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A Study of the Effectiveness of Heat-Mitigating Pavement Coatings in Singapore

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ABSTRACT

The primary cause of the urban heat island (UHI) phenomena is urbanization, whereby natural softscapes are replaced with hard surfaces that absorb and re-radiate thermal energy back into the environment. Asphalt roads and pavements, in particular, were found to be able to heat up to 60° C, and radiate the excess heat back into the environment. This paper highlights the effectiveness and suitability of a dark-colored pavement coating with high albedo, named PerfectCool, recently developed by NIPPO Corporation Co. Ltd, in Japan.

Laboratory tests revealed that PerfectCool was able to reflect up to 81% of near-infrared red waves, had a low heat conductivity of 0.252 W/mK, and had a high emissivity value of 0.828. Throughout the duration of the controlled mock-up experiment, PerfectCool consistently recorded lower surface temperatures than did concrete slabs with and without conventional paving coating. PerfectCool was able to reduce peak surface temperatures by up to 5° C.

Onsite measurements revealed that PerfectCool was able to reduce asphalt-surface temperatures to about 38° C. This was a temperature reduction of up to 17° C, as compared with a normal asphalt-surface without PerfectCool. PerfectCool was able to prevent a build-up of heat within asphalt roads, preventing them from becoming a heat sink, which could prolong the service life of the asphalt surface. This is clearly supported by the low sub-surface temperatures of 34° C, 16° C lower than for asphalt roads.

Potential cost savings were also determined through energy simulation using IES(ve). With the application of PerfectCool on pavements surrounding a development, a potential electrical yearly savings of 3.46% can be derived, with a highest possible monthly savings of 4.88%. On a typical hot day, the possible reduction of chiller load can be up to 7.69%.

Introduction

The urban island heat (UHI) effect is a phenomenon in which surface and air temperatures are elevated due to the retention and emittance of solar heat from hardscapes (e.g., roads, buildings, and other structures). UHIs are typically formed when city growth alters the urban fabric by replacing natural land cover with manmade asphalt pavements, buildings, and other infrastructure, resulting in the metropolitan area becoming significantly warmer than surrounding rural areas (source: http://eande.lbl.gov/heatisland/hightemps/).

Pavements (e.g., roads, pedestrian walkways) are one of the main hardscapes contributing to the UHI effect. They have high thermal-mass capacity, allowing them to absorb and retain a huge amount of thermal energy from the sun during the day, causing surface temperatures to reach as high as 60° C. When pavements become considerably hotter than the ambient canopy temperature, the excess heat is radiated back into the atmosphere throughout the day and night, resulting in a higher ambient temperature than those in rural areas. Although various studies have clearly linked human discomfort with the effects of hot pavements (Iwama et al. 2006), the slow progression of technologies in this area limits urban planners and building owners who are attempting to mitigate this problem.

The Public Works Research Institute, Nippo Corporation Co, Miracool Co. Ltd, Kanematsu Corporation Co., and the Tokyo Institute of Technology worked together on a project to develop a dark-pigment coating with high albedo. The concept was to develop a surface coating to restrict the heat-exchange process in a conventional pavement (see Figure 1). Through numerous studies, the pavement coating (named PerfectCool) was developed.

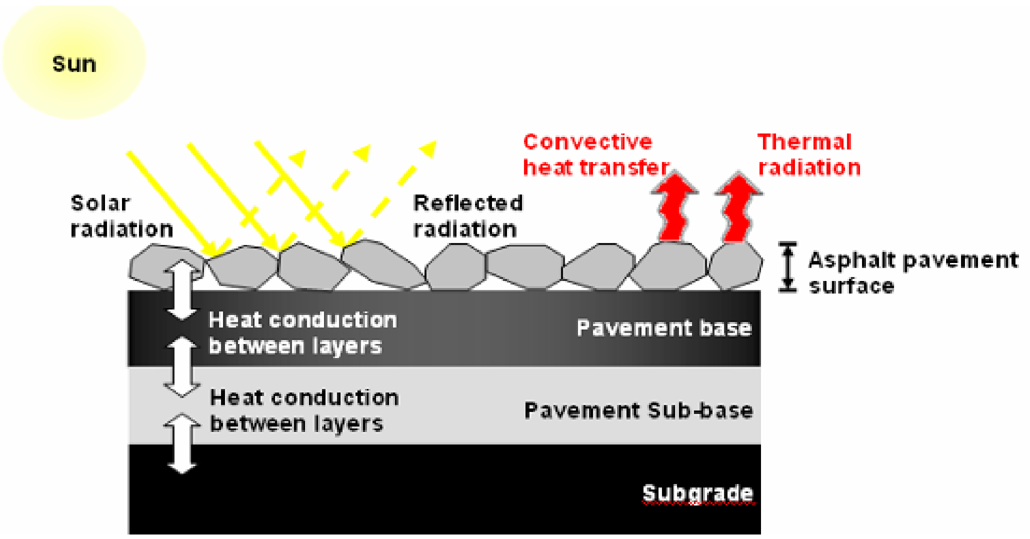

Figure 1 Heat exchange process in a conventional pavement (source: www.Nippo-c.co.jp).

PerfectCool is based on the principle that by increasing the reflectance of the pavement surface, less heat will be absorbed, thereby lowering the daytime temperature of the pavement. PerfectCool consists of dark, low-reflective color pigments mixed with high infra-red heat-reflective pigments and fine hollow ceramic particles to reduce thermal conduction and heating of the paint (see Figure 2).

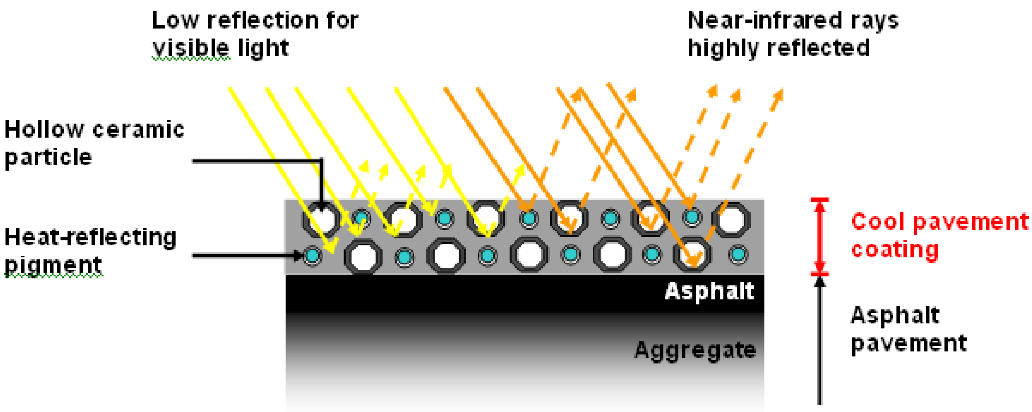

Figure 2 Close-up view of coating layer above the asphalt mixture (source: www. Nippo-c.co.jp).

With high reflectivity in the infrared-red region, PerfectCool is able to significantly reduce the surface temperature of pavements. This thus reduces the air temperature and long-wave radiation emitted from the pavement surface, while still maintaining low albedo in the visible region (Iwama et al. 2006). Other benefits of PerfectCool include good weatherability, good adhesion with a variety of pavement types, good torsional resistance, and good resistance to rutting (Road Technology Research Group 2003).

Although Iwama et al. (2006) recognized that reflected infrared-red rays might increase the wall temperature of surrounding buildings they showed through energy simulation that the increase in wall temperature was slight. In addition, the overall area-weighted temperature of the walls and floors was significantly reduced with increased pavement albedo. In a sensory survey conducted by the same group, the majority of the respondents felt that a coated surface was much "cooler" and more comfortable than an uncoated surface, despite the increase in reflected near-infrared rays. This is because near-infrared rays are not as likely to raise skin temperature in human body as are ultraviolet and visible rays (Narita et al, 2001), resulting in a much cooler sensation.

This paper presents the findings of a study on the effectiveness of PerfectCool in improving thermal comfort, reducing UHIs, and saving energy through its use in pavements in hot and humid Singapore.

Methodology

Two different color cool pavement coatings were supplemented for testing, as shown in Table 1.

Table 1: Cool pavement coatings and their respective sample reference and color codes

Coating	Color code	Sample reference
PerfectCool (light gray)	N65	CP65
PerfectCool (dark gray)	N40	CP40
Control sample (light gray)	N65	NP65

Note: The color codes indicate the intensity of color; the lower the color code, the darker the color.

This investigation of the effect of cool pavement coating was conducted through a four-pronged approach: laboratory testing, controlled measurements, onsite field measurements, and sensory surveys. Lastly, the potential cooling energy savings from large-area hard surfaces (e.g., parking lots, multi-purpose areas, and pedestrian walkways; hereafter collectively termed pavements) was performed via computer simulation.

The laboratory testing involved measurements of reflectivity, steady-state conductivity, and emissivity and were conducted in accordance with the ASTM, as recommended by Akbari et al. (1996).

The controlled experiment testing involved temperature measurements between CP65 and NP65 coated onto a concrete slab, measured at 5 minute intervals over a duration of 14 days.

The onsite experimental testing involved temperature measurements at various heights at two different locations: a concrete-based outdoor basketball court and an asphalt road. Matching color codes of PerfectCool coatings were selected to match the basketball court and asphalt road to reduce the discrepancy. The heights measured at these two locations are shown in Table 2.

Table 2: Heights of temperature measured for onsite experiment

Measurement points reference	Basketball court	Asphalt road
-50 mm	50 mm below surface	50 mm below surface
-10 mm	10 mm below surface	10 mm below surface
0 mm	On surface	On surface
+10 mm	10 mm above surface	10 mm above surface
+300 mm	300 mm above surface	300 mm above surface
+600 mm	600 mm above surface	600 mm above surface

A thermal sensory survey questionnaire was developed to gather responses about the thermal sensations felt by participants at the two locations in the onsite experiments. A questionnaire was handed out to each participant at each location. Each questionnaire was divided into two categories: pavement type 1 and pavement type 2. No additional information was provided. The participants were asked to carry out a few tasks: to stand for a few minutes, to place their hands for a few minutes at approximately 10 mm above the surfaces, and finally to touch the surfaces of each test site. The participants were than asked to rank on a scale of 1 to 7 (i.e., where 1 = very cold, 4 = neutral, and 7 = very hot) how their feet, body, and hands felt when they were at each site. The participants were asked to compare pavement types 1 and 2 at each location and gauge which was hotter.

Lastly, a three-dimensional massing model of a typical factory in Singapore was created for the energy simulation. Details of the factory model are given in Table 3.

Table 3: Details of factory model used for the energy simulation

Size	45 m x 30 m x 8 m
Layout	Two story office, 10 m x 30 m x 8 m high, and a double volume working area, 35 m x 30 m x 8 m high.
External wall	Standard wall construction
Internal wall	105 mm thick brick wall with 13 mm thick plaster on both sides
Fenestration	Low-e double glazing (6 mm + 6 mm)
Roof	Pitch roof
External pavement	Asphalt road along the perimeter of the factory

Two typical scenarios were modeled: a typical factory surrounded with asphalt pavement, and a typical factory surrounded with pavement coated with CP40. The parameters shown in Table 4 were taken as input for both scenarios.

Table 4: Input parameters for the energy simulation

Asphalt	
Albedo	0.15 (Lovell et al. 2005)
Emissivity	0.93 (source: website "Cole-Parmer")
CP40	
albedo	0.46
Albedo	0.828

The albedo of CP40 was calculated by pro-rating the reflectivity results with the proportion of spectral-energy distribution of solar heat radiated at ground level, as simulated from IEC 60068-2-5:1975. Occupancy and lighting consumption were kept the same for both scenarios.

Results and Discussion

Laboratory Results

PerfectCool coatings mainly limit heat transfer through high reflectivity in the infrared-red region (wavelengths beyond 700 nm). This high reflectivity is able to directly reduce the amount of heat transferred to a medium through radiation. The hollow spheres integrated into PerfectCool coatings allow the coatings to remain highly reflective to heat, irregardless of color.

Figure 3 shows that both CP65 and NP65 (both light gray) have a similar reflectivity profile in the visible-light spectrum (400–700 nm), indicating their similarity in color. CP40 (dark gray), on the other hand, has a much lower reflectance.

From 700 nm onwards (near infrared-red spectrum), the reflectance for NP65 remained consistently low, with a reflectance of 25%. However, the reflectance of CP65 jumped from 31% (visible light spectrum) to 77% (infrared-red spectrum). A similar profile was also noted for CP40, with the reflectance increasing from 12% to 81%.

Besides high reflectivity, it was also noted that PerfectCool coatings have lower thermal conductivity. The average conductivity results of the different coatings showed that the thermal conductivities for PerfectCool coatings (both CP 40 and CP65) were much lower than for NP65 (Table 5).

It is also worth noting that the dark gray-colored CP40 was better at dissipating heat than was the light gray-colored CP65. Table 6 shows that the emissivity of CP40 was 20% higher than that of CP65.

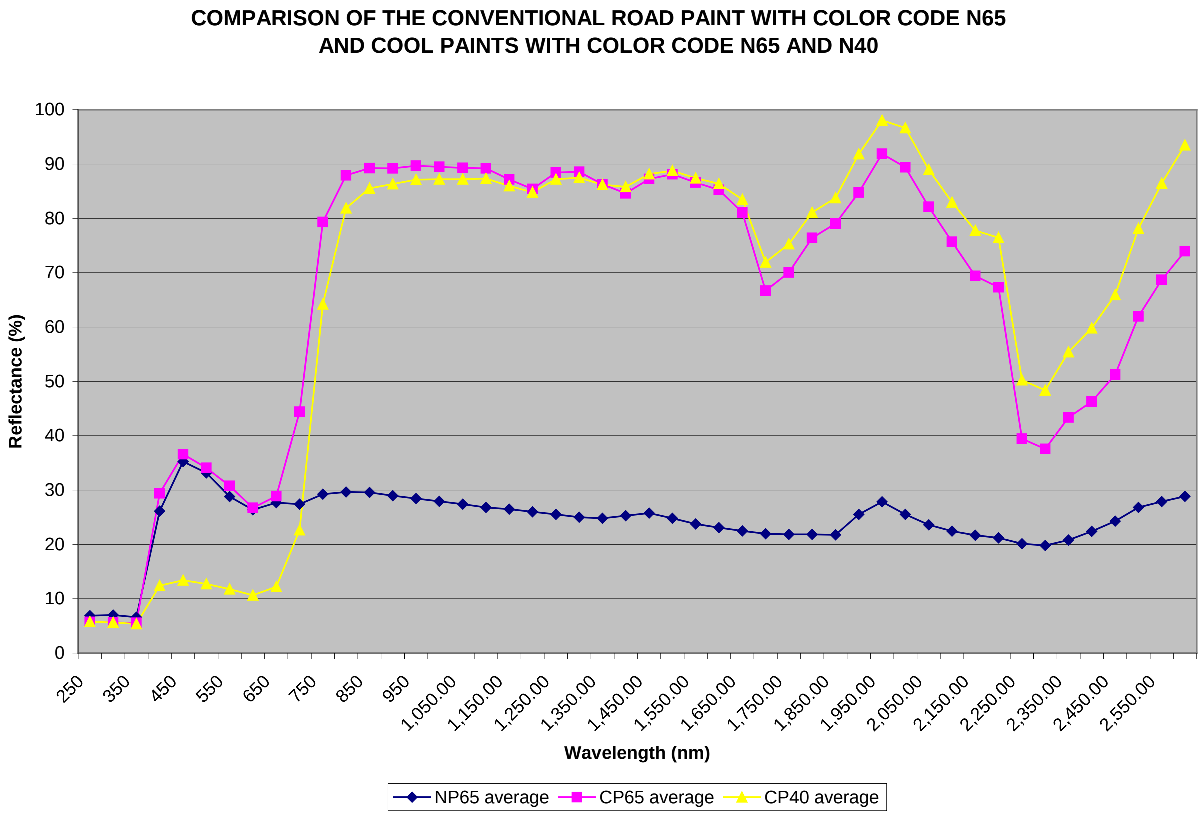

Figure 3 Reflectance of NP65, CP65, and CP40.

Table 5: Summary of results for conductivity measurement of the different coatings

Coating Type	Conductivity (W/mK)
CP40	0.264
CP65	0.252
NP65	0.422

Table 6: Summary of results for emissivity measurement of the different coatings

Coating Type	Emissivity
CP40	0.828
CP65	0.692
NP65	0.680

Controlled Experiment Results

The high reflectivity and emissivity properties of PerfectCool coatings are able to influence and reduce surface temperatures. This was clearly demonstrated from the results of the controlled experiment of coatings on concrete blocks. Figure 4 clearly demonstrates that the average surface temperature of CP65 was 4° C cooler than that of NP65.

During the 14-day experiment from June 28 to July 11, 2008, the day with the highest solar radiation and ambient air temperature was selected as a typical hot day. CP65 was noted to be 4.4° C cooler than the control and 3.8° C cooler than NP65.

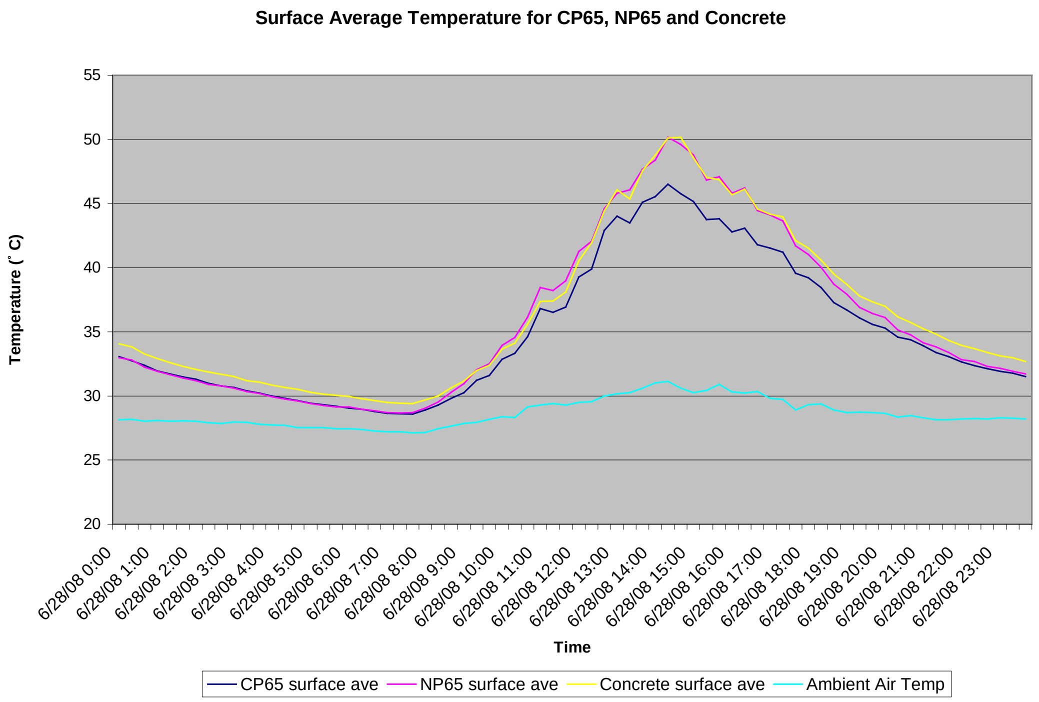

Figure 4 Comparison of average surface temperature of control slab, CP65 and NP65. Note peak temperature of CP65 is about 4° C lower than that of NP65 and the control.

Onsite Experiment Results

Similar to the controlled experiment, the onsite experiment clearly showed that PerfectCool coatings had significantly cooler surface temperatures than did other surfaces. Sub-surface measurements revealed a huge reduction in heat that was transferred into the substrate (concrete and asphalt from both sites) after the application of a PerfectCool coating.

The school site experiment ran for 18 days (April 20 to May 8, 2008). Figure 5 shows the temperature recorded plotted against the time for a typical day. A 5° C difference in peak temperatures were consistently observed for all four heights. It is also noted that the temperature for PerfectCool coatings was cooler by 1° C. Minimal differences in temperatures were noted for the ambient air temperature profiles recorded at +300 mm and +600 mm. This was probably due to external influences, such as wind.

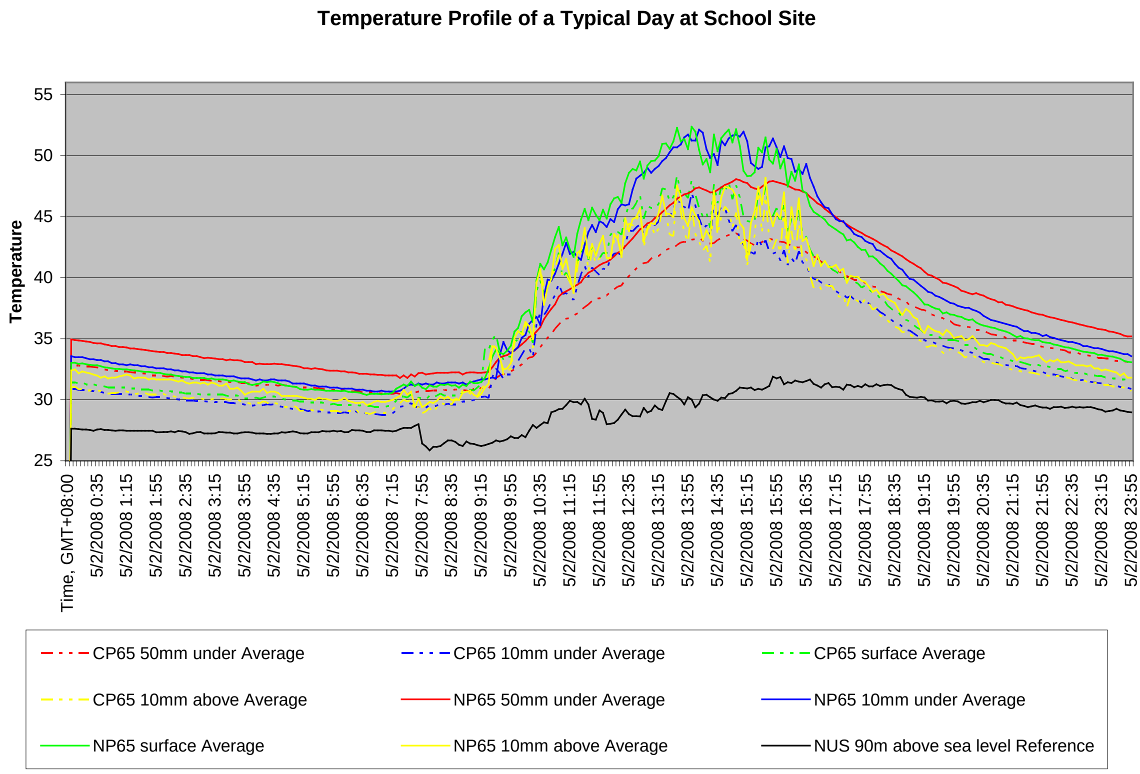

Figure 5 A 24-hour temperature profile of a typical day at the school site

The JTC site experiment ran for 23 days (from June 30 to July 22, 2008). Figure 6 shows the temperature recorded plotted against the time for a typical day. A minimum difference of 16° C in peak temperatures was noted for all four heights. Similarly, the night temperature for PerfectCool coatings was lower than that for the control by an average of 1.6° C. Minimal differences were noted between temperatures recorded for PerfectCool coatings and the control at +300 mm and +600 mm. Again, it was deduced that external influences (e.g., wind) reduced the impact of the coatings.

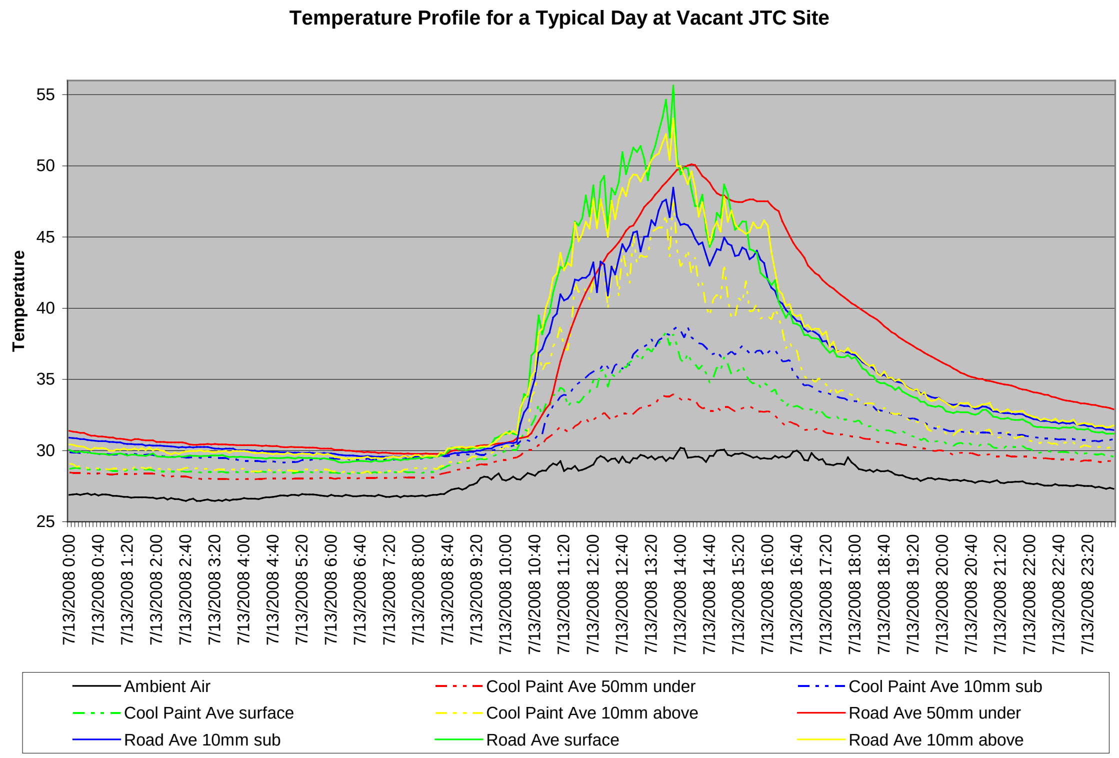

Figure 6 A 24-hour temperature profile of a typical day at the JTC site.

Survey Questionnaire

Although the ambient air temperature results were inconclusive, the temperature reduction caused by the cool paint could be felt by its users. This is because humans are sensitive to sensible heat. Cool paint is able to give a cooler sensation than that of asphalt roads due to mitigated heat conduction through the feet and the upward long-wave radiation (Kinouchi 2004). Results for the survey questionnaire clearly demonstrated this. The majority of the participants were able to feel the cooling effect of the PerfectCool coatings; the participants' ratings indicated they felt cooler when they were on the PerfectCool coatings than on the control.

The survey results from the basketball court showed that 90% of the participants felt that the control was hotter than PerfectCool. The remaining 10% were indifferent. At the asphalt road, all the participants felt that the control was hotter.

Energy Simulation

With the application of PerfectCool coatings, the amount of heat pavements throw back into the environment is significantly reduced. This results in a reduction of ambient air temperature, which in turn reduces the total energy consumption of neighboring low-rise buildings. Through the energy simulation, the yearly electrical consumption for the factory in two scenarios (i.e., surrounded with pavement made of asphalt and coated with CP40) was 354.82 MWh and 342.54MWh, respectively. This computes to a monetary savings of 3.46% for the factory with pavement coated with CP40.

The energy simulation also identified that peak electrical consumption falls in the month of June. The total electrical consumption and chiller load consumption were tabulated, and the percentage savings possibly achieved through the application of CP40 were 4.88% and 7.69%, respectively.

The external wall-surface temperatures of the factory for both scenarios, during the period of when peak electrical consumption was identified, were tabulated into a graph for comparison. It was observed that the external wall-surface temperature of the factory surrounded with CP40 was consistently lower than that of the factory surrounded with asphalt pavement.

Conclusion

PerfectCool coatings have a direct influence on the transfer of heat from the sun to the medium (e.g., asphalt road, basketball court) and back into the environment. The transfer of thermal energy (heat) from one medium to another only occurs via three methods: conduction, convection, and radiation. Conventional media (e.g., roads, basketball courts) have high thermal mass, absorbing a huge amount of solar radiation from the sun and building up their internal heat. This built-up thermal energy is thrown back into the environment, thus raising the overall temperature. PerfectCool coatings serve as a barrier, not only protecting the media from direct sunlight, but also limiting the transfer of thermal energy from the sun to the media and back into the environment.

Laboratory tests revealed that PerfectCool was able to reflect up to 81% of near-infrared red waves, had a low heat conductivity of 0.252 W/mK, and had a high emissivity value of 0.828. Throughout the duration of the controlled mock-up experiment, PerfectCool consistently recorded lower surface temperatures than did concrete slabs with and without a conventional paving coating. PerfectCool was able to reduce peak surface temperatures by up to 5° C.

Onsite measurements revealed that PerfectCool was able to reduce asphalt-surface temperatures to about 38° C. This was a temperature reduction of up to 17° C, as compared with the temperature of a normal asphalt surface without PerfectCool. PerfectCool was able to prevent a build up of heat within asphalt roads, preventing them from becoming a heat sink, which could prolong the service life of the asphalt surface. This was clearly supported by the low sub-surface temperatures of 34° C, 16° C lower than that of asphalt roads.

The potential cost savings were determined through an energy simulation using IES(ve). With the application of PerfectCool on pavements surrounding a development, potential electrical yearly savings of 3.46% can be derived, with a highest possible monthly savings of 4.88%. On a typical hot day, the possible reduction of chiller load can be up to 7.69%.

With a reduced surface temperature, the lifespan of roads can be extended due to increased durability. High temperatures soften the surfaces of roads, which increases the rate of rutting and shoving of surfaces, eventually leading to unevenness in the pavement surface. High temperatures also accelerate fatigue damage (e.g., gradual cracking of the surface, bleeding of asphalts). Cool paint is able to reduce significantly the surface temperatures of roads, making the asphalt less soft (Loustalot et al. 1995). A rutting experiment conducted by Pomerantz et al. found that when the surface temperature of roads was reduced by 10° C to 42° C, the lifespan of the pavement increased by more than 10 fold. With reduced surface temperatures, rutting, shoving, and other fatigue damage are less likely to occur, thus increasing the lifespan of the road and reducing the costs of repaving.

The lifespan of roads can also be increased with a reduction in internal temperature. Analysis showed that cooler asphalt roads slow down the chemical reactions that make them brittle, thereby maintaining their flexibility for a longer period (Monismith et al. 1994). As the internal temperature of the pavement builds up, the pavement loses its flexibility and becomes brittle. Cool paint is able to prevent this internal built up of heat, slowing down the chemical reactions, thus increasing the overall lifespan of the road.

With the increased lifespan of roads, the cyclical maintenance of those roads can be extended. Rosenfeld et al. (1998) estimated that a potential saving of $1.08/ m2 could be achieved.

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