USING COOL PAVEMENTS AS A MITIGATION STRATEGY TO FIGHT URBAN HEAT ISLAND – A REVIEW OF THE ACTUAL DEVELOPMENTS

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The full paper is published in **:** Renewable and Sustainable Energy Reviews, 2013

ABSTRACT

Heat island phenomenon rises the temperature of cities, increases the energy demand for cooling and deteriorates comfort conditions in the urban environment. To counterbalance the impact of the phenomenon, important mitigation techniques have been proposed and developed. The use of cool pavements presenting substantially lower surface temperature and reduced sensible heat flux to the atmosphere, appears to be one of the most important proposed mitigation solutions. The present paper investigates and describes the actual state of the art on the field of cool pavements. The existing results clearly show that the mitigation and cooling potential of cool pavements is very significant and can highly contribute to decrease temperature on the urban environment.

KEYWORDS

Heat Island, Cool Pavements, Mitigation Technologies, Reflective Pavements, Cool Materials, Permeable pavements

INTRODUCTION

Heat island refers to the development of higher urban temperatures of an urban area compared to the temperatures of surrounding suburban and rural areas Heat island has an important impact on the energy consumption of buildings and increases their energy consumption for cooling purposes. Various studies have shown that the cooling energy consumption of buildings may be doubled because of the important increase of urban temperatures

Counterbalancing the effects of urban heat island is a major priority for the scientific community. Several techniques have been proposed, developed and applied with quite high success. The impact of pavements on the development of urban heat island is very important.. Pavements cover a quite high percentage of the urban fabric and contribute highly to the development of heat island. Paved surfaces in Europe and USA, consist mainly of concrete and asphalt surfaces that present high surface temperatures during the summer period. Decreasing the surface temperature of pavements may contribute highly to improve the thermal conditions in cities suffering from high urban temperatures. This can be achieved by replacement of conventional paving surfaces with new ones presenting much lower surface temperatures during the warm period, reconstruction, preservation and rehabilitation of the existing pavements to improve their thermal performance and shading of the paved surfaces to decrease absorption of solar radiation. Advanced materials and surfaces, known as cool pavements, have been developed and are available for use in urban environments. Cool pavements are mainly based on the use of surfaces presenting a high albedo to solar radiation combined to a high thermal emissivity, (reflective pavements), or are using the latent heat of water evaporation to decrease their surface and ambient temperature, (water retention pavements). The present paper aims to present and analyse the actual status of development of the main technologies associated to cool pavements. It evaluates the recent developments concerning reflective and permeable paving surfaces while it presents new ideas and applications beyond the above technologies.

IMPROVING THE THERMAL PERFORMANCE OF PAVEMNENTS

Effective mitigation of the impact of pavements on urban heat island necessitates a serious reduction of the sensible heat flux released to the atmosphere by the paving surfaces. This is equivalent to the reduction of their surface temperature during the day and night period. Paving materials presenting a relatively reduced surface temperature are known as cool pavements.

Reduction of the surface temperature of pavements may be achieved by employing some of the following techniques :

a) To increase the albedo of the paving surfaces in order to absorb less solar radiation, (reflective pavements). Most of the existing techniques apply to asphalt, concrete and other types of pavements. Existing techniques to increase the albedo of pavements include. : The use of conventional cement concrete pavement, the use of concrete additives like slag cement and fly ash, the application of white topping and ultra thin white topping techniques, the use of roller compacted concrete pavement, the use of light aggregates in asphalt concrete surfaces, the use of chip or sand seals with light aggregates, the application of color pigments and seals and the use of colorless and reflective synthetic binders, the painting of the surfaces with a light color using or not microsurfacing techniques, the use of sand/shot blasting and abrading binder surfaces, resin based pavements, etc. Some of the techniques are appropriate for new pavements while other for pavement rehabilitation and maintenance.

b) To increase the permeability of the surfaces, in vegetated and non vegetated pavements, in order to decrease their surface temperatures through evaporation processes. These types of pavements are known as permeable, porous, pervious or water retaining materials. As stated, the words previous and permeable are synonymous and signify that water can flow through the material through a series of pores or connected holes. In porous materials holes are available in the material mass but are not necessarily connected. In general, permeable, porous or pervious pavements present a lower albedo than the impermeable equivalents, and higher convective fluxes to the atmosphere because of their higher effective surface area created by the increased void content.. Non vegetated permeable pavements include, porous or rubberized asphalt, porous and pervious concrete, permeable interlocking concrete pavers, concrete and plastic grid pavers filled with gravels. Vegetated permeable pavements provide cooling through evapotranspiration. It includes grass pavers, reinforced turf and concrete grid pavers use lattices of different types that allow grass to grow in the interstices.

c) To increase the thermal storage capacity of the surfaces by adding ingredients of high thermal capacitance or materials of latent heat storage. Common materials used in pavements present a high thermal capacitance and is quite difficult to increase it further. However, addition of latent heat storage materials in the mass of the pavements, contribute to reduce surface temperatures during daytime and decrease sensible heat release to the atmosphere.

d) To use external mechanical systems in order to reduce the surface temperature of the paving materials. This includes among other, circulation of a fluid in the mass of the pavement to remove the excess heat, and circulation of underground water in the pavement mass.

e) Provide efficient shading of the paved areas using natural or artificial solar control devices. Shaded surfaces present a much lower surface temperature as the absorbed direct solar radiation is seriously reduced. Solar shading devices may be natural like trees and green pergolas or artificial. Shading devices should allow infrared radiation emitted by the pavements to escape in the atmosphere to promote radiative cooling of the pavements surface.

In the following chapters the state of the art of the previously described types of pavements is presented.

REFLECTIVE PAVEMENTS

Increasing the albedo of pavements helps to decrease their surface temperature and reduce the amount of sensible heat released to the atmosphere. In parallel, it decreases the need for night lighting and increases the durability of the pavements.. Pavements consist mainly of aggregates bounded by a binder. Albedo may increase by either provide an appropriate surface coating, or aggregates of light color or a proper binder or a combination of the above.

Apart of the commercially available reflective pavements, important research developments are carried out and reported aiming to develop high reflective pavements. Five technological approaches are developed and tested.

a) The use of white high reflective paints on the surface of the pavement. New generation white paints of new generation present a very high solar reflectivity that in many cases exceeds 90 %. Use of such paints could significantly decrease the surface temperature of the pavements and decrease sensible heat released to the atmosphere. The use of high reflective paints applied on the surface or the mass of the pavements is studied. The highly reflective paints are applied on the surface of concrete pavement tiles. Albedos in both cases ranged between 0,8-0,9. Experimental testing was performed during hot summer conditions and comparative results are reported against conventional white tiles. . In particular, the thermal performance of 14 highly reflective white concrete pavement materials covered with reflective paints based on different types of technologies, were comparatively tested under hot summer conditions. The albedo of almost all tested materials was between 80-90%. The emissivity of the non-aluminum pigmented coatings was higher than 0,8, while for the aluminum based paints it varied between 0,3 and 0,4. It was found that the use of highly reflective coatings reduces the daily surface temperature of a white concrete pavement under hot summer conditions by 4 K and by 2 K during the night. The specific tiles were warmer than the ambient air by only 2 K during the day and cooler by 5,9 K during the night. A clear correlation between the emissivity of the materials and the nocturnal surface temperature was found. Pavements covered with aluminum based paints presented a higher surface temperature than the other tiles. Aging of the used paints is found to play a very important role on the thermal performance of the pavements. It is reported that the acrylic elastomeric coatings was the coolest coating during the daytime period of the first month of the monitoring period, but became a lot warmer during the second and third month of the testing. Highly reflective white coatings, (ρ=0,88), based on the use of calcium hydroxide were also prepared and tested against conventional white pavements, (ρ=0,76), under summer conditions. The infrared emittance of the material was close to 0,85. Such a coating is inexpensive, environmentally friendly, permits the air to pass through while it presents high dirt pick up resistance. The main disadvantage of the materials is the effect of chalking. To face the problem, an acryl binder was used. It is reported that during the daytime the prototype reflective materials have lower surface temperatures ranging between 1 and 5 K, while during the night the difference was close to 1 K.

b) Use of Infrared reflective colored paints on the surface of the pavement. When nonwhite pavement materials have to be employed, infrared reflective pigments may be used to increase their global albedo.. Such a pavement surface of any color, may reflect strongly in the near infrared part and thus present a much higher solar reflectivity than a conventional material of the same color. Infrared reflective paints are used to modify the surface albedo of colored concrete and asphalt pavements by five research groups.. Infrared reflective paints were applied directly on the surface of concrete pavements . IR reflective paints were applied on the surface of asphalt together with hollow ceramic spheres to reduce the conductivity of the pavement. Thin reflective asphaltic layers of different colors developed using infrared reflective pigments were applied on conventional ashalt pavements. Ten prototype cool colored pavement materials using infrared reflective pigments were tested against conventional materials of the same color, under hot summer conditions. As reported, the reflective black material presented an albedo close to 0,27 and had a mean daily surface temperature almost 10 K lower, compared to the standard black, ρ=0,05. In parallel, the reflective blue had an albedo close to 0,33 and almost 4,5 K lower mean surface temperature compared to the conventional blue having a reflectivity of 0,18.

The use of colored reflective pavements, based on the use of inorganic infrared reflective pigments, is already commercialized in the United States. The albedo of the proposed pavements is around 0,45 to 0,55. As reported, the use of the pavements reduces surface temperatures by 11-22 K.

Thin layer asphalt pavements are developed by mixing colorless elastomeric asphalt binders with infrared reflective pigments and aggregates of special characteristics. Five samples, (green, red, yellow, beige and off white), were developed and tested under hot summer conditions against samples of conventional asphalt. The albedo of the thin asphalt layers ranges between 27 % for the red and green samples and 55% for the off white sample. The reflectance of the conventional asphalt was measured around 4%. All samples presented a high absorptance in the UV range, while their reflectance in the infrared was high and between 39 to 56 %. Thermal monitoring of the samples has shown that during the day all samples demonstrated a surface temperature that was higher than the ambient one, while during the night time the air temperature was always higher than that of the asphalt samples, mainly because of the high emissivity of the materials. The average daytime surface temperature of the samples ranged from 36^{o} C for the off white sample to 43,6 ^{o} C for the red one. The corresponding surface temperature of the conventional asphalt was close to 60 ^{o} C. The nigh time surface temperature of all the developed samples was almost 1 to 2 K lower than that of the conventional asphalt.

c) Use of heat reflecting paint to cover aggregates of the asphalt. The use of IR reflective paints to cover the aggregates used in asphaltic pavements is proposed and tested.. The pavements are made using a heat reflecting paint that has coated each piece of aggregate, while in conventional reflective asphalt pavements the paint is applied only in the surface. The albedo of the pavements varied between 0,46 and 0,57. Monitoring showed that the developed pavements present a much lower surface temperature than a conventional drainage pavement, while temperature differences varied between 10,2 and 18,8 K. In parallel, a similar technology to prepare high albedo coatings for asphalt pavements was proposed and tested. The experiment taken place in Japan, during the summer period. It is reported that when the albedo of the pavement increased to 0,25 its surface temperature was almost 6,8 K lower than that of the conventional asphalt, while when the albedo increased to 0,6 the corresponding surface temperature decrease was close to 20 K. In a general way, it is found that when the albedo value increased by 0,1 the corresponding decrease of the surface temperature was close to 2,5 K.

d) Use of color changing paints on the surface of the pavement. Color changing coatings to be applied on pavements were proposed by several authors. In particular thermochromic coatings are able to respond thermally to the environment and change reversibly their color and reflectivity from lower to higher values, as temperature rises. Such type of pavements were developed and their thermal performance was tested in comparison to highly reflective and common coatings. Eleven tiles of different color were developed and tested under hot summer conditions. The pavement coatings were developed using organic thermochromic pigments together with an appropriate pigment and other stabilizing components. The infrared emittance was very similar for all the tested pavements. Monitoring of their surface temperature has shown that the daily mean surface temperature of the thermochromic coatings range from 31,0 to 38,4^{o} C, from 34,4 to 45,2^{o} C for the infrared reflecting cool coatings and 36,4 C to 48,5 ^{o} C for the common coatings. In all cases, the mean daily surface temperature of the thermochromic pavements was lower than that based on the use of infrared reflecting pigments and the common coatings. The nocturnal temperature of the three types of tested coatings was almost similar. Measurements of the spectral reflectivity of the thermochromic coatings, have shown that their maximum albedo increase from colored to colorless phase was 43%.

e) Use of fly ash and slag as constituents of the concrete. In particular fly ash and slag are used as constituents for the preparation of the concrete. It is reported that when 70 % of slag is used as cement replacement the mix presented an albedo of 0,582 which is 71 % than the albedo of the conventional mix. Although the results are quite important, developments on this field are limited and may not be considered as a strong research direction.

PERMEABLE PAVEMENTS

Permeable and water retentive pavements generally include additional voids than conventional pavements in order to allow water to flow through into the sub layers and the ground while may include water holding fillers to store water. Evaporation of the water helps to reduce the surface temperature of the pavements and contribute to the mitigation of the urban heat island while the risk of flooding is reduced. Three are the performance critera for water retentive pavements : a) the ability to decrease its surface temperature under fine weather, b) sustainability to suppress the temperature rise after rainfalls and c) Maximum durability and minimum decrease of its performance over time

Important research has been carried out to improve the thermal performance of permeable and water retentive pavements. Six technological approaches are developed and tested, for asphalt, concrete and ceramic pavements.

a) Use of water holding fillers made of steel by products as an additive to porous asphalt : A new water holding pavement consisted of water holding fillers made of steel by products and integrated in porous asphalt is presented and tested both experimentally and theoretically against porous asphalt used in permeable pavements with a porosity equal to 0,3. It is reported that the average surface temperature of the water holding pavement was 0,6 K lower than that of the infiltration porous asphalt, while the air temperature above the water holding pavement was almost 0,5 K lower than above the conventional porous asphalt. The sudden decrease of the surface temperature of the conventional porous asphalt was higher than that of the water holding pavement, however the evaporation and the cooling effect in the later continue for longer than the conventional porous pavement presenting a maximum of about 3 days.

b) Use of fine blast-furnace powder in water retentive asphalt .The development and testing of a water retentive pavement material for roads using fine blast-furnace powder is described. The fine blast furnace powder is an admixture used in cement and like and is generated by the blast furnace process. The material was tested experimentally under real conditions in roads for long periods and it is shown that the water absorbing properties of the material present only a small change after accelerated curing, while as it concerns its thermal performance it is reported that during the third year of its operation , its surface temperature was even 14 K lower that of a dense graded asphalt pavement.

c) Use of fine texture pervious mortar as an additive to pervious concrete : The development and testing of a pervious concrete pavement combined with fine texture pervious mortar is described. Mortar is produced using cementitious materials, aggregate and water and is is used in order to improve the surface texture of the pervious concrete. The water permeability of the final composition was quite low, (2-3 mm/s). No data are available about the thermal performance of the new material.

d) Use of bottom ash and peat moss as additives in pervious concrete : The development and the experimental evaluation of a novel porous pavement block using bottom ash and peat moss is described. Peat is a porous material that acts as an adsorbent to remove heavy metals from aqueous solutions. The developed pavement was tested experimentally against conventional asphalt and normal porous blocks. It is found that the proposed material presents almost 18 K lower surface temperature than asphalt after a rainfall, while the maximum surface temperature difference with the conventional porous pavement was almost 9 K.

e) Use of fly ash with very narrow particle size distribution in bricks : The development of porous bricks presenting an open porosity of 22-43 %. The bricks have an average porous size between 0,4 and 50 μm and were prepared using fly ash with very narrow particle size distribution. Experimental work , has shown that lower surface temperatures of water retentive materials in association to the limited reflected radiation helps to improve thermal comfort of citizens.

f) Use of industrial wastes as raw material for ceramic tiles : A new water retentive ceramic tile used for pavement has been developed and experimentally tested. The tile is made using industrial wastes as raw material and is considered as one of the most water retentive ones. The pavement has been experimentally tested outdoors under saturation conditions and is found to be almost 10 K of lower temperature than a concrete roof. In parallel, the air above the tile was almost 1-2 K of lower temperature. The use of water retentive materials presenting a high capillary ability has been proposed. As reported, these materials have the ability to suck up and spread efficiently the water in the whole surface of the pavement. Measurements have shown that the surface temperature of the proposed materials was almost 10 K lower than that of the dry material and almost 25 K cooler than the surface temperature of conventional asphalt. The measured sensible and latent heat fluxes from the wet material were 70 W/m^2 and 430 W/m^2 respectively.

CONCLUSIONS

Important research is carried out aiming to better document, understand and mitigate urban heat islands. New materials, systems and technologies have been developed and proposed in order to decrease the sensible heat flux to the atmosphere from different urban structures like buildings and paved surfaces. As it concerns the research objectives on the field of cool pavements, two main research streams have been developed aiming either to develop highly reflective paved surfaces or permeable pavements making use of the cooling evaporation capacity of water.

Actual research trends to develop highly reflective pavements focus on the use of highly reflective white coatings and infrared reflective colored pigments to increase the albedo of the pavements surface, the use of reflective paints to increase the reflectance of the pavement ingredients, and also the use of color changing paints to achieve a better thermal performance all year round. .Laboratory tests have shown that the albedo achieved can be very high and the pick surface temperature of the paved materials may decrease by up to 20 K. Newly developed reflective materials and techniques were tested in many demonstration and real scale projects. Unfortunately, few projects are monitored in detail to document precisely the expected benefits from a large scale implementation of reflective pavements It is considered that there is an urgent need for more large scale demonstration projects to assess experimentally and in details all aspects related to the modification of the local microclimate and the possible impact on thermal comfort and energy consumption.

Permeable and water retentive pavements, vegetated or not, are more appropriate for rainy and humid areas where the availability of water is not a problem. Actual research targets aim mainly to involve additional agents in the mass of the pavements like steel bioproducts, fine blast furnace powder, fine texture pervious mortar, bottom and fly ash, peat moss and industrial wastes. Research aims also to improve the capillary ability of the pavements i to increase the water content and the evaporation capacity of the materials.. Laboratory tests have shown that new generation permeable pavements seem to present a significant lower surface temperature than the corresponding conventional permeable materials. However, the thermal performance of the permeable and water retentive pavements depends highly on the availability of water.

Many demonstration and large scale applications of permeable and water retentive pavements have been realized. However, the existing scientific information regarding their thermal performance is quite limited, as very few projects have been monitored.

REFERENCES

Santamouris M : Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. Renewable and Sustainable Energy Reviews. In Press, 2013