ISSN : 0974 - 7435 Volume 10 Issue 18

2014

BioTechnology
An Indian Journal

FULL PAPER

BTAIJ, 10(18), 2014 [10411-10417]

Experimental study and environmental economic benefit analysis on Urban heat island mitigation based on low impact development

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ABSTRACT

Experiments on spot, surface temperature monitoring experiments through the different road surface with the traditional flat roof and ecological roof were implemented and the results were used to quantize the cooling effect of these LID measures. The environmental benefits and economic benefits from temperature lowing were estimated subsequently. The innovation points mainly have two aspects. First, A new concept based on Low Impact Development (LID) strategies for sustainable development to alleviate the Urban Heat Island (UHI) effect has been put forward firstly compared with traditional views. Second, the effective efficiency of LID measures mitigation heat island effect was quantified. Results show that permeable pavement, lawn ground and ecological roof can help cool the surface temperature. Permeable pavements, green landscapes and ecological roofs can build beautiful landscapes, adjust the temperature, and form natural air conditioning which is beneficial to improve the air quality. On the other hand, when applying the UHI effect mitigation measures, if the temperature dropped 1 ~ 1. 5 ^{o}C, a considerable amount of electric power resources had been saved. These findings could be used as a reference for UHI mitigation strategies and have certain application prospect.

KEYWORDS

Urban heat island (UHI); Low impact development (LID); Permeable pavements; Green landscapes; Ecological roofs; Environmental economic benefit.

INTRODUCTION

Cities are particularly vulnerable to climate change because of a phenomena known as the Urban Heat Island (UHI) effect which is one of the typical characteristics of urban climate. The reasons for UHI are increasing impervious underlying surface and decreasing green land and water area with influence of the artificial heat in metropolis. Nowdays, UHI effect has received extensive attention from many scholars and experts wordwide[1-7].

To monitor the UHI effect, the main research methods used were meteorological observations, remote sensing, and fixed-point observations, etc. Meteorological observations method makes use of the collected observation data to analyze the evolution pattern of the thermal environment during the urbanization process. Nonetheless, this needs a lot of long-term historical observations. Changes of measuring point (including changes in the longitude, latitude, and altitude), observation habit, and the error of the measuring instrument, can all affect the analysis and conclusion of UHI effect[8]. Remote-sensing can measure large areas of land surface temperature, reduce local environment human disturbance, and study UHI features intuitively and quantitatively. Whereas, the time resolution value by this method is lower than other monitoring methods affected by weather and clouds[9]. Fixed-point observation method could accurately measure the temperature, suitable for quantitative research of the urban thermal environment; however, the workload required for this method is bigger and usually limited by manpower and material resources. It is difficult to obtain field distribution of temperature of large areas[10].

Mitigation measures, such as developing urban green space and increasing water areas to slow down the UHI effect are theoretically proposed in a lot of studies. However, it is hard to find space to grow green plants in reasonably large areas, and expansion of water bodies in a densely-populated urban city. Moreover, References about field trial cooling experiment research are limited. A sustainable heat island effect mitigation technology names Low Impact Development (LID) which developed in the 1990s can just solve this difficult problem[11,12]. The technology mainly focuses on taking several dispersing, small-scale source measures to have the minimum impact on environment during the development, thus could decrease the surface temperature of the earth. These measures include: permeable pavements, green landscapes, ecological roofs, etc. Its outstanding feature is less land occupation, scattered, meanwhile combined with the landscape construction under planning. One of its advantages is that it has lower cost compared with traditional methods. It must be noted that these measures are also very important and effective to intercept urban rainwater resources and slow down heavy rain runoff pollution.

Permeable pavements

Compared with traditional impermeable pavement such as cement and asphalt pavement, permeable pavement lies on porous brick or permeable tar above underground sewer and infiltration wells, with setting backfilled sand. Therefore permeable pavements effectively relieve the negative influence on urban ecology caused by urban harden ground. Rainwater can permeate into the ground through the permeable pavements, and supply the groundwater. As well, permeable pavements connect with external air and bottom permeable cushion, making the ground warm in winter and cool in summer, which increase the sense of living comfort in the city. Some developed countries began to make research and developed permeable pavement materials from the 1970 s. The materials are applied to the yard, sidewalks, bicycle lanes, public squares, parking lots, park roads, both sides of the road and the central isolation belt, which increase the city's permeable breathable space and have a good effect in adjusting and keeping the ecological balance of the city. After 1990's, it has become a general experience for the developed countries in urban construction by applying permeable materials to replace the traditional materials for building roads[13].

Green landscapes

Growing a variety of plants and grassbetween the central streets and their sides, planting lawn and hydrophilous shrubs in the corner of street, or constructing small-scale rain gardens which forms an ecological treatment system with the function of cooling, rainwater collection, retention, purification, permeation and so on. It not only can create a beautiful natural street scene, but also really bring obvious environmental effects. Portland, a city of the United States, is a notable case for its green streets reconstruction design[14].

Ecological Roofs

Ecological roofs are the roofs with a layer of soil above the water-resisting layer, growing plants on parts or all of the roofs. Compared with traditional roofs, ecological roofs play the role of insulation, improve air quality, and reduce the temperature, so the wide application of ecological roofs could have the effect of mitigation on the urban heat island effect. When in use, the maintenance cost is extremely cheap[15,16].

Therefore, based on the sustainable development strategy with low impact on the city development, we implemented fixed-point field trial observation study in Xiamen, China to measure the effect of UHI mitigation methods and discussed the environmental economic benefit from Mitigation on Urban Heat Island. The innovation points mainly have two aspects. First, A new concept based on Low Impact Development (LID) strategies for sustainable development to alleviate the Urban Heat Island (UHI) effect has been put forward firstly compared with traditional views. Second, the effective efficiency of LID measures mitigation heat island effect was quantified.

MATERIALS AND METHODOLOG

study area and experiment sites

Xiamen City, (118°04'04" E longitude, and 24°26'46 N latitude), is located in estuary of Jiulong River, southeast Fujian Province, China, near the Taiwan Strait. The region of Xiamen is consisted of Xiamen island, Gulangyu isle, Tongan district, and inland areas by north coast of Jiulong river. The area of Xiamen island, the urban district, is about 132.5 km^2.

The experiments in the present study included monitoring surface temperature of several types of roads (granite, cement, permeable pavement, and lawn) and two types of roofs (traditional flat roof and ecology roof) in the field.

The road experimental sites were a granite plaza and lawn (small green landscapes) nearby Jiageng Buildings of Xiamen University, Xiamen. Also, a parking lot permeable pavement of Yifu Building not far from the plaza, and nearby a lane of cement road were all 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 surface monitoring points are selected without trees cover, so the influence of trees' shade can be ignored.

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[17].

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"[18].

Experiment methods

The surface temperature of several roads and two types of roofs were measured according to the relevant literature[13] 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 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 (Jul 22 to Jul 28) in July, the summer of 2013. Whereas for hourly temperature only was determined in Jul 23 for one day tracking. Each sample points were measured paralleled three times and data were averaged subsequently.

RESULTS AND DISCUSSION

Maximum surface temperature of different road types

As can be seen from Figure 1, 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 is 4-6 ^{o}C. Permeable pavement, followed by lawn ground, the temperature drop range is 2-5 ^{o}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 July 25, 26, and 28, 2013, was just after a shower (TABLE 1); 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 (0.5-2 ^{o}C), this may have been because the texture of granite road, in comparison with cement road is more solid and dense, which completely unable to link up external air above and connect bottom soil below.

TABLE 1 : The temperature and weather on Jul 22-28, 2013.

Date	The maximum temperature [^{o}C]	The minimum temperature [^{o}C]	Weather
Jul 22	33	25	cloudy
Jul 23	34	25	cloudy
Jul 24	33	25	cloudy
Jul 25	31	25	shower
Jul 26	30	25	thunder shower
Jul 27	31	25	cloudy
Jul 28	31	25	shower

Maximum surface temperature of different roof types

As can be seen from Figure 2, 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 5~ 7.5 °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 3, 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 a little variation in the underlying surface temperature range. For instance, the granite road and cement road surface temperature range is 9 °C a day respectively, whereas surface temperature range of lawn and permeable pavement is **7** °C.

Hourly surface temperature of different roof types

As can be seen from Figure 4, 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 was some difference in the underlying surface temperature range; for example, the flat roof surface temperature range is 14 °C a day, whereas the ecological roof planted shrubs is 7.5 °C.

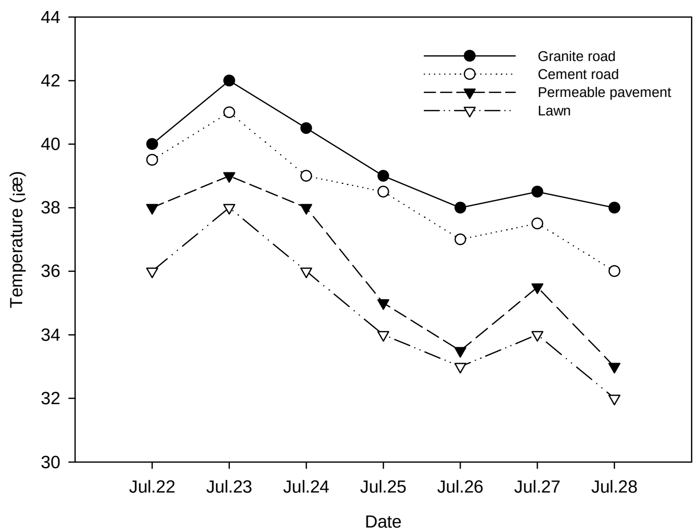

Figure 1 : Maximum surface temperature (°C) of different road types, Jul. 22- 28, 2013.

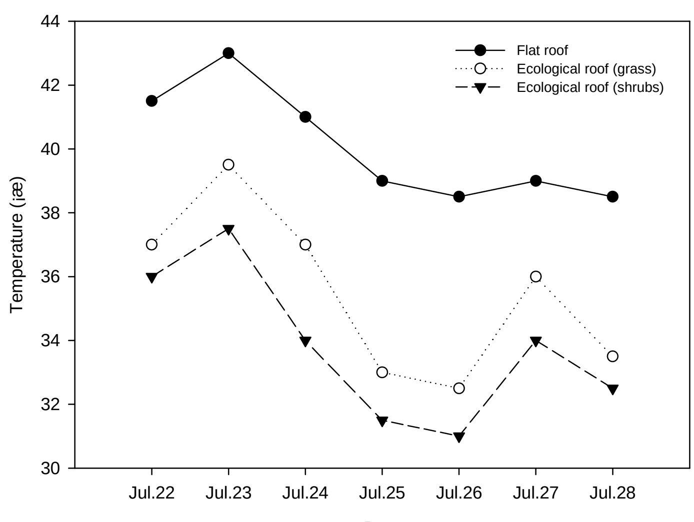

Figure 2 : Maximum surface temperature (°C) of different roof types, Jul. 22-28, 2013.

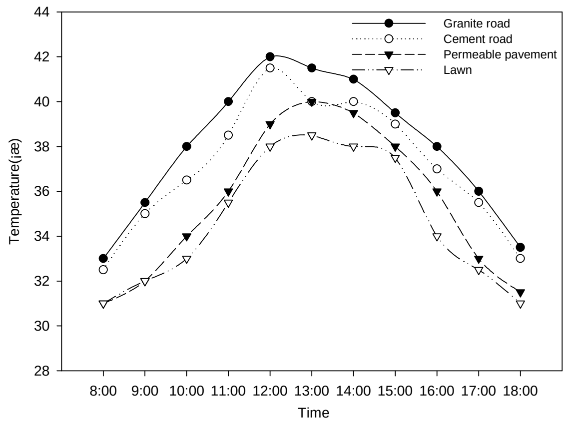

Figure 3 : Trends of daytime hourly surface temperature of different road types, Jul. 23, 2013.

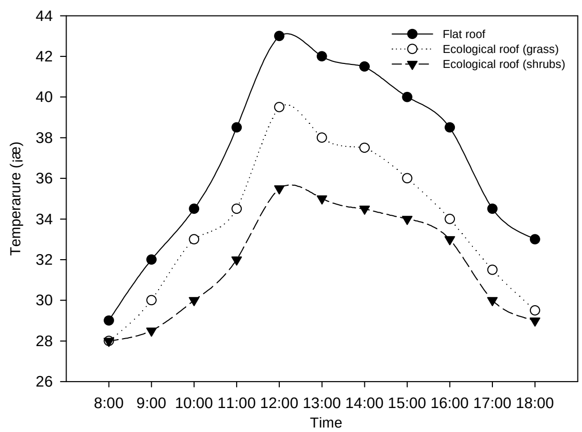

Figure 4 : Trends of daytime hourly surface temperature of different roof types, Jul. 23, 2013.

Heating rate of different road types

Linear regression analysis was conducted on the data for the heating process of all types of road surface temperature curves. The slope of the curves was the heating rate of the underlying surface (TABLE 2). It is obvious that the heating rate of granite road is the fastest, followed by the cement road, and then permeable pavement, while the lawn ground heating rate is the slowest. These results demonstrate that laying permeable pavements and planting green plants can significantly solve UHI problem.

TABLE 2 : Heating rate of different road types (day-time).

Different road types	Granite road	Cement road	Permeable pavement	Lawn
Heating rate (^{o}C /h)	2.25	2.15	2	1.75
Regression coefficient (R^2)	0.996	0.987	0.97	0.951

Heating rate of different roof types

Linear regression analysis was conducted on the data for the heating process of all types of roof surface temperature curves. The slope of the curve represented the heating rate of the underlying surface (TABLE. 3). It can be seen that the flat roof heating rate is the fastest, faster than the granite road. Ecological roof planted grass is the second followed by the flat roof. Heating rate for ecological roof planted shrubs is the slowest. Thus, use of ecological roofs may significantly reduce UHI effect compared with flat roofs.

TABLE 3 : Heating rate of different roof types (day-time).

Different road types	Flat roof	Ecological roof (grass)	Ecological roof (shrubs)
Heating rate (^{o}C /h)	3.45	2.75	1.85
Regression coefficient (R^2)	0.986	0.963	0.917

Environmental economic benefit analysis of mitigation on uhi effect

Environmental benefit

Using permable pavements can change urban air temperature and flow mode, as well as increase the air humidity, and slow down heat island effect. Large porous water drainage pavements belong to pervious roads, porosity, and fast evaporation rate, thus lead to cool faster than the traditional pavement roads. When rebuilding in cities, if the porous pavements can be connected with groundwater, more cooling can obtain through the groundwater evaporation, so as to further reduce the road surface radiation.

Green landscapes included lawn, small green gardens or green streets, with covering small areas and high feasibility. On one hand it can keep cool, and mitigate urban heat island effect, on the other hand it can absorb the greenhouse gases such as carbon dioxide, and maintain carbon-oxygen balance. Meanwhile green landscapes have the following functions, such as realize the function of rainwater collection, retention, purification and permeation.

Roof greenery is better than ground greenery for mitigation on urban heat island effect. The reasons are that: First, roof has a good circulation than the ground, and it’s easy for heat exchange with the atmosphere; Second, the shade effect of the green plants makes the ecological roofs receive far less net radiation heat than the non-greenery roof; Third, the plant transpiration and the evaporation of water in soil consume a lot of heat from the building, and reduce the thermal emission caused by building to the air.

Economic benefit

Research shows that when area of the urban roads increased to 25% of the whole city, completely applying the asphalt pavement (water-proof asphalt road surface + permeable grassroots) road can make the temperature 1 ~ 1.5 ^{o}C lower on the whole in downtown area; Especially when at noon to the evening, the temperature will reduce 1.5 ^{o}C or above at this intense heat island effect[19]. The above experiments in this paper also show that in the hot summer at noon until the evening, LID measures can reduce the urban temperature more than1.5 ^{o}C.

Heat balance formula is as follows:

$$Q = cm\Delta T \quad (1)$$

Q stands for the temperature change of the energetic changes (J); c stands for the specific heat contents. In the standard circumstances, the specific heat content of air is 1. 006 * 10^3 J / (kg. ^{o}C);m stands for the mass of the object at normal temperature atmospheric pressure. Average molecular weight of air is 29, density of 1. 29 kg/m^3; ΔT stands for the variation of temperature T (^{o}C).

Take Xiamen, Fujian as an example, Xiamen island covers an area of 132.5 km^2,the height of the high temperature layer of the city is 100 m, according to the Eq. 1, Xiamen island each reduce 1.5 ^{o}C temperature, atmospheric heat energy to radiation Q = 1. 006 * 10^3 * 1. 29 * 132.5 * 10^6 * 100 * 1.5 = 2. 58 * 10^{13} J, equivalent to 7.17 million kW. h (1 kW. h = 3. 6 * 10^6 J). And it’s exceeding the wind power plan (2-2.5 million kW. h) of Fujian province in 2020. Visible effect has been seen that LID measures has a very big influence on cooling and energy-saving urban heat island effect.

CONCLUSIONS

It is feasible for planting green plants and laying permeable pavements to mitigate the UHI effect. Based on LID concept, in the area suitable for planting and paving, making use of every single space is considered. It is not necessarily limited to laying grass, which might consider growing green plants in the central streets, planting shade trees to develop green streets, constructing small-scale rain gardens and building ecological roofs in the living community. Only reaching a certain scale can be formed low temperature area as the center of LID measures. In this way, thus could generate temperature difference between the low temperature region and the surrounding high temperature region, form small local air circulation, and actively mitigate UHI effect of the surrounding lots.

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 surface and further quantify the performance of LID measures to mitigate UHI effect.

CONFLICT OF INTEREST

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of the manuscript.

ACKNOWLEDGEMENT

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

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