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Concrete's Role in Reducing Urban Heat Islands

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Lawrence Berkeley National Laboratory (LBNL) research shows that on warm summer days, the air in large cities can be significantly hotter than surrounding rural areas. The annual mean air temperature of a city with one million people or more can be 1.8-5.4 °F (1-3 °C) warmer than its surroundings. In Baltimore, Phoenix, Tucson, Washington, Shanghai, and Tokyo, for example, scientific data show that July's maximum temperatures during the last 30 to 80 years have been steadily increasing at a rate of one-half to one degree Fahrenheit (0.3-0.6 °C) every ten years as a result of urban development.[1] Additionally, on a clear, calm night the temperature difference can be as much as 22 °F (12 °C).[2] This phenomenon is called the urban heat island effect (see Figure 1).

Urban development not only transforms ecosystems, but it also changes variables that affect weather and climate, including land surface temperature, surface roughness and evaporation. The National Aeronautics and Space Administration (NASA) uses specially equipped aircraft and satellites to collect thermal data of the Earth's surface. The images, such as the one of Atlanta on September 28, 2000, shown in Figure 2, document the differences in land surface temperatures that result when natural or agricultural vegetation is replaced with buildings and pavements. Scientists suspect that the urban heat island effect not only increases air temperatures within the urban environment but may be a factor that influences rainfall in their surrounding areas. The heated surface causes air to rise and, as it cools,

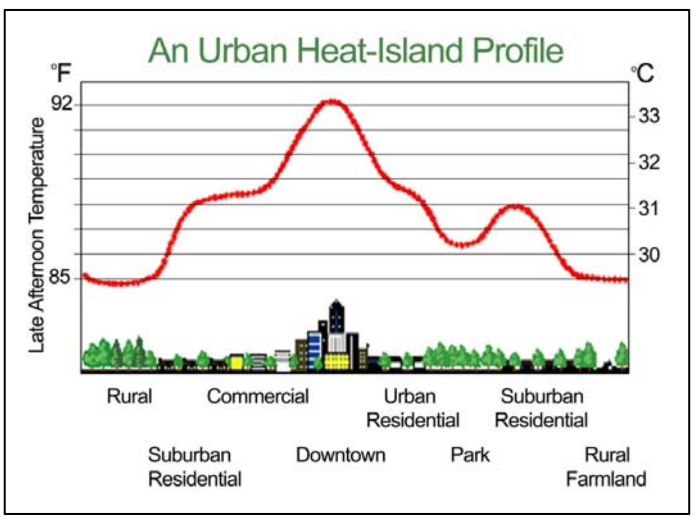

Figure 1. Fewer trees, along with dark colored roofing and pavements cause the heat island effect, raising temperatures in urban and suburban areas (adapted from LBNL).[1]

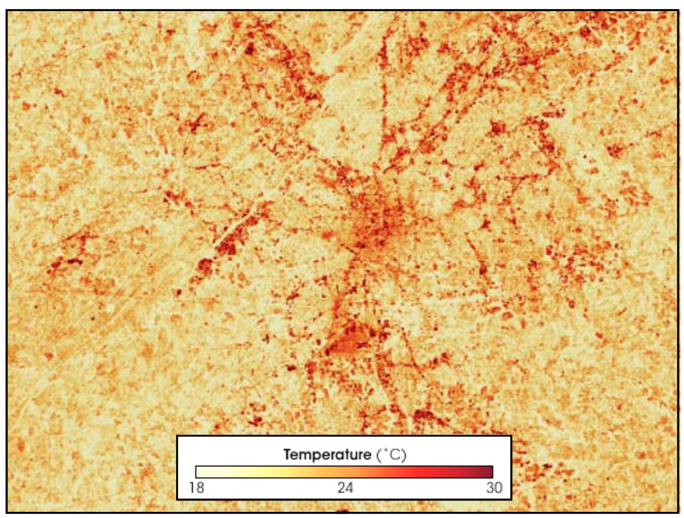

Figure 2. This thermal image of Atlanta on September 28, 2000, indicates the densely vegetated areas are 64 °F (18 °C) whereas the most developed areas are 86 °F (30 °C).[3]

causes water vapor to condense into rain that falls downwind of the city. Studies of rainfall patterns in the Southeast U.S. have shown that rainfall downwind of major urban areas can be as much as 20 percent greater than upwind areas.[3]

The U.S. Environmental Protection Agency (EPA) explains how an urban heat island (UHI) is created and states that "as urban areas develop, changes occur in their landscape. Buildings, roads and other infrastructure replace open land and vegetation. Surfaces that were once permeable and moist become impermeable and dry. These changes cause urban regions to become warmer than their rural surroundings, forming an 'island' of higher temperatures in the landscape."[4]

Rosenfeld explains it in simple terms—dark horizontal surfaces absorb most of the sunlight falling on them and consequently dark surfaces run hotter than light ones. This is the main cause of the urban heat island effect.[5]

On a smaller scale, heat islands can occur not only on a group of surfaces (like hundreds of roofs and pavements in an urban area) but also in the local, surrounding atmosphere (commonly referred to as a microclimate). For example, on a hot, sunny day, the sun can heat dry, exposed urban surfaces to temperatures 50–90 °F (27–50 °C) hotter than the surrounding air, while shaded or moist surfaces—often in more rural surroundings—remain close to air temperatures.[6] One study measured the temperature of various pavement types during a hot 90 °F (32 °C) summer day and found that dark colored pavement (asphalt) had a temperature of 195 °F (90 °C) at the surface and light colored pavement (concrete) had a temperature of 155 °F (68 °C).[7]

Impacts of Urban Heat Islands

Elevated temperatures in urban heat islands can have detrimental effects on a community's environment and quality of life, including increase demand on energy, increased air pollution, smog, greenhouse gas emissions, human health effects and decreased water quality.

Increased Energy Demand
Electricity demand for cooling increases 1.5–2.0% for every 1 °F (0.6 °C) increase in air temperatures, starting from 68 to 77 °F (20 to 25 °C). This means that 5–10% of the electricity demand for a city is used to compensate for the heat island effect.[2] During periods of extreme heat, businesses and households run air conditioning, lights, electronic equipment and appliances. This often overloads the electric utility systems and can result in brownouts or blackouts.

Increased Air Pollution and Greenhouse Gas Emissions
Because most electricity is generated by burning fossil fuels such as coal or natural gas, any increase in energy demand can increase air pollution and greenhouse gas emissions. Air pollutants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and mercury (Hg). These air pollutants can have negative effects on human health and contribute to the formation of ground-level ozone (smog) and acid rain.

Ground-level ozone is formed when NO_x and volatile organic compounds (VOCs) react in the presence of sunlight and heat, causing smog. Acid rain is a broad term used to describe wet and dry deposition from the atmosphere containing high levels of SO_2 and NOx resulting from fossil fuel combustion. As this acidic water flows over and through the ground, it can have a negative impact on plant and animal life. Greenhouse gases including carbon dioxide (CO_2) are also generated when burning fossil fuels, so any increase in demand for electricity increases global warming potential.

Reduced Human Health and Comfort
Heat waves are exacerbated in urban heat islands and can result in higher than average rates of mortality. The Centers for Disease Control and Prevention (CDC) estimates that 8,015 premature deaths were caused by excessive heat in the U.S. between 1979–2003.[8] This is more than the number of premature deaths resulting from hurricanes, lightning, tornadoes, floods and earthquakes combined. In addition, increased temperatures and high air pollution levels associated with urban heat islands can result in respiratory difficulties, exhaustion and non-fatal heat stroke. Children, older adults and those with existing health problems are especially affected by elevated temperatures.

Reduced Water Quality
Dark colored pavements and roofing absorbs the sun's energy, resulting in extremely high surface temperatures that can significantly increase temperature of stormwater runoff. This higher temperature stormwater drains into storm sewers and is eventually released into bodies of water like streams, rivers, ponds and lakes. Elevated water temperature can affect the metabolism and reproduction of many aquatic species and can be fatal to some aquatic life.

Mitigating Urban Heat Islands

EPA published a report titled *Reducing Urban Heat Islands: Compendium of Strategies* that offers compelling reasons for reducing the urban heat island effect.[9] The EPA report details several strategies to mitigate the effect of urban heat islands, including:

- Design and material selection for cool roof structures and surfaces;
- Design and material selection for cool pavement surfaces; and
- Incorporation more trees, planting and landscaping elements in urban communities.

In addition, the U.S. Department of Energy (DOE) provides several recommendations for reducing urban heat islands. The program suggests that by replacing dark colored pavements and roofing with light and heat-reflective concrete-based materials, along with careful planting of trees, the average summer afternoon temperature in urban areas can be significantly reduced.

Reflective Surfaces

Lighter surfaces tend to reflect solar light and heat while dark surfaces tend to absorb light and heat. Solar reflectance, or albedo, is the percentage of solar energy or short-wave radiation (typically visible light) reflected by a surface. A higher solar reflectance signifies greater ability to reflect light away; thus, greater solar reflectance reduces the amount of solar energy absorbed by a structure and keeps it cooler. Solar reflectance is measured on a scale of zero to one. Another similar measure is solar reflectance index (SRI) that incorporates both solar reflectance and thermal emittance in a single measure to represent a material's temperature exposed to sunlight. SRI is measured on a scale of zero to 100.

Researchers at LBNL have estimated that every 10% increase in solar reflectance in urban areas could decrease surface temperatures by 7 °F (4 °C). Further, they predict that if pavement reflectance throughout a city were increased from 10% to 35%, the air temperature could potentially be reduced by 1 °F (0.6 °C) which would result in significant benefits in terms of lower energy use and reduced ozone levels.[10] Another separate study estimated over $90 million per year in savings from temperature reductions attributed to increased pavement albedo in the Los Angeles area.[11] Table 1 provides a summary of solar reflectance (albedo) values for different pavement types. Roofing and cladding also directly affects cooling and heating energy use in buildings. Dark colored roofing and cladding are heated by the summer sun that in turn raises the summertime air-conditioning demand for the building. "Cool roofs" are roofs that are designed to maintain a lower roof temperature than traditional roofs while the sun is shining.

Pavement Type	Solar Reflectance
Asphalt (new)	0.05 - 0.1
Asphalt (weathered)	0.15 - 0.2
Portland cement concrete (new)	0.35 - 0.40
Portland cement concrete (weathered)	0.25 - 0.30
White cement concrete (new)	0.70 - 0.80
White cement concrete (weathered)	0.40 - 0.60

Table 1. Solar reflectance (albedo) for various pavement types (adapted from Pomerantz, et al)[12]

There is a sizable body of research documenting energy-saving effects of cool roofs.[13,14] Both simulated models and field experiments on individual buildings in Ontario, California and Florida show that coating roofs white reduces summertime average daily air-conditioning electricity use from 2-63%. Low roof temperatures lessen the flow of heat from the roof into the building, reducing the need for electricity for space cooling. Since roof temperatures peak in late afternoon, when summer electricity use is highest, cool roofs can thereby reduce peak electricity demand.

In another example, researchers monitored buildings in Sacramento with lightly colored roofing and cladding and found these buildings used up to 40% less energy for cooling than those with darker surfaces.[15]

Depending on the electric power fuel mix, decreased energy demand associated with cool pavements and roofing will result in lower associated air pollution and greenhouse gas emissions. Cooler air temperatures also slow the rate of ground-level ozone formation and reduce evaporative emissions from vehicles. A 2007 paper estimated that increasing pavement albedo in cities worldwide, from an average of 35 to 39%, could achieve reductions in global CO_2 emissions worth about $400 billion.[16]

Counter intuitively, using light colored roofing and pavements can also benefit cities in colder climates. For example, in New York City, the length of the day in December is half that of a day in June. Also, the sun is so low in the sky that it shines on only half the roof or pavement area in December versus June. In addition, New York experiences three times more cloudy days in the winter than in the summer. When you multiply these three factors (1/2 x 1/2 x 1/3 = 1/12), the potential for horizontal surfaces to absorb the sun's energy is only 1/12 in December as in June. This means that because so little sun ever reaches roofs and pavements in the winter months the benefits of lowering temperatures in the summer far outweighs raising temperatures in the winter.[5]

Moreover, research on the reflectivity of concrete pavements indicates that concrete pavements can help reduce lighting costs, energy demand and enhance safety on roads and parking lots. The essential quality that appears as the brightness of an object is called luminance. Luminance is the intensity of brightness and is measured in candela per unit area of a surface. Higher luminance values are associated with brighter surfaces. The average luminance of concrete pavements was determined to be 1.77 times that of asphalt pavements. As a consequence, asphalt parking lots use 57% more electrical energy than concrete parking lots. The report also concluded that better uniformity of the luminance also could be achieved with concrete surfaces.[17]

Radiative Forcing

Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word "radiative" signifies that the factors affect the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. Positive forcing tends to warm the surface while negative forcing tends to cool it.[18]

Human activities and natural processes cause direct and indirect changes in climate change drivers. In general, these changes result in specific radiative forcing changes, either positive or negative, and cause some non-initial radiative effects, such as changes in evaporation. Radiative forcing and non-initial radiative effects lead to climate perturbations and responses like global and local temperature fluctuations, changes in microclimate precipitation or can even cause extreme weather events.[19]

Utilizing high albedo surfaces, such as concrete pavements and white roofs, will reflect solar energy and therefore reduce the radiative forcing or produce a negative forcing effect. Akbari, et al, states that using cool roofs and cool pavements in urban areas can increase the albedo of urban areas by 0.1. The authors estimate that increasing the albedo of urban roofs and paved surfaces will induce a negative radiative forcing which is equivalent to offsetting 48.5 billion short tons (44 Gigatons) of CO_2 emissions.[20]

On a global scale, negative radiative forcing can result in huge reductions in global warming potential. At a conference in 2009, then U.S. Energy Secretary Dr. Steven Chu stated, "...if you look at all the buildings and make all the roofs white, and if you make the pavement a more concrete-type of color than a black-type of color, and you do this uniformly... It's the equivalent of reducing the carbon emissions due to all the cars in the world by 11 years."[21]

Shading, Infiltration and Evapotranspiration

Another mitigation strategy to reduce urban heat islands is to provide shade or canopies over pavements (e.g. shade canopies over residential streets or parking lots) or shade next to buildings. Traditionally, trees are used to provide the needed shade as well as provide CO_2 transpiration and evapotranspiration. The challenge in these situations is the amount of impervious cover in the urban environment which limits the infiltration of water into the surrounding soils and to tree roots.

Pervious or porous pavement systems provide direct infiltration of rain water into soil systems beneath the pavement structure. Typically, pervious pavements are constructed with a porous surface, an optional filtration material to filter out potentially harmful pollutants in the water and a permeable subbase from uniformly graded stone. The porous surface can be constructed with pervious concrete. Typically, pervious concrete has between 15% and 25% interconnected voids allowing rainwater to pass right through into the soil below. The infiltration of water into the soil can be a significant contributor to increased tree root growth which leads to fuller and denser tree canopies.[22]

In addition, pervious pavements provide cooling of pavement surfaces through enhanced evaporation.[9] Research shows that pervious pavements store less energy than traditional pavements as a result of their high porosity which can also help reduce the urban heat island effect.[23]

Figure 3. Hopkins Parking Structure at the UC San Diego Campus Illustrating Photovoltaic Cells for Parking Lot Canopies and High Albedo Concrete in the Driving Lanes.

Figure 4. Green roofs, such as Chicago City Hall's, help reduce urban heat islands through evapotranspiration and reducing heat gains and losses through the roof.

Another shading strategy is to cover parking areas or spaces with photovoltaic cells (solar panels). Panels not only provide shading for the pavement and parked cars, but the electricilty generated can be used to power nearby buildings. Panels were installed at the University of California San Diego Hopkins Parking Structure which demonstrates a perfect example of combining photovoltaic cells as parking canopies with high albedo concrete in the driving lanes (see Figure 3).[24]

Green roofs or vegetated roofs are also an innovative technology that can help mitigate urban heat islands and provide a range of public benefits. A green roof is a vegetative layer grown on a rooftop that provides shade to surfaces and removes heat from the air through evapotranspiration. Green roofs can be installed on a wide range of buildings, including industrial, educational, government facilities, offices, other commercial property and residences. For the most part, green roofs impart significant load to a structure and are often supported by concrete slabs.

A green roof is able to reduce urban heat islands through the plants and growing media. They provide the basis for evapotranspiration, reducing ambient air temperatures and generating a net cooling effect for the surrounding buildings. Plants absorb water through their roots and emit it through their leaves—this movement of water is called transpiration. Evaporation, the conversion of water from a liquid to a gas, also occurs from the surfaces of vegetation and the surrounding growing medium. Together, evapotranspiration cools the air by using heat from the air to evaporate water.

Reduced surface temperatures also help buildings stay cooler because less heat flows through the roof. Lower green roof temperatures result in less heat transfer to the air above the roof, which in turn keep urban air temperatures lower. Combined with the effects of shading, reflective surfaces, thermal mass transfer and insulation—significantly reduces heat gain within buildings, reducing the need for air-conditioning.

Additionally, the lower ambient temperature above a green roof increases the efficiency of roof-mounted HVAC systems through cooler air intakes. Air-conditioning systems begin to lose efficiency at about 95 °F (35 °C). Drawing cooler air into the system can help reduce energy costs. Green roofs tend to maintain an ambient temperature of 90 °F (32 °C), creating optimal conditions for air-conditioning systems.[25]

Studies at The Field Roofing Facility in Ottawa, Canada, concluded the green roof significantly moderated the heat flow through the roofing system in the warmer months. The average daily energy demand for space conditioning due to the heat flow through the roof was reduced from 20,500-25,600 Btu/day (6.0-7.5 kWh/day) to less than 5,100 Btu/day (1.5 kWh/day).[26]

Modeling studies also show that, especially with sufficient moisture for evaporative cooling, green roofs could play a role in reducing atmospheric urban heat islands on a city scale. A study in Toronto, Canada, predicted that adding green roofs to 50 percent of the available surfaces downtown would cool the entire city by 0.2-1.4 °F (0.1-0.8 °C).[27]

An entire urban area can benefit from implementing these mitigation strategies. If an entire community drops a degree or so in temperature, then everyone's air-conditioning load goes down—even those buildings that are not directly shaded or that still have dark roofs, cladding and pavements. This indirect annual savings would total an additional 12%—2,388 billion Btu (0.7 billion kilowatt-hours) or $70 million. Implementing mitigation strategies would lower the need for peak electrical generating capacity by about 5 billion Btu/hour (1,500 megawatts)—equivalent to two or three large power plants.[5]

Government Initiatives and Building Standards

There are several national initiatives and standards in the U.S. that are focused on reducing surface temperatures of buildings and pavements. The Cool Roof and Cool Pavements Initiatives of the DOE and EPA provide guidance for reducing urban heat islands based on research and strategies identified by LBNL, NASA and the National Academies of Sciences, among others. These initiatives highlight the critical part that concrete materials can play in providing highly reflective surfaces for both buildings and pavements.

In addition, green building standards such as the LEED Green Building Rating System and the International Green Construction Code (IgCC) provide incentives and minimum requirements for reducing urban heat islands. In LEED, incentives are provided for buildings that incorporated light colored roofing and pavements, pervious pavements, covered parking areas, green roofs and shading as strategies for reducing the urban heat island effect. IgCC has minimum requirements for incorporating these mitigation strategies. New standards for green roadways and infrastructure such as the GreenRoads rating system and the Envision infrastructure rating system incorporate standards for light colored pavements and roofing along with other mitigation strategies.

The Life Cycle Benefits of Mitigation

Reducing the urban heat island through mitigation strategies in an existing urban landscape is a long process. However, implementing these strategies in new construction or through the rehabilitation process of existing buildings and pavements can have a significant impact on the global warming potential (GWP) related to these structures. An important aspect to these strategies is the need for a combined approach to maximize the benefit of the mitigation strategies at the least possible cost over the life of the structure.

At the Massachusetts Institute of Technology (MIT) Concrete Sustainability Hub, life-cycle assessment methodologies have been developed to assess construction materials and processes on GWP from buildings and pavements. Life cycle assessment (LCA) considers all life-cycle stages, from initial material extraction to demolition. System boundaries are drawn to capture each mechanism by which pavements and buildings impact the environment. These boundaries not only include the product manufacturing and construction activities, but also the operational, maintenance and end of life stages.[28]

The MIT research quantified GWP for 12 major roadway classifications used in the United States. The research results were used to estimate GWP of new concrete pavement construction each year and identified strategies for reducing GWP of pavements, including increasing albedo (see figure 5).

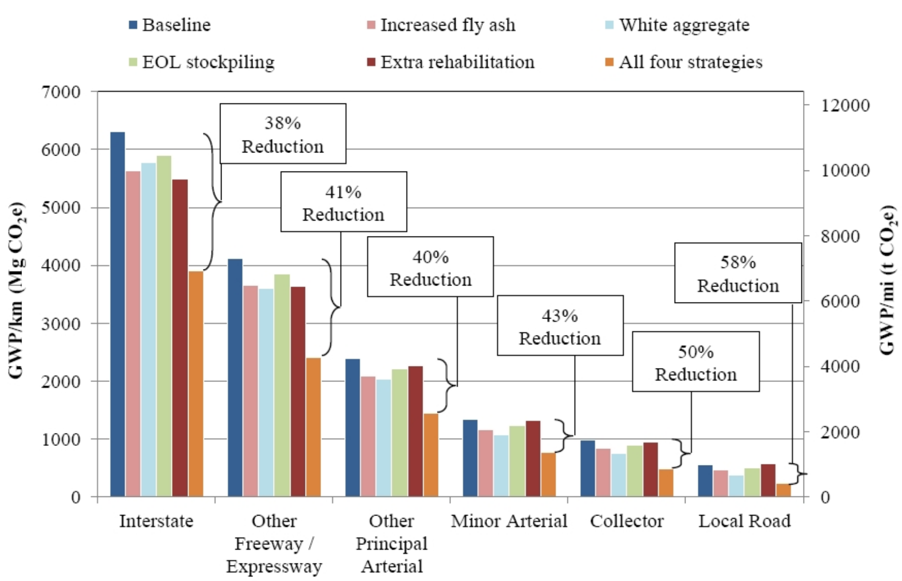

Figure 5. GWP reduction strategies for concrete roadways using Life Cycle Assessment (LCA) methodology.

Notable GWP reduction strategies identified by MIT include:

- 15% GWP reduction for urban interstates to 36% GWP reduction for local roads by increasing fly ash in concrete from 10% to 30%;
- Increase albedo reduces the urban heat island effect resulting in up to 43% reduction in GWP for rural local roads;
- Carbonation through crushing and stockpiling concrete for one year sequestered 28% of initial CO_2 released;
- Reducing roughness through extra pavement rehabilitations reduces GWP by 13% for urban interstates; and
- Implementing all four strategies could decrease GWP by 38% for urban interstates to 58% for urban local roads.

Conclusion

The urban heat island effect has been known and studied for decades and we know that it can cause increased energy consumption, elevated emissions of air pollutants and greenhouse gases, compromised human health and comfort, and impaired water quality. We also realize that a comprehensive approach to mitigating against urban heat islands can be achieved through the use of appropriate construction materials and changing the actual landscape of our urban environments.

The use of light colored pavements as well as cladding and roofing in our urban areas can contribute to overall energy savings and reduced carbon emissions. Because concrete is light in color, it absorbs less heat and reflects more light than dark-colored materials, therefore maintaining a relatively low surface temperature. Concrete has been demonstrated to have a positive impact on the localized ambient temperatures and can reduce energy required to air condition buildings.

In addition, we can implement other strategies such as pervious pavements, shading and green roofs, all of which rely on concrete to further mitigate urban heat island effects. Methodologies now exist to help quantify, from both an environmental and economic perspective, the impact that mitigation strategies may have on combating global warming potential and urban heat islands.

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