ISSN : 0974 - 7435 Volume 10 Issue 7

2014

BioTechnology
An Indian Journal

FULL PAPER
BTAIJ, 10(7), 2014 [1837-1845]

Heat island intensity and distribution pattern in Xiamen, China and a field trial study on urban heat island mitigation based on low impact development strategies

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ABSTRACT

Remote-sensing satellite imagery interpretation was conducted to explore the thermal ground field distribution and the Urban Heat Island (UHI) intensity in Xiamen, China. Field trials and effective measures were explored to mitigate UHI effect. Jimenez single-band algorithm was used to inverse surface temperature of Xiamen based on TM+6. Data reveal surface temperature distribution reflecting characteristic distribution in constructed areas. Fixed-point field trials to mitigate the UHI effect were implemented and the sustainable development measures were first put forward based on Low Impact Development (LID) strategies. Results show that permeable pavement and lawn ground can help cool the surface temperature. Ecological roof, especially shrubs-planted roof, significantly decreases temperature, compared to areas with the traditional flat roof. These findings could be used as a reference for Urban Heat Island mitigation strategies.

KEYWORDS

Urban heat island (UHI); Surface temperature; Permeable pavement; Ecological roof; Granite road.

INTRODUCTION

Urban Heat Island (UHI) effect refers to a city's air temperature being significantly higher than that of surrounding suburbs. In the near-ground temperature chart, the urban area is a high temperature zone, compared with the low temperature of the suburbs, just like the surface of islands. This phenomenon is called UHI. Since Lake Howard discovered this phenomenon for the first time at the beginning of the 19th century[1], while studying climate characteristics of London, UHI effect has received extensive attention from many scholars and experts. Many cities worldwide have been carrying out this research[2,3,4,5,6]. With the acceleration of urbanization in China, the UHI effect has become more and more obvious. This phenomenon has become one of the eight major environmental problems that influence urban sustainable development[7].

UHI effect has direct or indirect multiple impacts on city climate and its ecological environment. Such effect may have caused certain adverse effect upon the lives and health of the city dwellers[5]. UHI effect causes less humidity to occur in urban areas comparing to the suburbs, whereas rainfall and heavy rain occurs more frequently in the urban areas. UHI effect can cause heat island circulation which exacerbates pollution. The heat island circulation affects the city wind field, and prevents the low altitude of pollutants from spreading into the higher space, thus making the air pollution of the near-surface layer more serious and less visible in urban areas.

Xiamen City, (118°04'04" E longitude, and 24°26'46 N latitude), is located in the estuary of Jiulong River, southeast Fujian Province, China, near the Taiwan Strait. Xiamen consists of six districts: Siming, Huli, Jimei, Haicang, Tong’an and Xiang'an, and covers a land area of over 1565 square kilometers, which is an international seaport and a scenic city (Figure 1). Since the reform and opening up in the 1980s, rapid economic development has accelerated the pace of urbanization of Xiamen. Due to high density of human population coupled with the rapid increase of urban impervious areas, the average annual temperature of Xiamen urban area is increasing, especially for extreme maximum temperature which rose rapidly, from 35.1 °C in 1989 up to 39.2 °C in 2008, an increase of 4.1 °C. These data shows how the UHI effect has intensified considerably in Xiamen.

To monitor the UHI effect, the main research methods used were meteorological observations, remote sensing, and fixed-point observations, etc. Each method has its advantages and disadvantages. Therefore, this paper used remote sensing and fixed-point observation to study the UHI effect in Xiamen by combining their virtues.

Firstly, the present study analyzed the UHI intensity and its distribution pattern in Xiamen using remote-sensing method. Secondly, Fixed-point field trial observation study to mitigate the UHI effect was implemented and the sustainable development measures such as permeable pavements, small green landscapes, and ecological roofs were first put forward based on Low Impact Development (LID) strategies[8].

Figure 1 : Administrative map of Xiamen

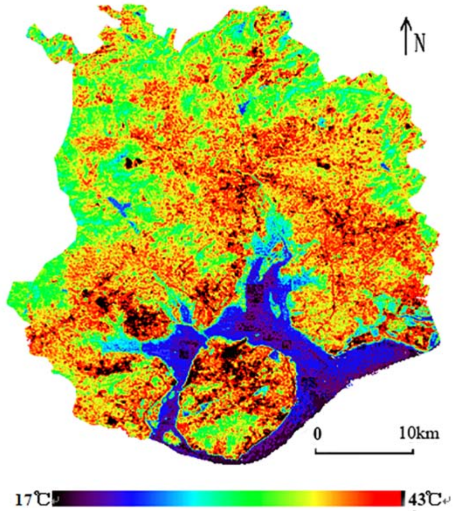

Figure 2 : T_{jim} surface temperature distribution in the various districts of Xiamen

RESEARCH CONTENTS AND METHODS

Field inversion of urban land surface temperature distribution

Jimenez single-band algorithm[9] was used to inverse land surface temperature instead of traditional brightness temperature of Xiamen based on TM+6, remote-sensing satellite imagery interpretation on August 17, 2006. The calculation formula is as follows.

$$\mathbf{T_{Jim} = \gamma[\varepsilon^{-1}(\varphi_1 L_{sensor} + \varphi_2) + \varphi_3] + \delta} \qquad \textbf{(1)}$$

Among them,

$$\gamma = \{\frac{c_2 L_{sensor}}{T^2{}_{sensor}}[\frac{\lambda^4}{c_1} L_{sensor} + \lambda^{-1}]\}^{-1} \text{ , } \delta = -\gamma L_{sensor} + T_{sensor}$$

While, c_1=1.19104×108 W• μ m^4•m^{-2}•sr^{-1}; c_2=1.43877×104 μm.

L_{sensor}、 T_{sensor} are radiation brightness and brightness temperature received by sensors.

ε , is surface emissivity; λ , is the effective wavelength for TM+6.

φ_1, φ_2 and φ_3 are the function of the whole layer of atmospheric water vapor content (w), which can be calculated according to the following formula:

$$\varphi_1 = 0.14714w^2 - 0.15583w + 1.1234$$

$$\varphi_2 = -1.1836w^2 - 0.37607w - 0.52894$$

$$\varphi_3 = -0.04554w^2 + 1.8719w - 0.39071$$

W, is atmospheric total water vapor content.

Calculation of UHI effect intensity

The surface temperature value discretion merely could not express UHI intensity, usually illustrated by comparing the temperature differential between high-temperature of urban city and low-temperature of suburban areas. Therefore, the present study designed a comprehensive calculation formula of UHI intensity effect considering the temperature difference and temperature range. The flowing Xiamen UHI intensity effect for August 17, 2006, was quantitatively analyzed and compared.

In the inversion of the temperature map, the average temperature of the suburbs was obtained. Between the urban high temperature and the suburban average temperature, the surface temperature region obtained from the inversion was densely segmented in to several temperature level zones. The urban areas of which surface temperature was lower than the average of the suburbs was the same way to be segmented in to several temperature level zones. While average temperature of different temperature level zones subtracting average suburb temperature, the temperature difference was obtained. Because UHI effect was relevant to the area of temperature zone, we designed a UHI intensity formula including temperature difference between urban areas and the suburbs as well as temperature zone area as expressed below:

$$I_{UHI} = \sum_{i=1}^{n} (T_i - T_0) * P_i \qquad (1)$$

Where:

I_{UHI}, is UHI intensity, and the unit is °C.

T_0, is suburb average temperature, and the unit is °C.

T_i, represents average temperature of different temperature level zones and the unit is °C.

P_i, is area ratio of the temperature zones in the study area.

i, is the level of temperature zones.

n, is the number of level of temperature zones.

Experimental study on mitigation of UHI effect

This experiment was based on the concept of sustainable development, and put forward the strategies of Low Impact Development (LID) to reduce surface temperature of the city. LID means trying to minimize the impact and destruction of the environment in management process through the source of scattered, small-scale measures, to achieve minimal possible adverse environmental impact[8].

These measures include permeable pavements, small green landscapes, and ecological roofs, etc. Surface temperature of several types of roads (granite, cement, permeable pavement, and lawn) and two types of roofs (traditional flat roof and ecology roof) were monitored in the field.

Experiment methods: The surface temperature of several roads and two types of roofs were measured according to the relevant literature[10] and the method in chapter 15 of “The Ground Meteorological Observation Standard". A glass liquid geothermal thermometer was used and the temperature measured by the thermometer was 1 cm above the ground surface.

Experiment sites

The road experimental used was a granite plaza site and a small lawn (green landscape) nearby Jiageng Buildings of Xiamen University. Also, a parking lot permeable pavement of Yifu Building not far from the plaza, and nearby a lane of cement road were all used as the test sites. Jiageng Plaza was built in 2001 with Jiageng buildings, an area of over 9000 m^2. It was paved with litchi face granite stone slabs. Yifu Building parking lot was paved with permeable grass brick (also known as lawn brick), and was built in 2003. This parking lot contained a total of 27 parking spaces, with an extremely high occupation rate. The road sites that were selected for experiment had no tree coverage so that there wouldn’t be any faulty result obtained caused by tree shades.

The roofs on the experimental sites were ecological roofs on the building for National Infectious Diagnostics and Vaccine Engineering Research Center, Xiamen University. The ecological roofs, planted with grass and low shrubs, were designed and built in 1996. The structure from bottom to top is 5-10 cm thick ceramsite; a layer of non-woven fabrics; a mixture of peat soil, red clay, fertilizers, and green plants. Construction load, plant species selection, water and drain water systems, irrigation systems and other technical details all have been described elsewhere[11].

Surface temperature measurement could ignore the weather factors for all the experimental sites were in close range, with each site conforming to "the ground meteorological observation rules and regulations"[12].

Experiment data determination and processing

Data were determined according to ground surface temperature measurement requirements in "The Ground Meteorological Observation Standard". Since those LID measures performed significantly in reducing surface maximum temperature of the whole day, the maximum surface temperature of different types of roads and roofs were determined for a week (August 22 to August 28) in August, the summer of 2011. Whereas for hourly temperature was only determined in August 24 after one day tracking. Each sample points were measured paralleled three times and data were averaged subsequently.

RESULTS AND DISCUSSION

UHI intensity in Xiamen

Figure 2 shows the surface temperature distribution map derived from inversion. The difference in temperature range of the urban areas and suburbs is obvious from the figure. Surface temperature distribution generally follows the distribution characteristics of built-up areas. For example, surface high-temperature region is concentrated in the industrial park, traffic field, and land on both sides of the roads and the city centre. High surface temperature distribution in the six districts of Xiamen represents different land-use characteristics.

For example, in Siming District, the high surface temperature areas are mainly located in and around the Xiamen Railway Station, Xiahe Road, Haitian Wharf, International Exhibition Center, Huangcuo Island Ring Road, and Longshan Industrial Zone. The high surface temperature areas of the Huli district mainly exist at the airport, Xiangyu Wharf, and Huli Industrial District. The high surface temperature areas in Haicang District are mainly distributed in Xinyang industrial zone, Haicang Port. Jimei District's high surface-temperature regions were mainly located in Xinglin, Guankou, and Houxi Town.

Average suburban temperature was 28 °C on August 17, 2006. The temperature map which was lower than the average suburban temperature was divided into two temperature levels zones: an ultra-low temperature zone ($T \leq 22°C$), and a low temperature zone ($22°C < T \leq 28°C$). The temperature map which was higher than the average suburban temperature was divided into four temperature level zones based on 3℃ intervals that were medium temperature region ($28°C < T \leq 31°C$), sub-high temperature region ($31°C < T \leq 34°C$), high temperature region ($34°C < T \leq 37°C$), and super-high temperature region ($T > 37°C$), respectively.

According to the range of afore-mentioned different temperature zones, mask exposure method was used to separate out their corresponding T_{Jim} figure, and then the average temperature level of different zones was calculated. The area ratio (P_i) of different temperature level zones was determined by using the number of pixels in the zone divided by the total pixel elements in the study area. According to the UHI effect intensity calculation formula, UHI intensity in Xiamen for 20060817 was obtained and it amounted to 2.3°C.

UHI distribution pattern in Xiamen in relation to surface types

Spectral characterization and normalized difference index were analyzed according to TM images of Xiamen, and the surface type of TM images of Xiamen was classified according to the former conclusion[13].

In the surface classification chart, surface type corresponding to the temperature range was separated using the mask exposure method. Statistics about the area ratio on surface type in its temperature zone was made. In this study, only the super-high temperature zone (strong UHI) and high temperature zone (sub-strong UHI) were analyzed (TABLE 1).

TABLE 1 : Area ratios for strong and sub-strong UHI surface types, Xiamen, August 17, 2006

UHI Surface Types	Area ratios (%)						
	Water	Mud flat	Sand	Bare soil	Impervious area	Woodland	Grass farmland
Super-high temperature zone (strong UHI)	0.00	0.00	0.52	5.32	59.88	15.46	18.82
High temperature zone (sub-strong UHI)	0.01	0.04	1.33	7.28	28.31	21.86	41.17

In the super-high temperature zone, the impervious area is mainly scattered, accounting for 59.88%, followed by grass farmland and woodland, 18.82% and 15.46% respectively. In addition, the proportion of the area of bare soil is 5.32%. In the high temperature zone, grass farmland and impervious area account for 41.17% and 28.31% respectively, while the proportions of woodland and bare soil are 21.86% and 7.28%, respectively.

Maximum surface temperature of different road types

As can be seen from Figure 3, the granite road has the highest surface temperature while the lawn ground seems to have significant effect in reducing the surface temperature. Comparing the lawn ground with the granite road, the temperature drop range was 3.5-7 °C. Permeable pavement, followed by lawn ground, the temperature drop range was 1.5-6 °C. At daily maximum temperature, the cooling effect of the lawn and permeable pavement is relatively remarkable. This is due to the porous structure of permeable pavement itself, which connects with external air and bottom permeable cushion. Water in the permeable brick ground and in the bottom cushion through evaporation under the solar irradiation, can make the surface temperature and near surface air temperature decrease. The lawn ground is the same situation as permeable brick ground.

Temperature drop comparison differed significantly on different dates. The monitoring time on August 25 and 26, 2011, was just after a heavy rain and the sun came out earlier as expected. Rain water can quickly penetrate into the ground, thus greatly reducing the surface temperature near the ground particularly in permeable grass and the water-permeable bricks.

The surface temperature of cement road is slightly lower than granite road (0.5-3°C), this may have been because the texture of granite road, in comparison with cement road is more solid and dense, which prevents the linkage of external air above to the bottom soil below.

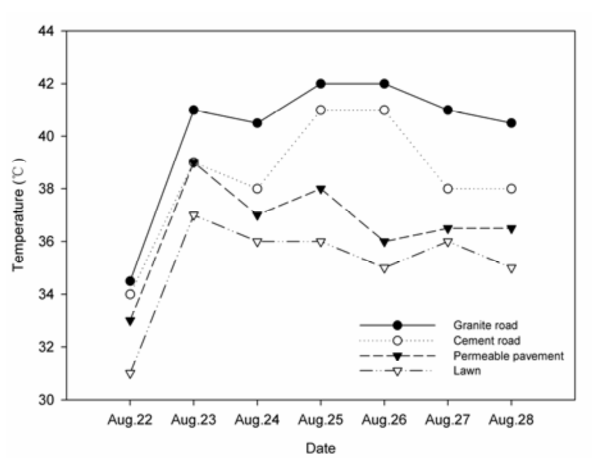

Figure 3 : Maximum surface temperature (   ) of different road types, Aug. 22- 28, 2011

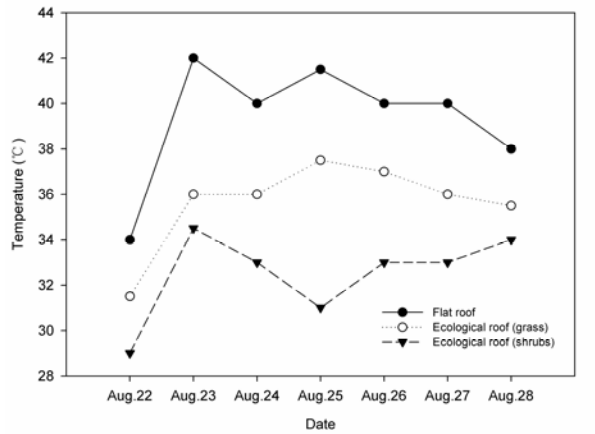

Figure 4 : Maximum surface temperature (°C) of different roof types, Aug. 22- 28, 2011

Maximum surface temperature of different roof types

As can be seen from Figure 4, the maximum surface temperature of different roof types varies significantly. The surface temperature of the flat roof is the highest, followed by ecological roof planted grass, and then the ecological roof planted shrubs. It is thus clear that the roof planted shrubs can effectively reduce surface temperature compared to the bare flat roof, and the cooling range was up to 4~ 10.5 °C. Different roof types reduced the temperature remarkably on different dates and the reason for this was the same as already explained for the different road types.

Hourly surface temperature of different road types

Surface temperature variation of different road types is basically similar. As can be seen from Figure 5, as time of the day progressed, all underlying road surfaces have showed a temperature trend of parabolic curve from low to high, then again high to low. And the surface maximum temperature occurs at 12:00, respectively. There is little variation in the underlying surface temperature range. For instance, the granite road surface temperature range is 8°C a day, whereas surface temperature range of lawn and permeable pavement is 7 °C, and the cement road is 6.5 °C respectively. At the maximum temperature, the cooling effect of lawn ground as well as permeable pavement was notable. There the recorded temperature is 4.5 and 3.5 °C lower than the granite road.

Hourly surface temperature of different roof types

As can be seen from Figure 6, hourly temperature at different roof types has very similar trend. In the morning, the roof temperature began to increase, reaching a peak at 12:00 noon, and thereafter the temperature gradually declined. There were some differences in the underlying surface temperature range. For example, the flat roof surface temperature range is 8°C a day, whereas the ecological roof planted shrubs °C is only 4 °C.

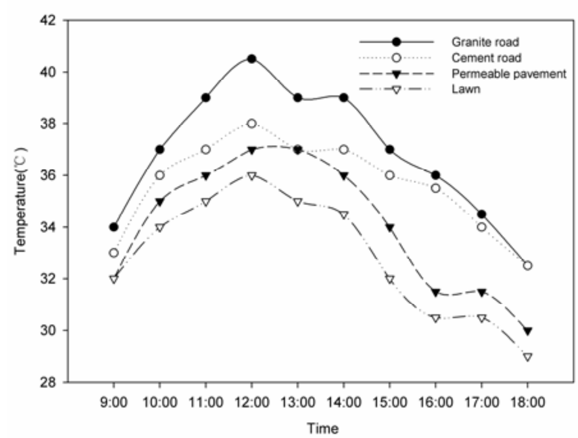

Figure 5 : Trends of daytime hourly surface temperature of different road types, Aug. 24, 2011

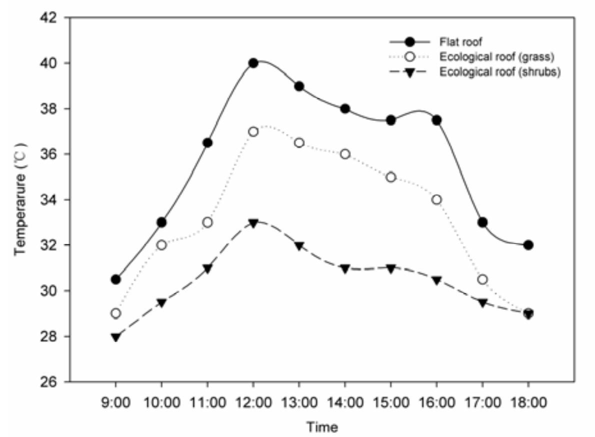

Figure 6 : Trends of daytime hourly surface temperature of different roof types, Aug. 24, 2011

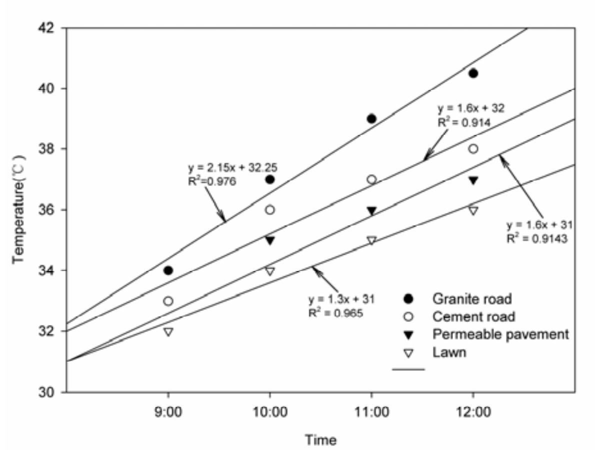

Figure 7 : Heating rate of different road types (day-time)

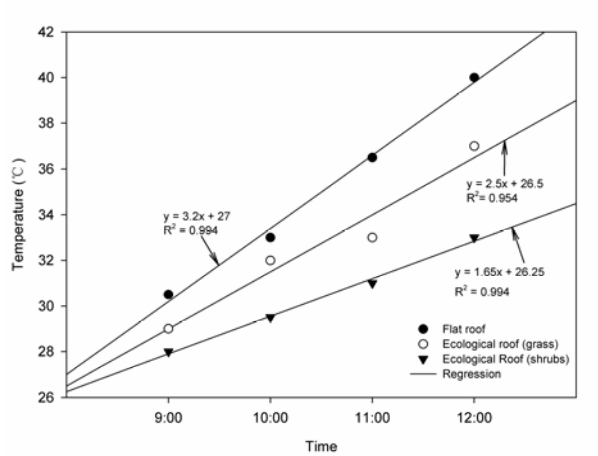

Figure 8 : Heating rate of different roof types (day-time)

Heating rate of different road and roof types

Linear regression analysis was conducted on the data for the heating process of all types of road and roof surfaces temperature curves. The slope of the curves was the heating rate of the underlying surface (Figure 7, Figure 8). It can be seen that the flat roof heating rate is the fastest, faster than the ecological roof planted grass. Granite road is the third and following is the ecological roof planted shrubs, the cement road, and then permeable pavement. As for the lawn ground heating rate comparing to other experimental site it was the slowest. These results demonstrate that laying permeable pavements and planting green plants can significantly solve UHI problem. Moreover, use of ecological roofs may significantly reduce UHI effect compared with flat roofs.

CONCLUSIONS

Jimenez single-band algorithm was used to inverse land surface temperature instead of traditional brightness temperature of Xiamen. Data reveal obvious temperature difference between urban and surrounding suburban areas in Xiamen. Surface temperature distribution reflects characteristic distribution in constructed areas. UHI region is concentrated in the industrial park, traffic field, land on both sides of the road and the city centre. High density of human population coupled with the rapid increase of urban impervious areas is the main reason for UHI in Xiamen.

Lawn, permeable pavement and ecological roofs, compared with granitic road, cement road and flat roofs all have a more cooling effect. It shows that based on LID concept, laying a certain scale of lawn, green plants, permeable brick and ecological roof on parking lot, activity place of living quarters, office area and the roadside pavements, not only help create beautiful scenery but also help reduce impervious areas. In this way, it does not change the road layout of the original city, which could notably reduce the ground temperature, and mitigate the UHI effect. In the future, long period of temperature drop experiment can be further implemented. Meanwhile we can monitor more detailed parameters such as the solar radiation intensity, terrestrial radiation intensity of different underlying surfaces and further quantify the performance of LID measures to mitigate UHI effect.

ACKNOWLEDGMENTS

This research was supported by the Natural Science Foundation of Fujian Province, China (No. 2013J01211); National Natural Science Foundation of China (No. 51378446).

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