TITLE: A MULTI-DISCIPLINARY STUDY OF URBAN CLIMATOLOGY AND URBAN PLANNING FOR DENSELY POPULATED CITIES

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Summary

While there are researches concerning environmental properties of buildings such as IAQ, there are limited researches that adopt multidisciplinary approach to urban sustainability, especially with respect to urban climatology through which Urban Heat Island is a topical study of environmental impacts from microclimate on planning in densely populated areas. The threats of diseases such as SARS in densely populated cities suggests that it is mandatory to integrate urban climatologically indicators into urban design of our cities. Such integration will not only help to improve living condition and healthy environment; it can also serve as a means to quantify energy savings and environmental benefits for purpose of planning policies of land resources.

In Hong Kong, nearly 60% of electrical energy use is for space conditioning during summer months. This paper describes findings of an ongoing research project at the University of Hong Kong that investigates the impact of design-related variables on outdoor micro level daytime heat island effect in residential developments that have in turn an impact on the mode and pattern of air conditioning energy consumption. The study hypothesizes that differences in outdoor temperatures within and between residential developments can be explained by the impact of design related variables on the overall environment. Any studies on environmental issues should be stratified to incorporate geographical and seasonal variation. The study covers several high-rise high-density residential areas, including mixed development urban blocks in inner city as well as coastal developments. The findings of the study will lead to specific environmental design guidelines in terms of density, building height, massing, and vegetation. These guidelines would help practitioners to make design decisions at micro-urban and urban scales. The overall impact of any physical development in urban residential areas of Hong Kong and other similar Asian cities can also be analyzed accordingly. These guidelines will help designers to *quantify crucial factors for low energy urban design* at the concept design stage itself and mitigate UHI in the long term for subtropical climate cities.

1. Introduction

The unfortunate incident of SARS disease at Amoy Gardens reveals the importance of health and environmental hygienic conditions of our living environment. The reports by the HKSAR government and WHO suggest that the outbreak of SARS in places like Amoy Garden was a likely to be the result of the spread of contaminated droplets in the Re-entrant, a poorly ventilated area, by stake effect (Figure 1).

Poor ventilation in the living environment is an undesirable factor as far as the spread of SARS and other infectious diseases are concerned. When natural ventilation is poor, the contaminated droplets could be higher in concentration for a longer period of time and thus imposing a higher risk (of spread of SARS and other infectious disease) on occupants.

Urban Heat Island (UHI) effect traps the air and causes poor ventilation in the environment. In addition, UHI is partially responsible for respiratory diseases, cardiovascular problems and highly responsible for heat stress (Chandler, 1976, Oke, 1990/91).

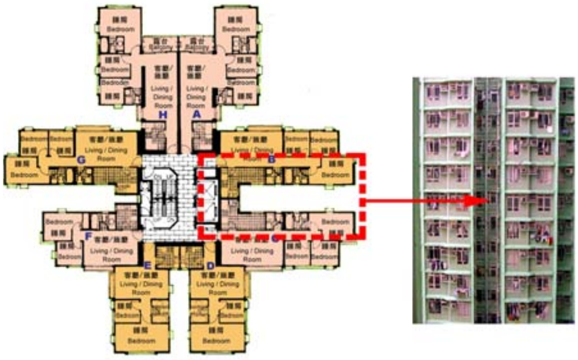


Figure1 *the red rectangular shape represents to an open area prescribed by local building regulations to permit the permeability of daylight and natural ventilation to habitable rooms such as kitchen, bathrooms and bedrooms. Described as a Re-entrant, such spatial arrangement is found to be a potential environment contaminant for the spread of bacteria due to poor ventilation and build-up of heat due to air conditioners.*

Urban residential development locations in Hong Kong can be categorized as inner city, coastal, hill area, and bay and water bound. Among the four categories, coastal area and inner city development are more susceptible to urban heat island effect due to the existing characteristics of the physical development. The study was conducted in four residential developments in coastal areas. The results of this study also contribute to our understanding of how the urban landscape affects our living environments.

The studied residential estates have high canyon geometry ratio of the order of 2 to 3. According to Oke (1987), 70–80% of daytime radiant energy surplus within canyon is dissipated to air through turbulent transfer. The balance 30 to 20% is stored and released in the night. The sky view factor is very low in most of the residential developments in Hong Kong. This is largely due to high-rise and high-density environment (Figure 2a & 2b). In principle, as described by Oke, Givoni and Santamouris, low sky view factor should lower the nocturnal cooling of the environment but increases the daytime shadow effect. But there has been no empirical research done to indicate the real impact of the low sky view factor on the outdoor environments in residential estates in Hong Kong.

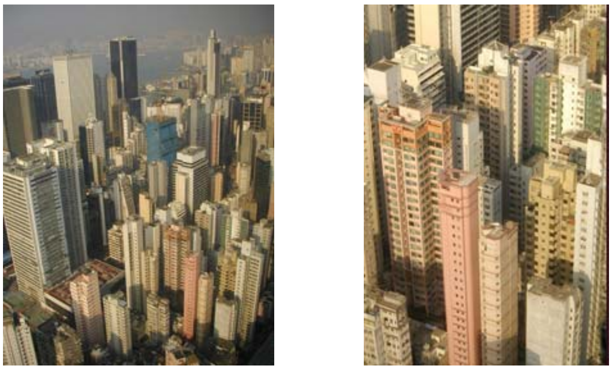


Figure 2a & 2b High-rise and high-density urban fabric of Hong Kong.

Most of the horizontal surfaces in the residential developments have very low surface albedo. This is largely due to a high proportion of concrete or asphalt paving in the open areas. In recent times, this trend is changing. The outdoor surface is generally paved with cement bricks or tiles. Both cement bricks and tiles have relatively higher albedo than concrete surfaces and asphalt. The level of vegetation in most of the inner urban residential estates is very poor. Even when vegetation is present, it is generally of 1m height and less denser. According to Oke, if the vegetation is less than 1m in height, the albedo lies between 0.18 and 0.25. This will have negligible contribution on overall albedo level. Some of the urban residential estates do not have enough vegetation within its premises but there may be enough vegetation in close proximity. The Wah Fu Housing Estates, both Phase I and II, are good examples (Figs. 4a and 5a). The thermal performance of a residential development in an inner city, as described by L. Aye et al. and Golany, is usually affected by land area, massing and surrounding buildings. Most of the residential developments in Hong Kong Island and Kowloon Peninsula fall under the inner city category. The compact urban form might be contributing to a lower thermal performance in Hong Kong. There has been only limited research interest in this field in Hong Kong; therefore there are no firm design guidelines for the creation of an energy efficient sustainable environment. On the other hand, there is adequate research on the relationship between energy consumption of individual buildings and natural forces internationally, but very little research on urban scale thermal performance and energy consumption phenomena, as observed by Golany (1996).

The HKU study investigates the impact of design-related variables on outdoor micro level daytime heat island effect in residential developments in Hong Kong in order to understand the design implications. The paper hypothesizes that a significant part of the differences in outdoor temperatures within and between residential developments can be explained by the impact of design-related variables on the overall residential environment. The initial investigations are carried out on four large estates in Hong Kong, i.e. Belchers, Wah Fu I and Wah Fu II. The Belchers is a new generation development while Wah Fu I and Wah Fu II belong to the first generation high-rise high-density developments of the 1960s. A detailed analysis of the Belchers is presented, as this scheme is more illustrative of the impact of urban design on outdoor thermal conditions.

2. Hypothesis

The environmental factors affecting environmental hygiene are air pollution, water quality, waste disposal, and heat stress. The main source for heat stress in urban areas is described by Urban Heat Island intensity. Heat stress affects the immunity system of a person and makes a person vulnerable for infectious disease like SARS. In addition, high UHI intensity in an environment will increase the need for air conditioning of indoor spaces, which normally re-circulate the trapped air. Therefore lowering of UHI will increase the human adaptability to environment and reduce the dependence on high degree of air conditioned space. In addition to air pollution, UHI also has very high degree of influence on the nature of urban water quality and waste disposal (Chandler, 1976; Oke, 1987; Givoni, 1998).

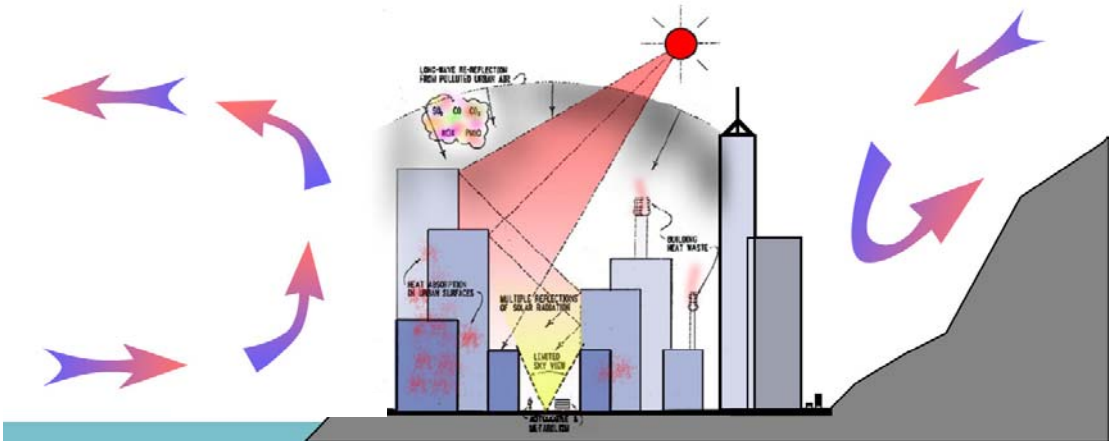


Figure 3 Conceptual characters of Hong Kong's urban geometry and heat generating process in high-rise high density environment. (Modified after Emmanuel, 1997)

According to Oke (1987), in tropical climates, roofs become more important than topography for considerations of thermal capacity. Hong Kong has a subtropical climate which makes the roofs just as important as the topography. Unlike most tropical cities, Hong Kong has considerable differences in topography within the city and this could have significant influence in the UHI. In Hong Kong, environmental consideration for roof design is negligible. Most of the roofs are hard built and flat and usually have a very low albedo level of around 0.1.

3.0 Pilot Study

3.1 Selection of variables

Changes in the quality of façade material, non-residential to total floor area ratio in the development, average non-residential to total floor area ratio of the building fabric, plot ratio and location quotient are negligible between estates and the variables are constant within each estates. Therefore, implications of these variables are discussed without incorporating them into the model.

Other changes in design variables will lead to changes in thermal, moisture and aerodynamic characteristic (Oke 1987, Givoni, Golany). The study will analyze the impact of urban design variables on summer time urban heat island intensity in high-rise high density residential developments of inner city and coastal Hong Kong.

3.1.1 Dependant Variables

The dependent variable (UHI) for multiple regression analysis is the temperature difference between a station point in the estate and Wong Chuk Hang (south of Hong Kong Island) observatory (HKO) at the particular time.

3.1.2 Independent Variables

Considering Hong Kong's geography, topology and built forms, the following independent variables are included in the multiple regression models: *Glass to surface area, total height to floor area ratio, surface albedo, local green area, width to height ratio, proximity to heat sink, sky view factor, surrounding built area ratio, altitude of the site, wind velocity and solar radiation.*

The independent variables chosen are likely to explain the variations in the dependent variable, the UHI, and can be further manipulated by designers at the concept design stage of high-density developments.

3.2 Measurement Protocol

In each of the three estates chosen for case study, two-fixed stations were placed. The two points were located such as to represent fairly the differences in layout of the development, thermal properties and vegetation cover. Each fixed point had a HOBO micro logger inside a mini weather station (Figure 4a & 4b). The micro loggers were at a height of approximately 1.5m above the ground. In addition, mobile measurements were executed on six to twelve points using an anemometer. The fixed point is also one of the mobile points. The mobile measurements were executed at 2m above ground.

Figure 4a Mini weather station at Belchers

Figure 4b Mini weather station at Wah Fu I

The micro loggers measured air temperature, relative humidity and absolute humidity. The anemometer measured air temperature and wind velocity. Due to restrictions by the housing estate management, the data collection period was limited to 13:00 hrs to 20:00 hrs. Once every hour measurements were conducted at all points. Generally all the points in an estate were covered within thirty minutes. Data between 15:00 and 18:00 were used for analysis of daytime UHI as the highest temperatures recorded during these hours. The nocturnal UHI research work done by Kolev et al indicate that the air temperature data between 18:30 hrs and 21:00 hrs is fairly reliable for studying the impact of urban design variables on nocturnal UHI. The current study uses data collected between 18:00 hrs to 20:00 hrs of three days for analysis of nocturnal UHI due to field measurement restrictions as mentioned above. Temperature measurements over three days were taken for analysis. Oke too had used temperature measurements over three days to analyze the influence canyon geometry on temperature differences.

The data for most of the independent variables were collected from developer's briefs, electronic maps and land use documents from the Planning Department of Hong Kong SAR. The sky view factor (SVF) is calculated based on a graphical method suggested by Watson and Johnson. The calculated sky view factor value is further reduced by 0.08 to 0.1 depending on the location and allowing for obstructions *such as mountains and other buildings* from the immediate surroundings. The albedo levels for the surfaces are based on the research work of Oke, Santamouris, Fathy, Sailor and Taha. The local green area ratio is calculated for the area lying within approximately 30 m radius from the point of measurement (1000 m^2). For each measurement point, the mean value of glass to surface area ratio (GS), total height to floor area ratio (HA) and sky view factor (SVF) of all four sides of the station points were considered in the analysis.

4.0 Observations

Three estates, Wah Fu I, Wah Fu II and Belchers were studied during July to September of 2002. All three estates are situated in the South of Hong Kong Island and are subjected to quite similar geographical conditions such as topography, proximity to sea etc. (Table 1) Wah Fu I and Wah Fu II are public housing estates completed in 1960. Belcher is a private development completed in 2001. Table 2 presents a summary of the field observations collected.

The atmosphere during the study period was fairly *stable* in the night especially with lower wind velocity and clear skies. In general the summer climatic conditions during 2002 especially temperature, cloud cover and humidity, were not normal as per Hong Kong Observatory report. The August and September mean daily global solar radiation levels were less by 10% and 21% respectively.

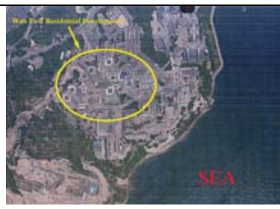
Description	Belchers	Wah Fu-1	Wah Fu-2
Location			
Layout Plan			
Temperature range	28.3 deg C to 30.5 deg C	28.3 deg C and 30.8 deg C	29.1 deg C and 30.8 deg C
Humidity range	69% to 83%	56% to 76%	89% to 68%
Wind velocity range	0.25 m/s to 4.25 m/s	0.0 to 1.05 m/s	0.02 m/s to 2.0 m/s

Table 1 Summery of field observations

5.0 Results and Discussions

The *first part* of the discussion deals with results of UHI within and between the chosen estates. The *second part* of the discussion will cover all the regression models that deal with influence of design variables on UHI and design implications arising from the regression analysis.

5.1 Part 1: Differences in UHI

Daytime mean UHI at Belchers, Wah Fu-1 and Wah Fu2 to be of the order of 0.23 deg C, 1.18 deg C and 1.13 deg C respectively. The highest difference within the estate was found in Belchers. On any given day, Wah Fu II is warmer during daytime and it has a mean UHI of 1.319 deg C during the study period.

The difference between maximum and minimum nocturnal UHI within Belchers, Wah Fu I and Wah Fu II are 1.38 deg C, 0.20 deg C and 0.32 deg C respectively. But the mean UHI in Belchers, Wah Fu-1 and Wah Fu-2 are 0.09 deg C, 0.5 deg C and 0.24 deg C respectively. At Belchers, except for the Station ST1 UHI (1.33 deg C), which is closer to Pokfulam Road, the UHI at other stations are in the region of -0.01 deg C to 0.25 deg C. Generally, most of Belcher's areas are cooler (Table 4) than the observatory in the night. This condition is analyzed below. This pattern of nocturnal UHI within Belchers makes the environment pleasant to live in.

The nocturnal mean UHI is less than the daytime mean UHI by 150%, 136% and 370 % respectively. Therefore the heat stress is high in daytime compared to night. Nighttime UHI in residential estates in inland areas like Wan Chai and Kowloon could be of higher order due to higher residential densities. In the case study areas, even with low nocturnal UHI, the night is more uncomfortable compared to daytime due to higher relative humidity (in the order of 30% to 40% more compared to the daytime). Since occupancy level and usage of air conditioning is high in the residential developments during night times, mitigating nocturnal

UHI is of great importance. In all three estates the mean UHI shows good correlation to population density but the sample is too small to establish a correlation coefficient.

In general, during both day and night of the summer months, Wah Fu I and Wah Fu II outdoor environments were observed to be uncomfortable despite being close to the sea which normally functions as a heat sink.

5.2 Part 2: Multiple regression analysis

The multiple regression analysis was carried out in two stages. The dependent variable was UHI in both stages of the analysis.

5.2.1 Description of stage 1 analysis

The multiple regression analysis in Stage 1 was carried out on ten independent variables using sets of four variables each time, in order to establish the most influential variables. The plot ratio was excluded from the statistical analyses since it is the same within the estate. The (Stage 1) analysis was based on six, eight and twelve sets of data for Wah Fu I, Wah Fu II and Belchers respectively. The same regression model consisting of four variables was initially employed for each estate individually, and thereafter for data from all three estates combined. The latter is hereinafter referred to as the *combined model* (Table 2). The most important variables are surface albedo, sky view factor, height to total floor area ratio and altitude.

5.2.2 Description of stage 2 analysis

In Stage 2, a regression model involving eight independent variables was developed for Belchers since it has substantial variation in design variables between station locations compared to other two estates (Table 3). Thereafter, the regression analysis was extended to a combine model incorporating ten independent variables (Table 3).

5.2.3 Stage 1 analysis

The explanatory powers of variables for all estates are significant (Table 2). The models of Wah Fu I and Wah Fu II are fairly weak due to lack of variation in data leading to low F statistics. This is largely due to the insignificant influence of height to floor area ratio and altitude on UHI of Wah Fu I; in the case of Wah Fu II, the sky view factor and surface albedo are revealed as less important. The model combing all three sites and incorporating four variables at a time emerges as significant and it has a R^2 value of 0.8. The significant variations in the design variables within Belchers compared to Wah Fu I and Wah Fu II have influenced the combined model. The nocturnal four variable combined models have better explanatory power (0.8) than the daytime four variable combined models (0.4). Because of the absence of direct solar radiation in the night, urban geometry accounts for the changes in nocturnal UHI than daytime UHI.

In Belchers and Wah Fu I, there are significant variations in the ground coverage. In Belchers, the ceramic tile paved surfaces are mixed with artificial water bodies and greenery. This provides a higher albedo value. In Wah Fu I, the concrete surfaces are dispersed with natural rock and greenery. Therefore the negative signs of the surface albedo coefficient for Belchers and Wah Fu I are in line with theory. The entire land surface of Wah Fu II is paved with concrete and asphalt. The positive sign of surface albedo coefficient of Wah Fu II is due to this lack of variation in surface albedo.

The coefficient of sky view factor should show a negative sign with respect to nocturnal UHI. However, the sky view factor in all three estates shows a positive sign. The numerical values are closer to zero and thus potentially demonstrate a tendency towards negative values when compared to daytime. Similar phenomena could be found with height floor area ratio coefficient in the case of Wah Fu I and altitude coefficient in the case of both Wah Fu I and II. In Wah Fu I, the closed layout with tall blocks at the outside boundaries deflects the incoming winds and the internal blocks have no wind blowing to cool the thermal mass. Increase in height and intensity of buildings will increase the nocturnal UHI in closed layouts, even if they have opportunities to experience mountain wind and sea breeze. In Wah Fu II, as the entire open area is covered with concrete (old) and asphalt, they radiate heat in the night and contribute to increasing nocturnal UHI. The influence of the albedo of concrete and asphalt on UHI in Wah Fu-2 is insignificant due to lack of variation in heat radiated in the entire open area. In general increase in surface albedo and altitude by 1% will decrease UHI by 0.8% and 0.002% respectively.

5.2.4 Stage 2 analysis

The four variables model of Belchers has already demonstrated significant differences in thermal properties in Stage 1. In Stage 2, four additional variables - glass to surface area, local green area, proximity to heat sink and wind velocity- were included in the Belchers model. All together eight variables were included (Table 3). The explanatory power R^2 has increased from 0.74 to 0.91, an increase of 22%. The explanatory powers of the independent variables for day and night time analyses are almost the same (Tables 2&3). The *sign* of the coefficients of *surface albedo, sky view facto, height to floor area ratio and altitude* in the four variable models (Stage 1) and eight variable models (Stage 2) remain same (Tables 2&3). The numerical coefficients too remain almost the same.

In Belchers, increase in glass area (glass to surface area ratio) will reduce the nocturnal UHI since glass will help to transmit outdoor heat into relatively cooler thermal mass due to good cross ventilation (wind speed of 1.6 to 2 m/s) and usage of air-conditioning. Similarly being closer to a heat sink (sea) tends to reduce the UHI in Belchers but an increase in green area will increase the nocturnal UHI due to blocking of long waves and transpiration. But the effect of increase in green area on nocturnal UHI is really insignificant. Belchers is closer to a heat sink (sea) and this generally increased the daytime UHI and reduced nocturnal UHI. However, those parts of the Belchers closer to the sea were obstructed from receiving sea breeze at all times, and this contributed to a higher UHI during day and night. The opposite locations within Belchers were free to receive mountain winds (land breeze), and therefore recorded a lower nocturnal UHI.

In ten variables combine model, an increase in albedo level, height to floor area ratio, glass to surface area ratio and proximity to heat sink by 1% will lead to decrease in nocturnal UHI by 1.3%, 8.7%, 2.2%, and 4.3% respectively. Increase in local green area by 1% will increase nocturnal UHI by 0.15%. The influence of the sky view factor is not correctly revealed by the model due to limited period of measurement as discussed in Stage 1. The influences of proximity to heat sink and local green area are marginal. Therefore, design variables such as surface albedo, height to floor area ratio and glass to surface area ratio have significant influence on nocturnal UHI level of Belchers, Wah Fu I and Wah Fu II. By manipulating the above mentioned three design variables, the nocturnal UHI in all three estates could be mitigated significantly.

Theoretically, sky view factor and altitude have significant influence on nocturnal UHI, but the ten variables model (stage 2) was unable to capture the influence due to small set of data (Table 3). For all practical reasons these variables should be considered in the formulation of design guidelines. Further, the climatological parameters change directions of influence regularly in an environment, i.e. increase in sky view factor increases daytime heat island intensity but decreases nocturnal heat island intensity. Therefore vector characteristics of urban design variables are important in formulating design guidelines.

The late evening solar radiation shows an abnormal influence (negative) on UHI (Table 3). It is noted that the solar radiation measured at Hong Kong Observatory is used in the regression equation. Ideally the models should use solar radiation measured on the sites. This could explain largely the differences between the measured and predicted UHI. Therefore, the regression model developed in this study should be refined further.

6.0 CONCLUSIONS

Ideally urban design guidelines developed from a study of this nature should be applicable throughout the Territory of Hong Kong, and during all seasons and all times of the day and night. The geographical location and seasonal variations have an impact on UHI measurements (Oke 1990-91, Chandler 1976). It is practically impossible to study the entire geography of Hong Kong throughout the entire calendar year. As a result, there is a need to control the seasonal and geographical variables as much as possible in different phase of a long term study in order to understand the influence of variables related to physical design and then develop design guidelines. This study reports the result from such phase. The control over geographical variations is done by focusing on coastal area residential estates. The control over seasonal variations is achieved by focusing on summer. Further, by looking at day and night separately, research shows which variables influence both day and night.

The explanatory power of the nocturnal four variables model is 76% more than corresponding daytime model. Therefore the above-mentioned four variables (sky view factor, surface albedo, height to floor area ratio and altitude) explain the nocturnal UHI better than daytime UHI. The sign of coefficient of surface albedo and sky view factor is same in both the four variables combined model (Stage 1) and the ten variables combined model (Stage 2). But height to floor area ratio and altitude coefficient signs have changed but the magnitude of the shift is marginal and it could be attributed to the small number of observations.

Although the nocturnal UHI intensity is low relative to daytime UHI, thermal distress is high in night especially in Wah Fu I and Wah Fu II. Proximity to heat sink has insignificant influence on nocturnal UHI compared to daytime UHI. However, changes in surface albedo, height to floor area ratio, sky view factor and altitude have better possibility in mitigating nocturnal UHI than daytime UHI. Nocturnal UHI is largely due to daytime heat storage. Therefore designers should focus on design variables that mitigate daytime UHI and do necessary modifications to enhance nighttime ventilation. Substantial variation in the ground surface albedo of Belchers has enhanced the ventilation level and created a pleasant outdoor environment. Therefore designers should maximize the variation in albedo level within the environment. This study did not cover the benefits of changes in the vertical surface characteristics of buildings. It is clearly logical that designers should seek to maximize the albedo level of these surfaces as well. The influence of some of the variables is not correctly represented in the above study, especially sky view factor. This problem could be avoided if the measurements are done for a longer period of, say, 18 to 22 hours.

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