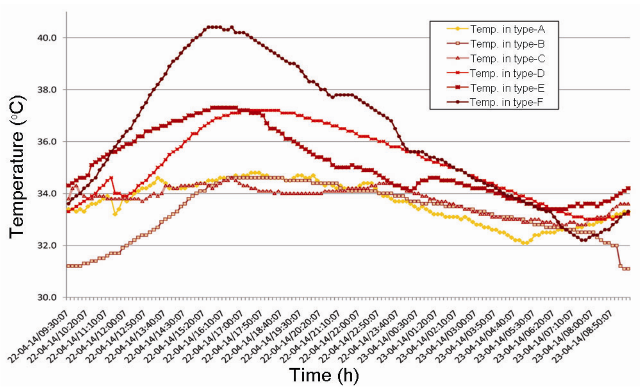

Figure 10. Temperature graph of top floors of six buildings with different roof treatments in April 2014.

of wind pressure, the following thumb rules are developed[10]:

- Openings should accommodate a wide range of wind speed and direction without causing wind drift.
- Widely distributed smaller openings are better than few larger openings in creating better pressure difference and hence better airflow.
- Depth of cross-ventilated space may be reduced to prevent flow of heat, dust and pollution from windward side to leeward side.

To have better air movement in the interior through cross ventilation, the architectural design of residences may consider the following:

1. Check options for installation of windows at windward and leeward sides, both for spontaneous air movement.
2. For some apartments, providing windows on two opposite walls of every room may not be possible to design for constraints, but it is possible to incorporate a ventilating screen/blind above lintel level between rooms and adjoining spaces like corridor, living–dining, study, etc. except the toilet or kitchen to provide movement of air.
3. The room height of the top floor may be proposed to be 3.35 m with ventilators near ceiling level to allow exhaust of hot air and air movement.
4. To have a window always open at the leeward side of the staircase is necessary for possibility of forced airflow in an apartment building.

Fenestration

Fenestration, that is, the arrangement and design of windows in a building enhances or minimizes the extent of air ventilation in a room. In old buildings of Kolkata, timber Venetian doors and windows were used for allowing airflow though retaining privacy (Figure 2). Steel or aluminium-framed glass windows and flush doors of present architectural installation and use limit the scope of airflow. Hence, steel or aluminium encased windows having louvers with semi-transparent, translucent, tinted or reflective glass variety and internal doors with louvered timber panels can be used in rooms which may reduce heat intake without compromising on privacy and airflow[4] (Figure 11).

Wall insulation

A thermal insulating material is that which provides high resistance to heat flow. The objective of providing insulation on the wall is to minimize the solar heat gain through the wall into the interior. The wall design should aim at keeping the decrement factor as low as possible. Insulation on outer surface of the wall is much more effective than its placement on the inner surface. For example, 40 mm glasswool on the outer surface of 100 mm concrete has shown 11.5 h time lag with 0.046 decrement factor, while these values are 3 h and 0.450 for the other case[11]. Insulating materials such as extruded polystyrene (EPS), polyurethane (PUR), etc. are light-weight and their air-filled porous structure leads to low heat conductivity. For 200 mm thick brick wall, 40 mm EPS can be used as external insulation with cement rendering applied directly with wire mesh inserted into it. However, physical damage or moisture absorption reduces the insulating property, and hence special care should be taken to prevent the same.

Insulation on the outer surface of a wall would be the most effective. The following measures could be taken for wall insulation:

1. Construction of an outer wall within 500 mm projection from the building line for beautification of façade is allowed in Kolkata. This is to be taken as an advantage for wall insulation by constructing a double wall as wide as possible on the south and west elevations for cooling as well as beautification[4].
2. A cavity in the wall containing air layer or minimum 25 mm thick polystyrene, or 40 mm thick EPS or PUR would be effective for heat insulation. We suggest that a 250 mm thick brick wall can have an outer leaf of 125 mm and inner leaf of 75 mm thickness (in 1 : 4 cement–sand mortar ratio with wire mesh at every third layer) with 50 mm gap or block of polystyrene in between as insulating material. At every couple-of-layers interval (say @ 750 mm) vertically in the wall, a 250 mm thick brick layer may be placed[4].
3. Reflective insulation by coating the outer wall with reflecting light colour paint can be adopted[12]. Recently, cool colour paints or coatings with solar reflective surfaces with high thermal emissive capacity in white[13] or other shades[14,15] are appreciated for their

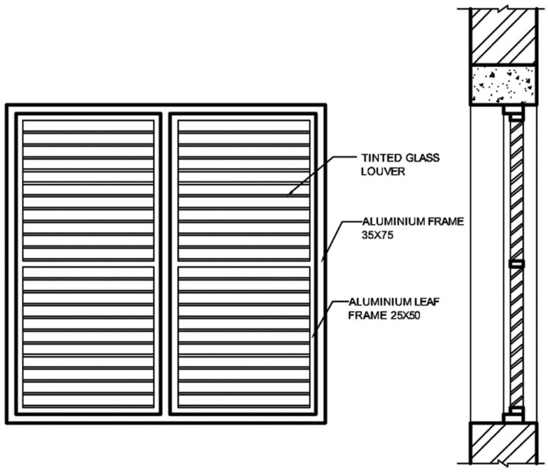

Figure 11. Proposed glass-louvered aluminium window.

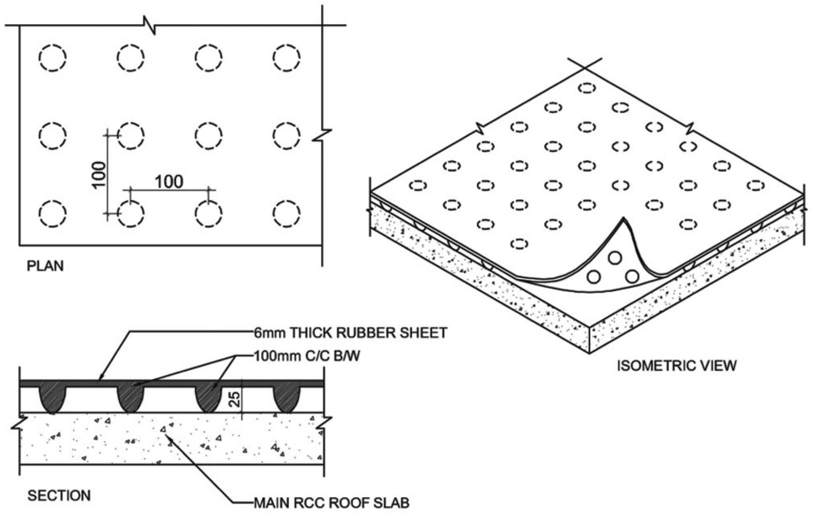

Figure 12. Details of proposed mat for placement over roof for heat insulation.

thermal performance. Doya *et al.*[16] noted reduction of 1.5°C in surface temperature and 2.5°C in indoor air temperature for selective cool brown paints compared to normal paints of the same colour.

4. Vertical greenery acts as an external insulation to the wall. Recently, a new version of vertical greenery, namely green/living wall with pre-vegetated substrates (panels, modules, planted blankets or bags) made of plastic, EPS, synthetic fabric, clay, concrete, etc. fixed on a wall or on a free-standing frame has found vast application in mitigating urban heat island effect. It provides better cooling effect due to the presence of substrate, while green façade has the benefits only from shading effect and evaporation–transpiration from the plant leaves[17]. However, proper fitting of equipment for holding vertical greenery is required as Kolkata suffers from cyclonic storms and heavy rainfall.

Roof insulation

The roof of any building absorbs maximum solar heat and transmits it to the top floor making its interior hotter. Providing thermal insulation on the roof minimizes this extra heat gain. Roof surfaces constitute a large percentage of the total urban surfaces and contribute to urban heat island effect[18] in the city. Reflective insulation cannot be applied on a flat roof due to fast loss of reflective property caused by dust accumulation, especially in Kolkata where 30% of air pollution comes from building industry[19]. The following applications may be considered:

1. Traditional application of lime terracing on the roof for thermal insulation and protection from rainwater penetration should be reintroduced.
2. From the simple example of an umbrella that gives shade and shelter to people from the Sun and rain, we have proposed a mat made of rubber (Neoprene or EPDM) for placement over the RCC roof surface (Figure 12). The mat is 6 mm thick over elliptical props having 25 mm diameter and placed @ 100 mm centre-to-centre both ways. The gap between the bottom surface of the rubber sheet and the roof surface being 25 mm (due to the rubber-prop), there will be air for breathing and shed/shadow on the roof in summer. During rainy season, the mat can be rolled and stored elsewhere, if required. A standard size of the mat can be configured – 1 m × 3 m or so; it can also be cut to other desired sizes for fitting onto the roof of various spans. The cost of the mat to be produced through industrial fabrication would not be high. 'Micro cellular closed cell nitrile rubber' sheet (K-FLEX ST Sheet of Class-O of thickness 10 mm) may also be used as insulating material. This would be inexpensive[4]. However, this application is subject to practical fabrication of such a mat and testing for its structural strength and durability before industrial production and use.
3. The RCC roof may be treated with 62 mm average thick screed concrete layer with damp proof admixture and IPS/cement mosaic finish over RCC roof for protection from rainwater penetration and then the mat be placed on it for thermal insulation.
4. Solar panels can be placed over roofs of expensive buildings thus providing shed/shadow as well as electricity. However, as roofs in the homes of middle and low-income group people are used for household activities, positioning of solar panels on roofs of such buildings would be totally or partially restricted, or they need to be placed over a firm structural network of steel members to make a shed of desirable coverage over roof.
5. Making a watertight layer of concrete over the roof and with processed earth, growth of vegetation is

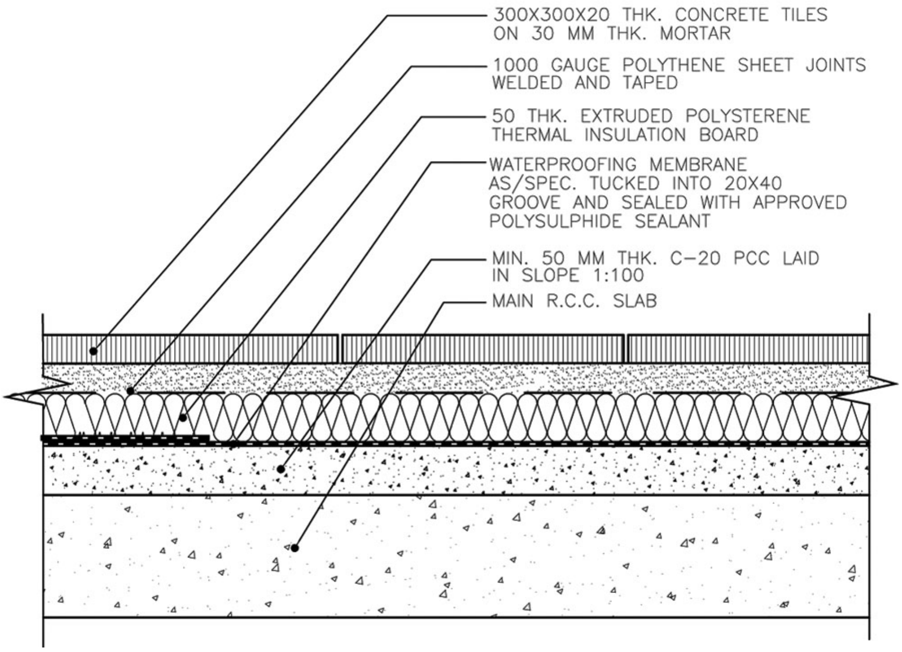

Figure 13. Section of a modern roof showing insulation.

possible, thus providing shed/shadow over roof and producing urban agriculture. Again, this application is costly and needs periodic maintenance.

Conclusion

This study, though conclusive up to establishment of the problem, is to be further extended for examination of the proposed applications for betterment of existing conditions and recording the results of those applications. This would establish a novel approach to architectural design of the top floor with suitable materials and techniques for providing comfortable living conditions to the inhabitants of the top floor and better strength of the roof against rainwater leakage.

There is great need and demand for housing for low and middle income group people in Kolkata. The minimum unit cost of construction of common low-rise residential buildings in Kolkata is Rs 1200/sq. ft of floor area[20]. The present cost of construction of 4″ (100 mm) thick grade RCC roof in Kolkata is about Rs 74/sq. ft according to the latest Delhi Schedule of Rates (DSR) of Central Public Works Department (CPWD), Government of India[21,22], and Rs 93/sq. ft according to the actual socio-political business norms prevailing in the city[20]. Price of one brick in Kolkata is Rs 10 and carrying cost to the site is extra. There is no mention of cost of construction of traditional lime terracing in the DSR 2014 of CPWD. The cost of providing and laying an integral cement-based waterproofing treatment of average thickness 120 mm that includes use of brick bats, cement, sand, water proofing compound, glass fibre cloth and neat cement slurry in a phase-wise and complicated manner prescribed by the CPWD, is Rs 102/sq. ft of the roof area in Kolkata[21,22]. This is about 8.5% of the unit cost of construction of the building (floor area-wise) and more than the cost of construction of the roof slab, and not in use in privately developed modern buildings. A novel roof insulation technique (Figure 13) that combines use of waterproofing compound with polysulphide sealant, 50 mm thick screed concrete, 50 mm thick extruded polystyrene, polythene sheet with adhesive tapes and 20 mm thick concrete tiles costs about Rs 200/sq. ft of floor area[20]. This application has not yet been used in any low-rise residence in Kolkata. Cost of construction of a false ceiling along with expanded polystyrene on the top floor is also high. Installation of air-conditioning units is a solution where architecture with air-circulating fan fails to provide minimum comfort condition in the summer months. Because of high price for application of roof insulation, people often opt for installation of air-conditioners in their top-floor flats.

Any solution for improvement of the indoor environment quality at the top floor of low-rise residences should be cost-effective, that is within acceptable limits of affordability (for example, Rs 50/sq. ft), which may draw inspiration from the traditional methods but technically sound and customized to suit the modern context. The solution should eliminate the need for installation of air-conditioning units, thereby minimizing the demand for energy and emission of chlorofluorocarbons and greenhouse gases in the summer months. Any technical solution is to be embedded into the process of architectural design, construction and operation of housing stock and not as an addendum or option.

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