Energy Research and Development Division
CONSULTANT REPORT

URBAN HEAT ISLAND MITIGATION PHASE 2

Cool Communities: Phase 2

Prepared for: California Energy Commission
Prepared by: Lawrence Berkeley National Laboratory

OCTOBER 2014
CEC-500-2015-018

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Contract Number: 500-10-052-P#5

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ACKNOWLEDGEMENTS

This work was supported by the California Energy Commission through its Public Interest Energy Research (PIER) Program. The authors wish to thank PIER managers Dustin Davis and Chris Scruton for their guidance and continued support of Cool Communities research. In addition, the authors also recognize the guidance and support from California Air Resources Board staff and managers Heather Choi, Ash Lashgari, Eileen McCauley, Dana Papke, Courtney Smith and Annemarie Rogers who supported Cool Communities Phase 1 and continued to advise and collaborate on Cool Communities Phase 2.

This research project has benefitted many stakeholders. The authors acknowledge the contributions of Paulette Salisbury and Tom Tietz (California Nevada Cement Association); Tom Van Dam (CTL Group); Marc LaFrance (U.S. Department of Energy); Tom Pyle, Hector Vergara, and Dulce Rufino Feldman (California Department of Transportation); David Ware and Payam Bozorgchami (California Energy Commission); Sherry Hao and Alexis Wong (Cool Roof Rating Council); Kurt Wengler and Steve Condrin (University of California at Davis); Dave Rapkin, Rongzpong Wu, Hui Li, James Signore, and John Harvey (University of California Pavement Research Center); Tom Sani and Nolan Zail (Carmel Partners); Bruce Carter (Lehigh - Hanson Corp.); Bill Clarkson (Teichert Construction); Kristin Race (Cunningham Engineering); Tony Chiovare (Custom-Bilt Metals); Kevin O'Neill (Duracoat Products, Inc.); Misha Sarkovich (Sacramento Municipal Utility District); Herb Gong and Peter Turnbull (Pacific Gas and Electric); Paul Berdahl, George Ban-Weiss, Jonathan Slack, David Faulkner, Douglas Sullivan, Woody Delp, Susan Brady, Jeff Miller, Ross Lyon, Doug Davenport, and Sondra Jarvis (Lawrence Berkeley National Laboratory); Hashem Akbari (Concordia University); Mike Gable (Gable Associates LLC); Darin Robinson and Ming Shiao (CertainTeed); Yoshi Suzuki and Jennifer Freeman (MCA Tile); Gary Weberling, Annette Sindar, and Greg Peterson (Eagle Roofing Products); Toney Seaton, Terry Anderson, Darius Assemi, Mike Bergeron, and Karl Gosswiller (Granville Homes); Steve Jackson (Western Colloid); Ken Alex and Sandy Goldberg (Governor's Office of Planning and Research); Roshini Das and Chad Fenwick (Los Angeles Unified School District); Glen McCrady and Jacob Dobson (Quest Construction Products); Sheri Roese (Emerald Cities); Ron Rudi (Sacramento City Unified School District); William Savidge (California Department of General Services), Don Barrett (GraniteRock); Karen Irwin (U.S. Environmental Protection Agency); David Fink (Climate Resolve); Amy Dickie and Kurt Shickman (Global Cool Cities Alliance); Brendan Reed (City of Chula Vista); Craig Tranby and Greg Spotts (City of Los Angeles); and Kathy Dervin (California Department of Public Health). The authors also acknowledge the guidance, support, and directives of the members of the Cool Schoolyard stakeholder group and the computing services provided by the High Performance Computing Services Group at Lawrence Berkeley National Lab.

For the cool pavement demonstration project, the authors would like to thank and recognize the U.S. Department of Energy for providing financial assistance for the construction of the cool pavement demonstration, several companies that donated materials for the project (CEMEX, GraniteRock, Emerald Cities, and Quest Construction Products), and Biondi Paving for completing the construction.

PREFACE

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Urban Heat Island Mitigation Phase 2 is the final report for the project of the same name (Contract Number 500-10-052) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

In 2006, California introduced the Global Warming Solutions Act (Assembly Bill 32, Núñez, Chapter 488, Statutes of 2006), which requires the state to decrease its greenhouse gas emissions to 1990 levels by 2020. Several "cool community" strategies (utilizing surfaces that stay cooler by strongly reflecting sunlight), including cool roofs, cool pavements, cool walls, and urban vegetation, were identified as effective voluntary measures to reduce emissions and save energy. The team from Lawrence Berkeley National Laboratory evaluated the benefits of cool roof tiles compared to standard asphalt shingles in Fresno, California. Relative to the standard home, the home with cool tile roofing saved 26 percent in annual site energy use. Using local climate models in Bakersfield, Lawrence Berkeley National Laboratory found that deploying cool roofs and cool pavements reduced maximum air temperatures in the downtown area. In a cool pavement demonstration in Davis, California the more reflective pavement surfaces were found to decrease the pavement temperature and thereby reduce the heat that is transferred to the local environment and atmosphere. In addition, outreach and technical assistance activities drove interest in the voluntary adoption of these measures and led to the inception of several new pilot projects, policies, and programs. These measures help California take strides toward meeting emission-reduction goals and help conserve energy. Furthermore, the project components demonstrated co-benefits for California residents, such as reduced utility bills, improved air quality, and enhanced urban livability.

Keywords: Cool roof, cool pavement, solar reflectance, albedo, building energy, energy efficiency, community, urban climate modeling, cool communities

Please use the following citation for this report:

Gilbert, Haley, Benjamin Mandel, Pablo Rosado, Mel Pomerantz, Dev Millstein, Ronnen Levinson. (Lawrence Berkeley National Laboratory). 2014. ***Urban Heat Island Mitigation Phase 2.*** California Energy Commission. Publication Number: CEC-500-2015-018.

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EXECUTIVE SUMMARY

Introduction

Several "cool community" strategies (utilizing surfaces that stay cooler by strongly reflecting sunlight) including cool roofs, cool pavements, cool walls and urban vegetation have been identified as effective voluntary measures with statewide potential emission-reductions of 4 million metric tons of carbon dioxide equivalent per year. In addition, cool community strategies provide benefits for California residents, such as reduced utility bills, improved air quality, and enhanced urban livability. To achieve these savings, Lawrence Berkeley National Laboratory (LBNL) was tasked with advancing the science and implementing cool community strategies.

Project Purpose

This project provided technical assistance to California communities for developing "cool community" programs that save energy, reduce emission of greenhouse gases, and improve the urban environment.

The scope of this project included the following:

- Continue and advance the original Cool Communities project (Contract 500-08-059R; hereafter, Cool Communities Phase 1), including:
    - The cool roof (a roof that stays cool by strongly reflecting sunlight) study and demonstration.
    - The cool pavement (a pavement that stays cool by strongly reflecting sunlightstudy and demonstration.
    - The cool roof website for consumers.
    - "Cool community" courses and resources.
- Expanding outreach, developing model codes, and providing technical assistance
- Quantifying benefits of cool community measures.

Recommendations

Cool Roof Study and Demonstration

In a hot California area, substituting a cool tile roof for a standard asphalt shingle roof can offer substantial annual energy cost savings to a homeowner. In this this study, the cool tile roof achieved 26 percent energy savings over the standard shingle roof in Fresno, California. Tile roofs are already a popular choice for California homes but are less common than asphalt shingles because of initial higher cost.

California will save energy statewide by encouraging the selection of cool tile products for re-roofing. To quantify this potential, the California Energy Commission (Energy Commission) could explore these questions.

1. In a climate like that of Fresno, California how does the life-cycle cost of a cool tile roof compare to that of an asphalt shingle roof? This analysis would necessarily consider the installed cost and service life of each product, as well as the annual energy cost savings.

2. Could Title 24-approved building-energy simulation tools be used to estimate annual savings in California's other 15 climate zones, using savings measured in Fresno (Zone 13) as a check? Also, is there enough information about the construction, operation, and heating, ventilation, and air conditioning (HVAC) equipment of the state's existing home stock to model savings upon re-roofing?

3. What are the potential statewide energy savings, emission savings, and peak demand reductions if cool tile products were selected in place of asphalt shingle products in (a) all climates or (b) in all climates for which the life-cycle cost of the cool tile roof is less than that of an asphalt shingle roof?

4. Should Title 24 promote the use of cool tile roofing through a prescriptive requirement?

5. To what extent can cool tile roofs mitigate the summer urban heat island (lower summer day and night outside air temperatures), and thereby increase comfort, slow the formation of smog, contribute to global cooling (negative radiative forcing of the atmosphere), and further reduce air-conditioning demand?

Meanwhile, the Energy Commission should share the results of this study with California's utilities and consider how rebate and incentive programs could be updated to promote the use of cool tile roofing, especially in hot regions like the Central Valley (population 6.5 million) and Inland Empire (population 4 million).

Cool Pavement Study and Demonstration

The authors advocate that the measurements be continued at the test site so that the effects of time and use can be quantified. The paving industry is just beginning to explore cool pavement technologies; therefore a wide variety of pavement options do not exist. However, the results from this research should stimulate further exploration of new technologies. The authors endorse that the cool pavement demonstration be continued as an experimental site to allow LBNL to test new products as they are developed and to gain experience using and monitoring promising cool pavement technologies.

The project has identified some other areas for recommendations, including improving long-term albedo of cool coatings by further researching the self-cleaning capabilities of products. In addition, CTL Group's study concluded that it is best to measure the albedo of cement concrete as part of the mixture design process to ensure that the mix ratios will result in the specified pavement albedo. LBNL and CTL Group both advocate that manufacturers continue to test all curing compounds and sealants under various climate and pavement use applications to ensure that these products do not negatively affect the albedo of the pavement after placement.

Cool Community Website Content

LBNL proposes that the California Air Resources Board (ARB) upload the local government cool communities content to CoolCalifornia.org as soon as it is feasible. Furthermore, LBNL

wishes to recommend that if future funding is available for website development, LBNL set aside a maintenance fund to address technical issues as they arise. LBNL endorses the additional promotion of the consumer cool roof and local government cool communities' websites.

Since the websites are close to completion, connecting consumers and local governments with these resources is imperative. For the cool roof consumer website, targeting outreach to audiences that implement roofing choices, (namely roofing manufacturers, roofing contractors, and roofing supply companies) is essential. Furthermore, the spread of cool roofs will be facilitated by connecting current cool roof website audiences, mostly homeowners, with more informed suppliers and service providers. The new local government content on cool communities must target its outreach to local government-coordinating organizations (for example, the Local Government Commission, the Institute for Local Government, the International Council for Local Environmental Initiatives – Local Governments for Sustainability) that share resources and best practices among California localities. In addition, presenting at local government events would also help increase visibility and use of the website.

Cool Community Courses and Resources

The projects must continue reaching out to stakeholders in California. At the moment, the Heat Island Group (a team of scientists at LBNL focused on developing strategies to cool cities) serves as the main portal of information on both the science and implementation of these strategies. Building on the success of the first phase of "cool communities," the group has built stronger alliances with partners to leverage resources, a process that must be advanced as the cool community moves forward.

Distributing and presenting cool community resources to additional networks (for example, the Local Government Commission, Coalition for Adequate School Housing, County Public Works Officers) will increase interest in these strategies.

The authors advocate for a survey of existing statewide and local government policies and programs. Results from the survey will be used for group-specific outreach to increase awareness of cool community strategies and mutual benefits/goals.

Codes and Technical Assistance

The number of inquiries from policy makers, manufacturers, the public, and other stakeholder groups has grown significantly since the initiation of the project. Although the number of cool community projects has increased across the state, technical assistance is still essential, especially with organizations and stakeholder groups that have difficulty sifting through existing resources and understanding product claims. These groups require tailored resources that help them make the most responsible decisions for their unique applications, projects, or policies.

Also, the development of additional cool pavement pilot projects can help demonstrate proof of concept and lessen or eliminate uncertainties that prevent the wider adoption of cool pavements. To complement pilot projects, manufacturers of cool pavement products need

continued technical guidance to develop products that can meet more diverse applications and structural demands in cities and communities.

Benefits of Cool Community Measures

The widespread addition of cool roofs and pavements can reduce afternoon air temperatures in Bakersfield, California. These temperature reductions would lower air-conditioning use and decrease the rate of ozone formation in downtown Bakersfield. Similar benefits would be expected in other California cities that are alike in size and climate to Bakersfield.

However, the average temperature reductions found in this study are relatively small compared to the expected warming from climate change; thus, additions of cool roofs and pavements offer only partial reduction of future urban temperature increases. This analysis was designed to capture average temperature changes, and it is possible that average temperature reductions are an underestimate of temperature reductions that occur during the hottest days of year. The team recommends continued research to model the effects of cool community strategies (reduced ambient air temperatures in urban environments) to better understand how to address extreme heat events in the future.

Project Benefits

This project demonstrated the benefits of cool community strategies and drove interest in the cool community voluntary measures. In Fresno, California, the team evaluated the benefits of cool roof tiles relative to the standard home. LBNL found that the annual site energy savings for the cool roof home were 26 percent. In the cool pavement demonstration, the team found that more reflective pavement surfaces decrease the pavement temperature and thus reduce the heat that is convected and emitted to the environment. By applying local climate models to Bakersfield, the team found that the deployment of cool roofs and cool pavements reduced maximum air temperatures by 0.3 degrees Celsius (°C) over the downtown area. Outreach and technical assistance was successful in increasing the voluntary adoption of cool community measures, and led to several new pilot projects, policies, and programs in line with California's emission reduction goals. These activities produced a range of benefits for California's ratepayers by reducing utility bills, improving air quality and enhancing urban livability.

CHAPTER 1: Introduction

1.1 Background

The Global Warming Solutions Act of 2006 (Assembly Bill 32 [AB 32], Chapter 488, Statutes of 2006) was signed by California Governor Arnold Schwarzenegger on September 27, 2006. It set up an enforceable statewide program to cap all greenhouse gas emissions from major industries, including emissions like carbon dioxide (CO_2). The bill, authored by Assembly Speaker Fabian Núñez and Assembly Member Fran Pavley, requires that bythe year 2020 the state's greenhouse gas (GHG) emissions be reduced to 1990 levels – a roughly 25% reduction of GHGs under normal estimates. The California Air Resources Board (ARB) is the lead agency responsible for preparing plans to achieve the objectives stated in the bill and for monitoring and regulating GHG emission sources under AB 32. ARB has specified a voluntary "cool communities" program as an early action program (Tier 1) in support of AB 32.

By 2020, AB 32 seeks to reduce GHG emissions by 174 million metric tons of carbon dioxide equivalent per year (MMT CO2e/yr), of which about 16% (27.3 MMT CO2e/yr) are expected to come from voluntary programs (ARB 2008a). ARB staff estimates that about 15% of these voluntary reductions, or 4 MMT CO2e/yr, could be achieved through "cool-community" measures (ARB 2008b). Shade trees and cool roofs specifically have been identified as strategies to improve energy efficiency and meet green building criteria.

Increasing the albedo of roofs and pavements statewide has been estimated to provide an additional one-time GHG offset estimate of 470 – 1130 MMT CO_2e through negative radiative forcing, also known as "global cooling" (Akbari et al. 2008; Akbari et al. 2009; VanCuren 2010). This offset estimate would equal 17 times the annual GHG reduction yielded by all voluntary measures.

1.2 Project Objectives

The project objective was to research and provide technical assistance to California communities for development of "cool community" programs that save energy, reduce emission of greenhouse gases, and improve the urban environment.

The scope of this project included the following activities:

- Continue and advance the original Cool Communities project (Contract 500-08-059R) by:
  - Continuing the cool roof study and demonstration project.
  - Continuing the cool pavement study and demonstration project.
  - Updating and maintaining the website that serves as a one-stop source of cool roof information for consumers.

- Updating and continuing cool-community courses and developing new resources for stakeholders.
- Expanding outreach, developing model codes, and providing technical assistance to key stakeholders.
- Quantify benefits of cool community measures by estimating decreases in local air temperature.

1.3 Report Organization

This report is organized to present the approach and goals, outcomes, conclusions, and recommendations for each of the activities.

Chapters are:

- Cool Roof Study and Demonstration (Chapter 2)
- Cool Pavement Study and Demonstration (Chapter 3)
- Cool Community Website Content (Chapter 4)
- Cool Community Courses and Resources (Chapter 5)
- Codes and Technical Assistance (Chapter 6)
- Benefits of Cool Community Measures (Chapter 7)

CHAPTER 2:
Cool Roof Study and Demonstration

Roofs with high albedo or solar reflectance (SR) stay cooler in the sun than traditional dark roofs. Lower roof temperatures decrease the heat transfer into a building, saving energy if the space is air conditioned or increasing comfort if it is not. Choosing roofing products with high thermal mass and above-sheathing ventilation (the airflow between a roofing product and the boards that secure it to the roof) can further reduce heat flow into the conditioned space. This cool roof study and demonstration quantifies the energy-savings benefits of using a cool tile roof instead of a standard asphalt shingle roof on a single family home in California's Central Valley.

The full journal manuscript is presented in Attachment 1

2.1 Approach and Goals

Temperatures, heat flows, and heating, ventilation, and air-conditioning (HVAC) energy uses were measured for a year in two side-by-side single-family homes in Fresno, California. Fresno is located in the state's Central Valley, a hot climate in which homes use air conditioning from about May to October. Each single-story home has a floor area (and ceiling area) of about 188 square meters (m^2) or 2,020 square feet (ft^2). One house has a reflective concrete tile roof (initial SR 0.51; thermal capacity 40 kilojoules (kJ)/m^2•kelvin (K), and the other a standard dark asphalt shingle roof (initial SR 0.07; thermal capacity 22 kJ/m^2•K) (Figure 1). The flat tiles were mounted on battens, creating an air gap between tile and deck; the shingles were nailed directly to the deck. The buildings were otherwise similar in construction and occupancy, with some differences in heat gains from plug loads and windows.

By monitoring temperatures, heat flows, and energy consumption in these air-conditioned houses, the project team investigated the extent to which over a year, the cool roof reduces (a) roof and attic temperatures, (b) conduction of heat into the conditioned space and into HVAC ducts in the attic, (c) cooling and heating energy uses, and (d) peak-hour electric power demand. Furthermore, measured cooling energy savings were also compared to cooling energy savings calculated from heat flow and temperature measurements to evaluate whether a simplified experimental configuration without power meters can be used in future cool roof experiments.

This study is of particular importance as it examines the combined benefits of high SR, high thermal mass, and above-sheathing ventilation—all inherent to cool tile roofing, the second most popular roofing product in California.

An LBNL website reported in real time the temperature profiles and energy use in each home, as well as the weather. Television monitors installed inside the homes displayed this analysis for the visitors and potential home buyers. The display can be accessed at http://CoolRoofDemo.lbl.gov.

2.2 Outcomes

On a representative summer day (July 6, 2012), maximum roof top, roof bottom, and attic air temperatures in the cool home (tile roof) were 13.8, 14.3, and 10.5 °C lower than in the standard house (shingle roof), respectively. Maximum rates of ceiling, HVAC duct, and ceiling + HVAC duct heat gain in the cool home were 1.50, 0.89, and 2.4 kilowatts (kW) lower than in the standard house, respectively. Minimum roof top, roof bottom, and attic air temperatures in the cool home were 2.1, 2.4, and 2.4 °C *higher* than in the standard house, respectively.

On a representative winter day (January 21, 2013), maximum roof top, roof bottom, and attic air temperatures in the cool home were 11.0, 10.6, and 6.9 °C lower than in the standard house, respectively. Maximum ceiling, duct, and ceiling + duct rates of heat gain in the cool home were 0.83, 1.33, and 1.17 kW lower than in the standard house. Minimum roof top, roof bottom, and attic air temperatures in the cool home were 0.4, 2.1, and 2.3 °C *higher* than in the standard house.

In the cooling season (May – October), the mean rates of ceiling and duct heat gain in the standard home were about 310 watts (W) and 130 W lower in the cool home than in the standard home. However, mean rates of ceiling and duct heat gain in the heating season (November – April) were about 46 W and 32 W *greater* in the cool home than in the standard home, thanks to the higher thermal capacity of the cool roof.

Seasonal mean reductions (standard vs. cool roof) in roof top, roof bottom, and attic air temperatures in the cooling season were about 3.4, 3.7, and 2.4 °C, roughly twice those of the heating season. Above-sheathing ventilation cooling the deck of the cool tile roof may have made the temperature difference (standard vs. cool roof) at roof bottom (underside of roof deck) larger than that at roof top (just below tile surface or shingle).

Cool-roof energy savings in the cooling and heating seasons were computed two ways. Method A divides by the HVAC's coefficient of performance (COP) the difference (standard vs. cool roof) in ceiling + duct heat gain. Method B measures the difference in HVAC energy use, corrected for differences in plug and window heat gains. Methods A and B agreed well in the cooling season, but not in the heating season. Therefore, all savings are reported based on Method B, which yielded more conservative savings in winter.

Relative to the standard home, annual cooling (compressor + fan), heating fuel, and heating fan energy savings at the site were 2.82 kilowatt-hours (kWh)/m^2 (26%), 1.13 kWh/m^2 (4%), and 0.0294 kWh/m^2 (3%), respectively at the cool roof home. Annual conditioning source energy savings were 10.7 kWh/m^2 (15%); annual energy cost savings were 0.886 \$/m^2 (20%). Annual air conditioning CO_2 , NO_x, and SO_2 emission reductions were 1.63 kilograms (kg)/m^2 (15%), 0.621 grams (g)/m^2 (10%), and 0.0462 g/m^2 (22%). Peak-hour cooling (compressor + fan) power demand reduction was 0.88 W/m^2 (37%).

Fractional annual cooling energy savings (26%) were 2.6 times the 10% daily cooling energy savings measured in a previous study that used a white coating to increase the albedo of an asphalt shingle roof by the same amount (0.44) (Parker & Barkaszi 1997). Fractional peak-hour

cooling power demand savings (37%) were 2.3 times the 16% savings observed in the earlier study. Since both studies used RSI-3.3 (R-19) roof insulation, these improved savings likely resulted from the high thermal capacity of the cool tile roof (80% greater than that of the shingle roof) and above-sheathing ventilation.

The slightly positive fractional annual heating energy savings is likely a result from the high thermal capacity of the tile roof, which increased the overnight temperature of the attic air.

Figure 1: Image and Plans of Adjacent Single-Family Homes in Fresno, California, Showing (a) Cool Concrete Tile Roof (foreground) and Standard Asphalt Shingle Roof (background); and (b) Plans of Home With Cool Roof (top) and Home With Standard Roof (bottom)

(a) (b)

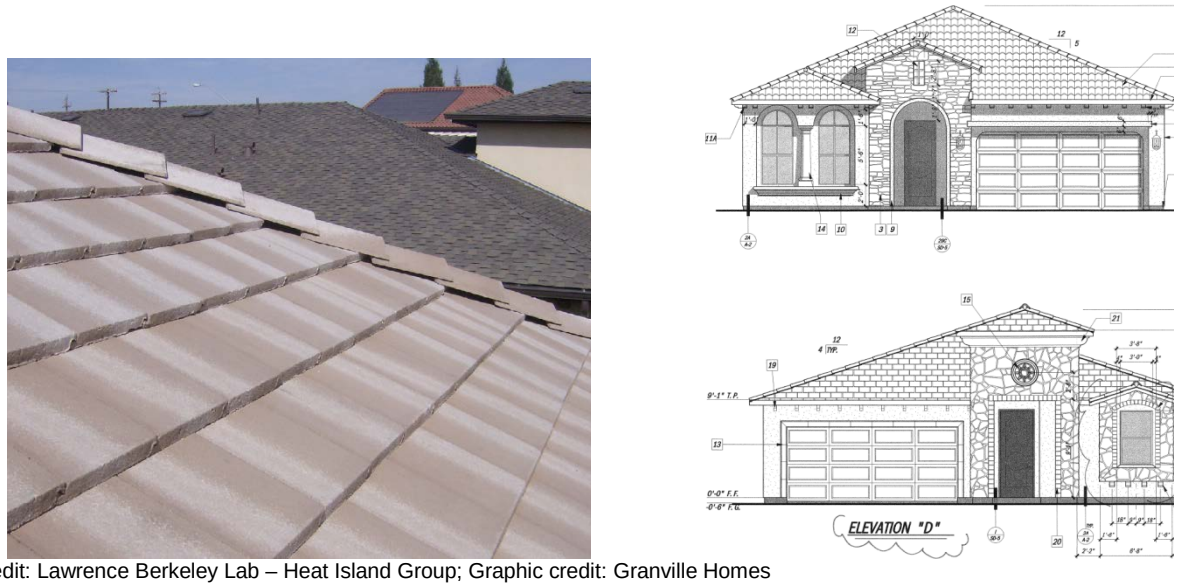


Photo credit: Lawrence Berkeley Lab – Heat Island Group; Graphic credit: Granville Homes

2.3 Conclusions and Recommendations

2.3.1 Conclusions

Choosing a cool tile roof in place of a standard asphalt shingle roof offers substantial benefits. For the homes studied (ceiling area 188 m^2), annual savings were $167 in energy costs, 307 kg CO_2, 117 g nitrous oxide (NO_x), and 8.69 g sulfur dioxide (SO_2); peak-hour power demand reduction was 165 W.

In the cooling season, energy savings calculated from heat flow and temperature measurements (Method A) closely matched those based on measured energy use (Method B). The two methods did not agree well in the heating season thus energy savings data from Method B were shown as the analysis was the more conservative of the two.

2.3.2 Recommendations

This study shows that in a hot California climate (Fresno, California Climate Zone 13), substituting a cool tile roof for a standard asphalt shingle roof can offer substantial annual

energy cost savings to a homeowner. Tile roofs are already a popular choice for California homes but are less common than asphalt shingles because of their higher first cost.

If most California homes have asphalt shingle roofs with a service life of about 20 years, California will save energy statewide by encouraging the selection of cool tile products for reroofing. To quantify this potential, LBNL recommends that the Energy Commission explore the following questions.

- In a climate like that of Fresno, how does the life-cycle cost of a cool tile roof compare to that of an asphalt shingle roof? This analysis would consider the installed cost and service life of each product, as well as the annual energy cost savings. It is outside the scope of this study (which measured annual savings in one location) because it requires California-specific information about installed cost and service life.
- Could Title 24-approved building-energy simulation tools be used to estimate annual savings in California's other 15 climate zones, using savings measured in Fresno (Zone 13) as a check? For example, do the currently approved tools adequately model the effects of increased albedo, increased thermal mass, and addition of above-sheathing ventilation? Also, is there enough information about the construction, operation, and HVAC equipment of the state's existing homes to model savings upon reroofing?
- Based on the number and locations of homes in California, what are the potential statewide energy savings, emission savings, and peak demand reductions if cool tile products were selected in place of asphalt shingle products in (a) all climates or (b) in all climates for which the life-cycle cost of the cool tile roof is less than that of an asphalt shingle roof? Both newly constructed roofs and reroofing should be considered.
- Should Title 24 promote the use of cool tile roofing through prescriptive requirement? If a codes and standards enhancement study is performed, it should consider reroofing of older, less efficient homes as well as initial roofing of new, more efficient homes.
- To what extent can cool tile roofs address the summer urban heat island (lower summer day and night outside air temperatures) and, thereby, increase comfort, slow the formation of smog, contribute to global cooling (negative radiative forcing of the atmosphere), and further reduce air-conditioning demand?

Meanwhile, it is recommended that the Energy Commission share the results of this study with California's utilities and consider how rebate and incentive programs could be updated to promote the use of cool tile roofing, especially in hot regions like the Central Valley (population 6.5 million) and Inland Empire (population 4 million). Outreach to roofing manufacturers, professionals, and consumers would be helpful. Information about cool tile benefits could be shared through utility billing literature, utility websites, the Cool California website, and the cool roofing courses developed by LBNL.

2.3.3 Benefits to California

This study demonstrates that cool tile roofs offer substantial annual energy cost savings and emission reductions in Fresno and belong in the state's portfolio of energy efficiency

technologies. Homeowners benefit from the annual conditioning energy cost savings (20%), while the public benefits from reduced emissions of CO_2 (15%), NO_x (10%) and SO_2 (22%) yielded by these annual conditioning energy savings. The electric grid also benefits from the 37% reduction in peak-hour cooling and fan energy use.

A program for comprehensive analysis of statewide benefits is recommended above.

CHAPTER 3:
Cool Pavement Study and Demonstration

A section of a residential street was paved with six different materials with varying albedos. The pavements were instrumented to measure temperature and heat flow. Over the course of 16 months, LBNL evaluated changes in pavement albedo and corresponding effects on pavement temperatures and heat flows. The results confirmed that higher-reflectance pavements increase skyward reflection of short-wave radiation (sunlight), which reduces pavement temperature and decreases solar heat gain. This in turn reduces convective flow of heat into surrounding air and emission of long-wave radiation to the atmosphere. The site also served to test new pavement technologies, understand proper installation methods, and assess their performances over time under realistic conditions.

3.1 Approach and Goals

3.1.1 Motivation

This activity was designed to demonstrate various cool pavement technologies for a residential street, and monitor the effects of soiling on pavement temperatures and heat flows. In a study of four U.S. metropolitan areas – Chicago, Illinois; Houston, Texas; Sacramento, California; and Salt Lake City, Utah – paved surfaces comprised about 35% of the land cover (above the tree canopy) of the metropolitan areas (Akbari and Rose 2008). Unshaded pavements absorb a portion of the solar energy they receive, and reflect the remaining energy. About 75-80% of the reflected sunlight makes it back to space. Some of the absorbed energy is conducted into the pavement; the rest is dissipated from the pavement surface as heat through convection into to the air and thermal radiation into the atmosphere and surroundings. In summer, when sunlight is strongest, pavements absorb more solar energy, causing more heat to be transferred to their surroundings, which increases air temperatures. This causes air temperatures in cities, where pavements are more densely clustered, to exceed air temperatures in nearby rural and suburban areas—a phenomenon known as the summer urban heat island effect.

Increasing the albedo of paved surfaces is one effective measure to mitigate the urban heating that is characteristic of heat islands. For example, it has been estimated that increasing pavement albedo from 0.10 to 0.35 could reduce average excess temperature in the Los Angeles heat island by about 0.6 °C [1 degree Fahrenheit (°F)] (Rosenfeld et al. 1996). However, about 90% of current pavements in the country use asphaltic binders (Asphalt Handbook 2007), which absorb roughly 90% of incident sunlight. Therefore, LBNL seeks to study various pavements to measure how more reflective pavement materials can reduce the diurnal heat convected to local air and emitted into the atmosphere.

In this activity the team built an experimental site on a residential road and divided it into six equally-sized sections. Each section was constructed with a different material to test various pavements under real-world conditions. Each section was instrumented to enable remote measurement of pavement temperatures and heat flux, and intermittent on-site albedo measurements were taken. The site also permits modification of the sections to expand the

number of tested pavements. Consequently, the study serves two purposes: (1) study the ability of various pavement types to reduce solar heat gain, and thereby stay cooler than conventional paving materials; and (2) to test the initial and long-term performances of new pavement technologies, with attention to both materials and installation practices.

3.1.2 Site Selection

The site selected for the demonstration is located on the campus of the University of California at Davis (UC Davis). In addition to the University's interest in the study of pavement technologies, the setting of the site in Davis is important because the climate in Davis is characterized by dry and hot summers, meaning that Davis can benefit from cool community measures such as cool pavements.

A satellite photo of the test site before construction is presented Figure 2. The chosen site is a 36.6 m [120'] long section of Orchard Park Drive. Orchard Park Drive carries typical residential traffic, as it primarily services student housing, a child-care center and a swimming pool. The demonstration site is located between entrances of the student housing complex parking lot. This stretch of road was chosen because it has no diversions—that is, any vehicle that enters would traverse the entire length and pass over all the test sections. In addition, whenever the demonstration site needs to be closed to traffic for construction or measurements, traffic can be rerouted through the parking lot, located east of the site, with minimal traffic disturbance.

Figure 2: Satellite View of the Cool Pavement Demonstration Site on Orchard Park Drive, UC Davis, Before Construction on the Experimental Site Had Started

Photo Credit: Google Earth

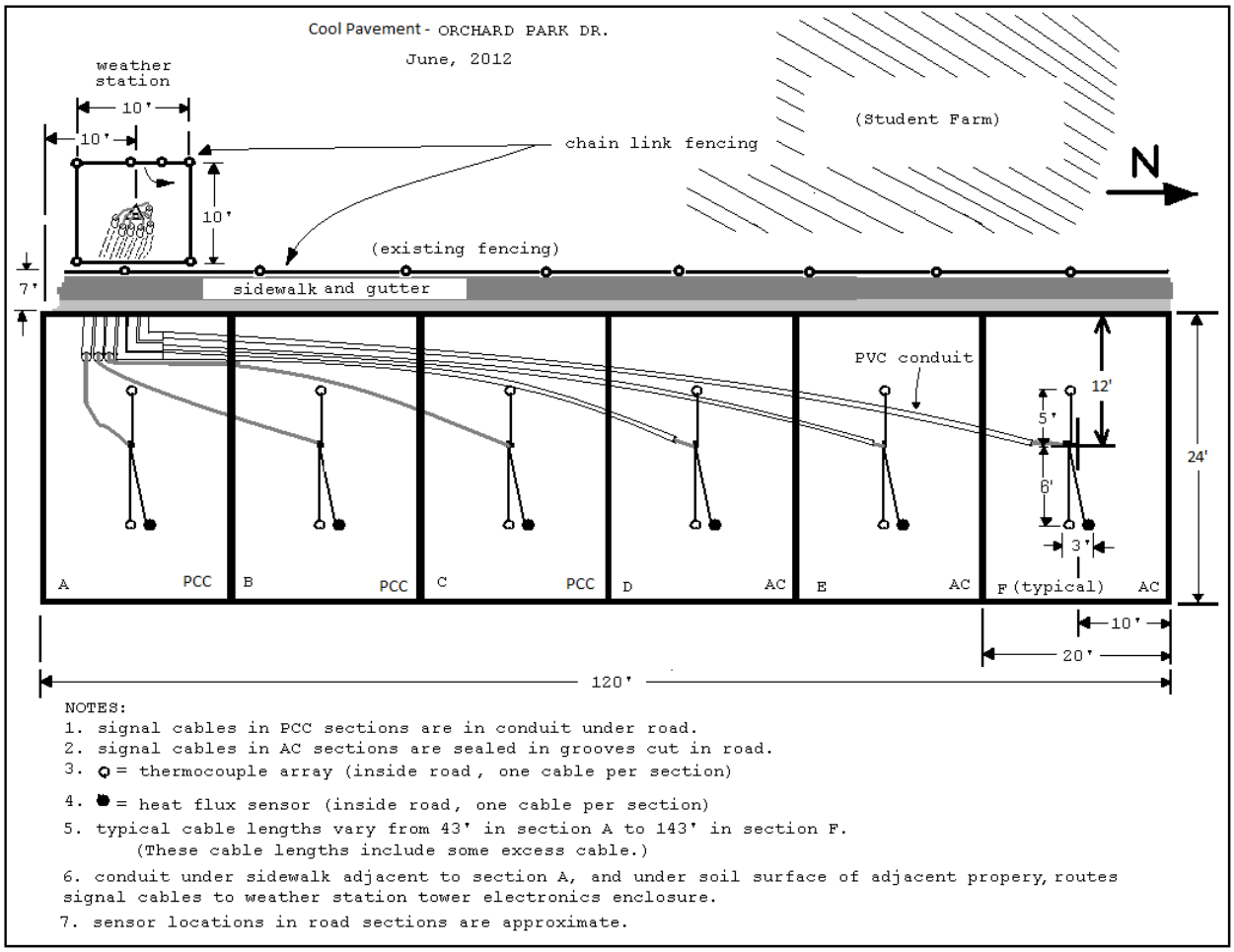
3.1.3 Initial Construction and Instrumentation

The experimental site was divided into six equal sections, each 6.0 meters (m) [20'] long and 7.3 m [24'] wide (Figure 3). The sections were labeled A (southernmost) through F (northernmost). Each pavement section was instrumented to measure temperatures at four different depths (1.3 centimeters (cm) [0.5"], 3.8 cm [1.5"], 6.4 cm [2.5"] and 18 cm [7.0"] from the surface) on both east and west lanes, and heat flux (2.5 cm [1"] below surface) on the east lane. A weather and data

collection station was built adjacent to the experimental road, inside a student farm area. Engineers from the University of California Pavement Research Center installed all sensors used in the pavements and constructed the weather and data collection station.

The first three sections (A, B, and C) were built with Portland cement concrete (PCC) as their common constituent. The other three sections (D, E, and F) were made of asphalt concrete (AC) with variations in surface treatments.

Figure 3: Drawing of the Demonstration Pavements and of the Weather/Data Collection Station. The Conduits Carry Wires to the Thermocouples (open circles) and to the Heat Flux Sensors (dark circles)



Graphic source: University of California, Davis

Construction for the three cement concrete sections was performed by Biondi Paving Inc., and began on 29 August 2011 with excavation of 18 m [60'] from south to north of Orchard Park Drive to a depth of 20 cm [7.9"] to accommodate the new PCC sections. Temperature sensors for the four different heights were mounted on dowels and one of each set was placed in each side (east and west) of each cement section. The thermal flux gauge of each section was placed 1 m [3'] north of the east lane's temperature sensors, as shown in Figure 3.

CEMEX donated and delivered the cement that was used for sections A, B and C. On the morning of 31 August 2011, the standard gray PCC (section A) was poured in the southernmost 6 m [20'] long section. On the afternoon of 31 Aug 2011, the white/catalytic cement concrete section (B) was placed. Because white cement is expensive, the lower 15 cm [5.9"] were first filled with standard gray PCC, and 5 cm [1.9"] of nominally white/catalytic PCC were added on top[1].. Section C was poured on 1 Sept. 2011, but the cement used was 50% regular cement and 50% slag cement. All PCC mixes were hand-laid around sensors to ensure that sensor heights were set accurately and uniformly. The three PCC sections were allowed to cure for a week before opening the road to traffic.

A 6 m [20'] segment was also excavated by Biondi Paving on 29 Aug 2011 to a depth of 15 cm [6"] to accommodate the new AC section (D). The excavated section D was filled with hot-mix asphalt concrete on 7 September 2011. During pouring, the AC had to be maintained at an elevated temperature that would have damaged the wires and sensors. After the fresh asphalt had cooled, 5 cm-wide channels were sawed to a depth of 10 cm in section D and also into the other two existing AC sections (E and F). Holes were cut in each AC pavement to house its thermocouple arrays and the heat flux meter. The wires to the sensors were then laid in the channels and the sensors were aligned in the holes. The holes were then packed with sand to protect the embedded sensors and wiring. The channels and holes were next filled with hot-mix AC. This was completed on 10 September 2011 for all the AC sections.

Figure 4 shows a satellite view of the demonstration after the PCC pavements were installed.

Figure 4: Satellite View of the Cool Pavement Demonstration on Orchard Park Drive After the PCC Sections Were Installed

Photo Credit: Google Earth

1 As described in Section 3.1.5.2, Section B of the pavement demonstration was not installed as planned. The top 5 cm thick layer had 50% gray cement mixed with 50% white cement, instead of pure white cement.

The remaining two sections of existing AC (E and F) were covered in the summer of 2012 with higher-albedo chip seal (E) and a green pavement coating (F). The chips, donated by GraniteRock, were placed on 08 June 2012. In a chip seal, the aggregate is laid on top of the binder that holds the aggregate. Thus, with an aggregate of high albedo, it is possible to create a pavement with an initial albedo (ideally greater than 0.30) higher than regular asphalt concrete simply by using a light-colored aggregate. The goal was to have a high initial albedo aggregate that met the structural standards. The team used an aggregate that met California Department of Transportation specifications for abrasion resistance, adhesion to asphalt, cleanliness and size distribution (CalTrans 2010). On 10 June 2012, Emerald Cities Cool Pavement Company coated Section F with a green pavement coating at their expense. Table 1 summarizes the initial pavement construction design.

Table 1: Approximate Initial Expected SR for Pavement Types

Section	Initial pavement types (as designed)	Approximate expected initial albedo
A	Standard PCC pavement	≥ 0.25
B	A 5 cm [2"] layer of TiO_2 photocatalytic white cement concrete over 15 cm [6"] standard cement concrete	≥ 0.60
C	50% slag / 50% standard Portland cement concrete	≥ 0.40
D	Fresh standard asphalt concrete	0.05
E	Chip seal with light-colored aggregate over old asphalt concrete	0.23
F	Emerald Cities (green colored) coating over old asphalt concrete	0.40

3.1.4 Data Collection

A weather/data collection station was installed in a 3 m × 3 m area to the west of section A on the other side of the sidewalk. The instruments in the station monitor the air temperature, wind speed and direction, solar irradiance, and precipitation. This data and the readings from the sensors embedded in the pavement sections are recorded using a data logger, which transmits the information to LBNL via cellular modem. A photovoltaic (PV) solar panel charges a battery that provides diurnal electric power to the data logger and modem. The station, including the PV panel, battery, data logger, and modem, was enclosed in a barbed-wire fence within the gated student farm adjacent to the experimental site.

3.1.5 Experimental Complications and Troubleshooting

3.1.5.1 Theft of PV Panel

After successfully collecting data for approximately 2 months during the summer of 2012, the PV panel used to power the data logger and wireless modem was stolen. The last date of data collected during that period was 2 August 2012. The team ordered and obtained a new PV panel at the end of 2012. To prevent future burglary attempts, the team obtained tamper-resistant equipment and put in place a strategy for securing the panel. The new PV panel was installed on 20 May 2013 and data collection was successfully restored on 04 June 2013. No problems with data collection have been encountered since then.

3.1.5.2 Cement Concrete Sections

The solar reflectances of the cement concrete sections (A, B, and C) were first measured 10 months after their installation. The values were much lower than expected. To find the causes of the discrepancies, 9 cores – 3 from each section – were extracted on 26 October 2012, with the help of the California Nevada Cement Association. Each core was 10 cm [4"] in diameter and 20 cm [8"] tall. They were sent for analysis to CTL Group in Illinois to assess the general condition of the concrete at the microstructural level and to determine, if possible, why the surfaces appeared darker than expected. The full report can be found in Attachment 2. The conclusions of the study can be summarized as follows:

- The measured solar reflectances at CTL Group laboratory are consistent with the values measured on site.
- The presence of a thin intermittent layer or coating of a dark brown-black, noncrystalline and opaque material is the primary reason of the low solar reflectance. This atypical layer adhered to the concrete surface, but it is unclear whether it was applied externally, is the result of something inherent in the concrete, or a combination of the two.
- From pictures taken during the pavement installations, CTL Group concluded that construction did not follow normal paving operation practices and that proper finishing and curing techniques were not employed.
- CTL Group suggested the use of sandblasting or moderate-pressure power washing to increase the reflectivity of the three PCC sections.

From discussion with cement industry partners and CTL Group, the authors also concluded that the cement mix in section B was not correctly specified and resulted in the markedly lower-than-expected SR. The surface was expected to have albedo equal to 0.60 or greater because it was specified as 5 cm [2"] of TiO2 photocatalytic white cement concrete over 6 in. of ordinary gray Portland cement. As applied, the top 5-cm thick layer had 50% gray cement mixed with 50% white cement, instead of pure white cement. Upon checking the mix specifications, it became evident that it was not made perfectly clear that the mix was to be pure white cement (which is quite unusual for a pavement specification). It might also have been confused with the next day's order for a 50% – 50% mixture of slag and gray cement.

3.1.5.3 Postinstallation Resurfacing and Treatment

In addition to the cement concrete, other sections also performed below expectations for albedo after construction. To improve the albedos, some sections were cleaned (following CTL Group recommendations) and section B was re-surfaced with a different cool pavement technology. Here the authors detail the various post-installation treatments.

- To correct section B, it would have been very expensive to excavate the steel-reinforced pavement and replace it with the correct cement concrete mix. The wiring and sensors in this section would also be destroyed in the excavation, adding to the replacement cost. Therefore, LBNL partnered with a cool pavement coating manufacturer, StreetBond, to apply a highly reflective pavement coating to increase the albedo. Their first attempt to coat the section was performed on 31 May 2013. The application consisted of a primer, then four sprayed layers of the StreetBond 150 white coating, and finally a sealer. While it had an initial albedo of 0.69, the section rapidly soiled and the albedo decreased to 0.14 in five weeks. StreetBond realized that the coating was applied improperly and was not given enough time to dry before opening the road to traffic. Scrub-washing was tried on the section in an attempt to remove the soiling, but this effort only slightly improved the albedo—the soiling was embedded in the coating itself. Consequently, the section was recoated by StreetBond on 26 August 2013. This time, the application consisted of one thick rolled layer of StreetBond150 white with no sealer. While the initial albedo was 0.67, it decreased to 0.30 after just two weeks and to 0.25 after eight weeks.

- On 30 May 2013, a day before resurfacing section B, the three cement concrete sections were power-washed to restore their initial albedos. The power-washing increased their albedo but was not enough to bring them to their expected initial values. However, the team hypothesize that after section B was coated with the StreetBond product, its sealer—which had not properly adhered to the base coating— was dispersed to sections A and C as cars passed between the sections. The sealer retained dirt and contributed to additional soiling not just for section B, but also for sections A and C.

- Although it is possible to create a chip seal pavement that has a high initial albedo (ideally greater than 0.30) by using a light-colored aggregate, the team was not able to find a local quarry to supply highly-reflective aggregate while meeting CalTrans chip aggregate specifications. While the albedo of a sample of the aggregate was measured before the installation, albedo of 0.25, the aggregate delivered for the installation had an albedo of 0.19, which was also the same value for the installed chip seal. Aggregates with higher albedo have not been in demand until now; so many quarries do not yet produce high-albedo aggregate for chip seal applications.

- The initial albedo specified for the Emerald Cities green coating (section F) was 0.40, and this was confirmed in sample measurements at LBNL. However, the coating used at the Davis demonstration had a different formulation and the initial albedo as installed was 0.30. Within a year its albedo had dropped to about 0.20. Emerald Cities has committed to resurface the section with a new coating formulation they assure will have initial albedo of at least 0.40. The section is scheduled for resurfacing in December 2013.

Table 2 summarizes the types of pavements and applied surface treatments that have been, or are expected to be, used.

Table 2: History of Pavement Types and Treatments on Each Section

Date	Note	Type of pavement/treatment	Section					
			A	B	C	D	E	F
Aug./ Sept. '11	Initial construction	A: Standard PCC B: titanium dioxide (TiO_2) photocatalytic white PCC C: 50% slag / 50% standard PCC	X	X	X			
Sept. '11	Initial construction	D. Newly paved AC				X		
Jun. '12	Initial construction	E: Chip seal over old AC F: Emerald Cities coating over old AC					X	X
May '13	Surface treatment	Surface power washing	X	X	X			
May '13	Re-surfacing	StreetBond white coating (1st attempt)		X				
Aug. '13	Re-surfacing	StreetBond white coating (2nd attempt)		X				
Nov. '13	Re-surfacing	New Emerald Cities coating formula (projected)						X

3.2 Outcomes

The project team oversaw the construction of six different pavements sections. Temperature and heat flux sensors were imbedded in each. Albedo measurements of these pavements were also made over time. It was evaluated how pavement albedo and the surface soiling affected the pavement temperatures and heat gain. The thermocouples and heat flux sensors embedded in each section allowed for recording the temperatures within the pavement and compare the heat gained through the various sections.

3.2.1 Albedo Measurements

Albedo measurements were taken using an albedometer positioned over each section. This requires that the road be closed to traffic and so it was done only occasionally. The measurements describe how pavement albedo changes over time as the road soiled and stained. Table 3 presents measurements of albedo over a period of 14 months

Table 3: Albedo Measurements of the Six Pavement Sections Performed During 2012-2013

Date	Notes	Albedos					
		A: gray PCC	B: nominally white PCC	C: 50% slag PCC	D: new AC	E: chip seal on AC	F: EC green coating on AC
20 Jul 2012		0.17	0.22	0.21	0.07	0.15	0.29
20 May 2013	Before power washing PCC sections	0.17	0.22	0.22	0.09	0.13	0.22
30 May 2013	After power washing PCC sections	0.22	0.29	0.27	0.08	0.12	0.20
31 May 2013	StreetBond coating added to section B (1st attempt)		0.69				
13 Jun 2013	Follow-up visit after 1st attempt on StreetBond coating	0.17	0.20	0.22	0.08	0.12	0.20
24 Jul 2013	Before scrub-washing section B	0.15	0.14	0.19	0.08	0.12	0.21
24 Jul 2013	After scrub-washing section B		0.17				
25 Aug 2013	StreetBond coating added to section B (2nd attempt)	0.16	0.67	0.20	0.08	0.11	0.21
10 Sep 2013	Follow-up visit after 2nd attempt on StreetBond coating	0.15	0.30	0.19	0.08	0.12	0.20

Figure 5: Albedo Measurements of the Six Pavement Sections Performed During 2012-2013

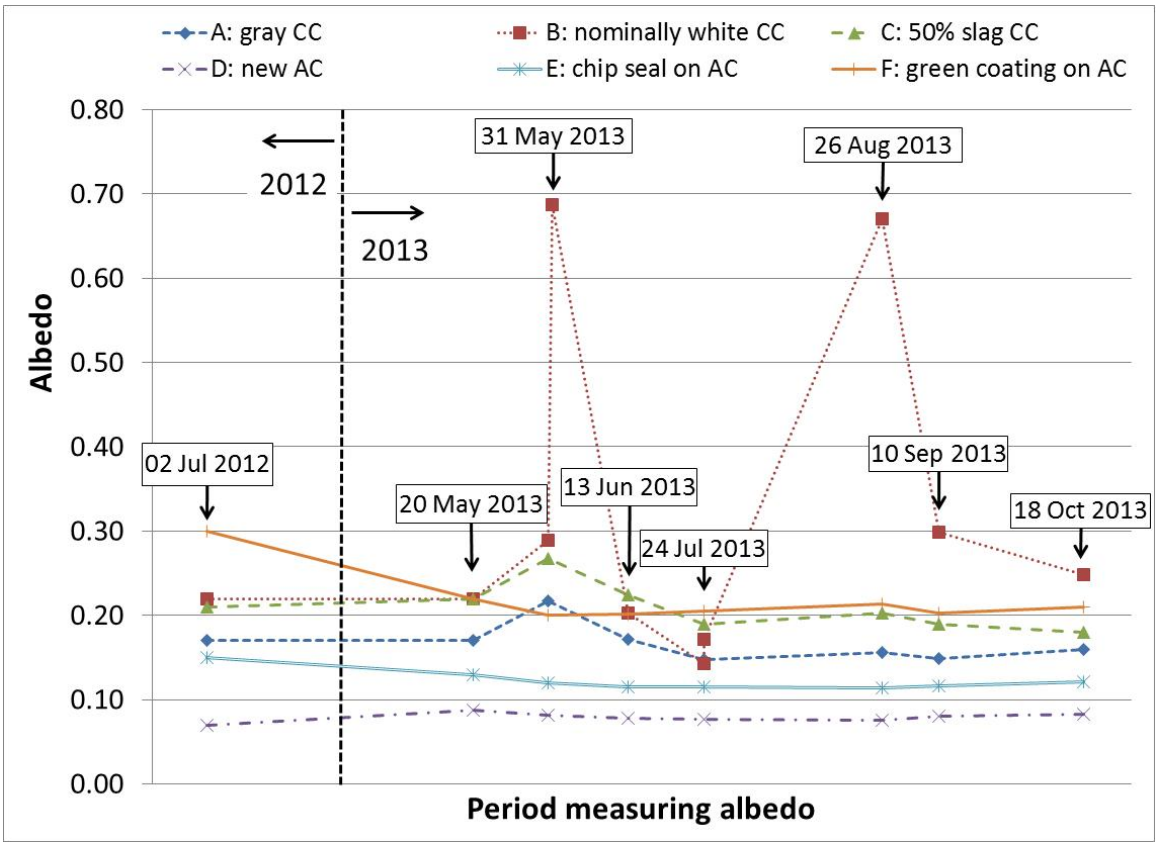


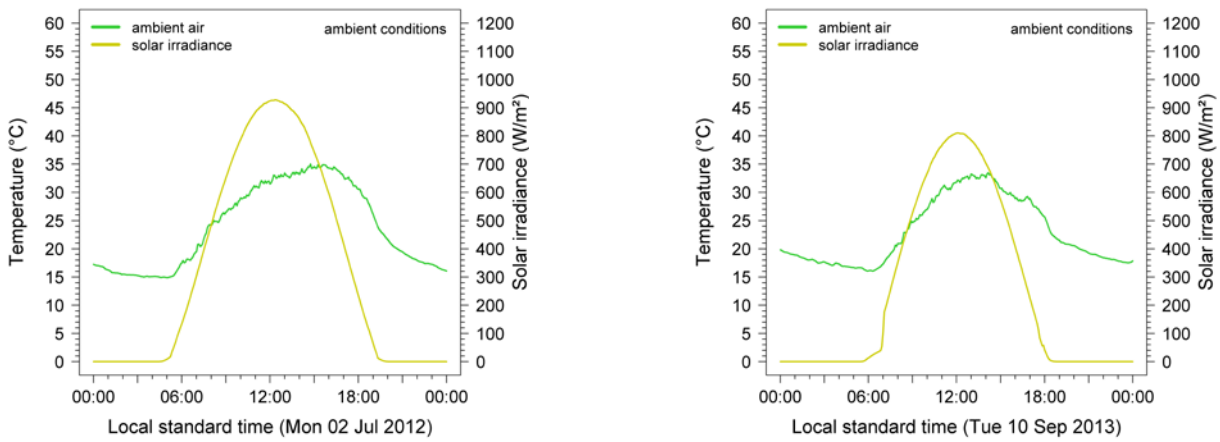
Figure 5 is based upon the data shown in Table 3. The general tendencies are for the albedo to converge toward values between 0.1 and 0.2. However, it was observed that the section with an initially high albedo (above 0.6) dropped down to about 0.3. For clarity the time scale in Figure 5 is not linear. The jumps in albedo around 31 May 2013 for sections A, B and C are due to power-washing of the surfaces (30 May 2013). The sharp rise of section B to 0.69 comes from the first white coating applied by StreetBond, described above in section 3.1.5.3. Within five weeks, section B had dropped to 0.14, caused by the wrong application of the white coating. When the sealant was applied incorrectly, the top layers of the sealant did not fully dry in the time that the road was closed and remained sticky. The tires of passing cars may have deposited some of this sealant onto the adjacent sections A and C. As a result, by 24 July 2013, the albedo of these two sections had also dropped to their lowest values to date.

3.2.2 Two Representative Summer Days

3.2.2.1 Weather

Figure 6 shows solar irradiance and outside air temperatures for 02 July 2012 (a) and 10 September 2013 (b). On 02 July, solar irradiation peaked at 926 W/m² at 12:00 local standard time (LST) and outside air temperature peaked at 36 °C [97 °F] (16:00 LST). On 10 September the peak solar irradiance (also at solar noon) was 810 W/m2 and the ambient air temperature peaked at about 32 °C [90 °F] (14:30 LST).

Figure 6: Outside Air Temperature and Global Horizontal Solar Irradiance on (a) July 2, 2012 and (b) September 10, 2013



3.2.2.2 Albedo vs. Near-Surface Temperature

Table 4 compares the albedos with the noon-time near-surface temperatures (depth of 1.3 cm [0.5"]), as measured on 02 July 2012 and 10 September 2013. The noon time air temperatures (Tair) were 31.5°C and 31.8°C respectively; solar irradiances (I) were 924 W/m² and 810 w/m². Although the albedo for most of the sections are below expected (Table 1) a correlation exists between the albedo of the pavement and the noon-time temperatures reached at 1.3 cm [0.5"] beneath the surface (Figure 7). On 02 Jul 2012, the noon-time pavement temperatures decreased by about 6.6 °C for an albedo increase of 0.1. On 10 Sep 2013, the decrease was 5.3 °C per 0.1 increase in albedo. Earlier reported measurements, taken between 2000 and 2001, with infrared (IR) thermometers were lower, about – 5 °C for an increase of 0.1 in albedo (Pomerantz et al. 2003). The values will depend mostly on solar irradiance but also on influences like the wind and the thicknesses of the pavements (which are unknown for the earlier results). All of these results demonstrate a considerable decrease in near-surface temperatures with an increase in albedo.

Table 4: Albedo And Noontime Near-Surface Temperature (T_{air}) on July 2, 2012, and September 10, 2013

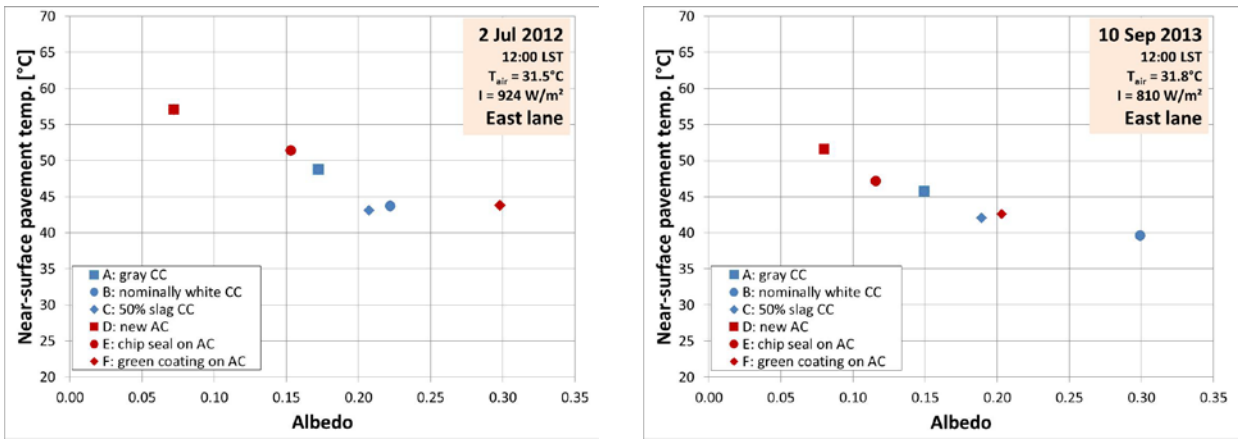
Section	02 July 2012		10 September 2013	
	Albedo (ρ)	Noon time near-surface temp.	Albedo (ρ)	Noon time near-surface temp.
A: gray PCC	0.172	48.8	0.149	45.8
B: nominally	0.222	43.7	0.299	39.6
C: 50% slag	0.207	43.1[a]	0.189	42.1
D: new AC	0.072	57.0[b]	0.080	51.6
E: chip seal on	0.153	51.4	0.116	47
F: EC green	0.298	43.8	0.203	42.5
Air (ambient)		31.5		31.8
Max. solar		924		810

Values in blue represent the lowest maximum near-surface temperature of the pavements that day.

Values in red represent the highest maximum near-surface temperature of the pavements that day.

Figure 7 plots the near-surface temperatures versus albedos given in Table 4.

Figure 7: Noontime Near-Surface Temperatures (depth of 1.3 cm [0.5"]) vs. Albedo on (a) July 2, 2012, and (b) September 10, 2013. Air Temperature (T_{air}) and Solar Irradiance (I) Provided for Context



3.2.2.3 East Lane Pavement Temperatures and Conducted Heat Flux

As an example of the data collected from the pavement sensors, Figure 8 shows temperature as a function of time of all pavement sections at depths of 1.3 cm [0.5"] (panel a) and 18 cm [7"] (panel b) on 02 Jul 2012. Section D (bare AC) experienced the highest temperature at 1.3 cm [0.5"] depth. Its sudden drop around 15:00 LST was caused by the shade from the tall tree located west of the section. The temperature of section D continued to drop after 15:00 LST to the lowest temperature of all sections. Sections C and F were the next to be affected by afternoon tree shading – their near surface (1.3 cm [0.5"] deep) temperatures dropped until they roughly equaled the temperature of section D. At the depth of 18 cm [7"], section A had the highest temperature, while sections C and F continued to have the lowest temperatures.

Figure 8: Temperatures at (a) 1.3 cm [0.5"] and (b) 18 cm [7.0"] Below the Surface on July 2, 2012

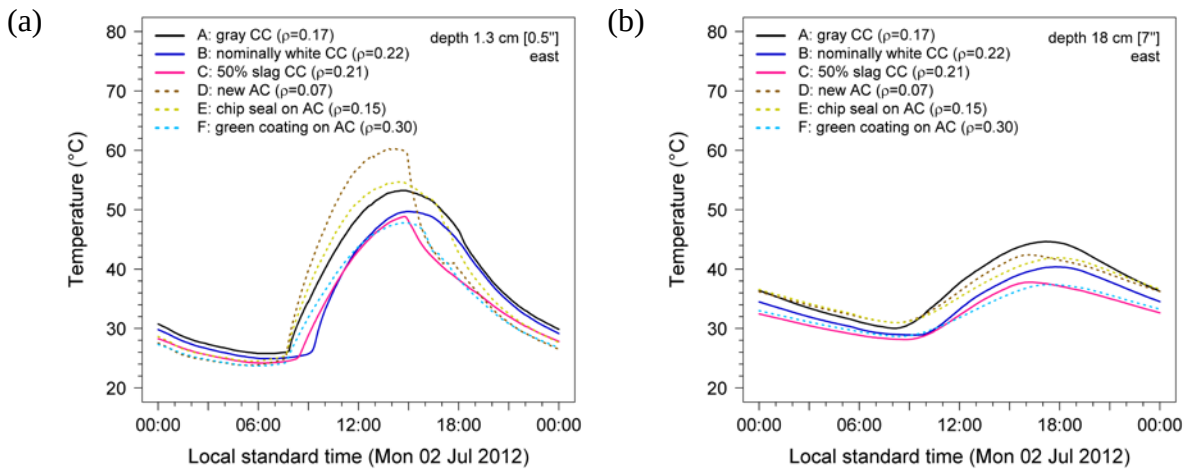


Figure 9 shows similar data for 10 September 2013. On this day, section B had the highest albedo and the lowest temperatures at 1.3 cm [0.5"] and 18 cm [7"] from the surface.

Figure 9: Temperatures at (a) 1.3 cm [0.5"] and (b) 18 cm [7.0"] Below the Surface on September 10, 2012

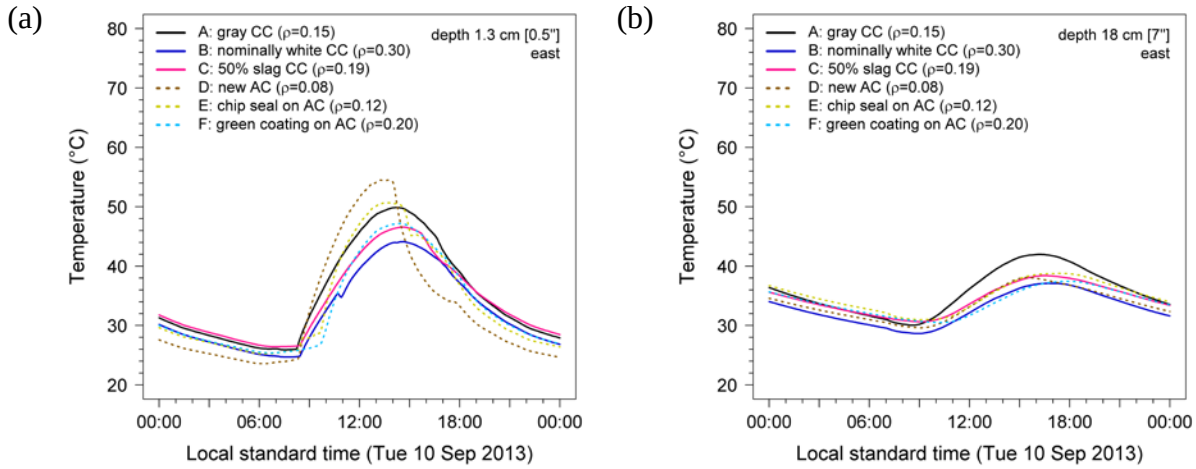
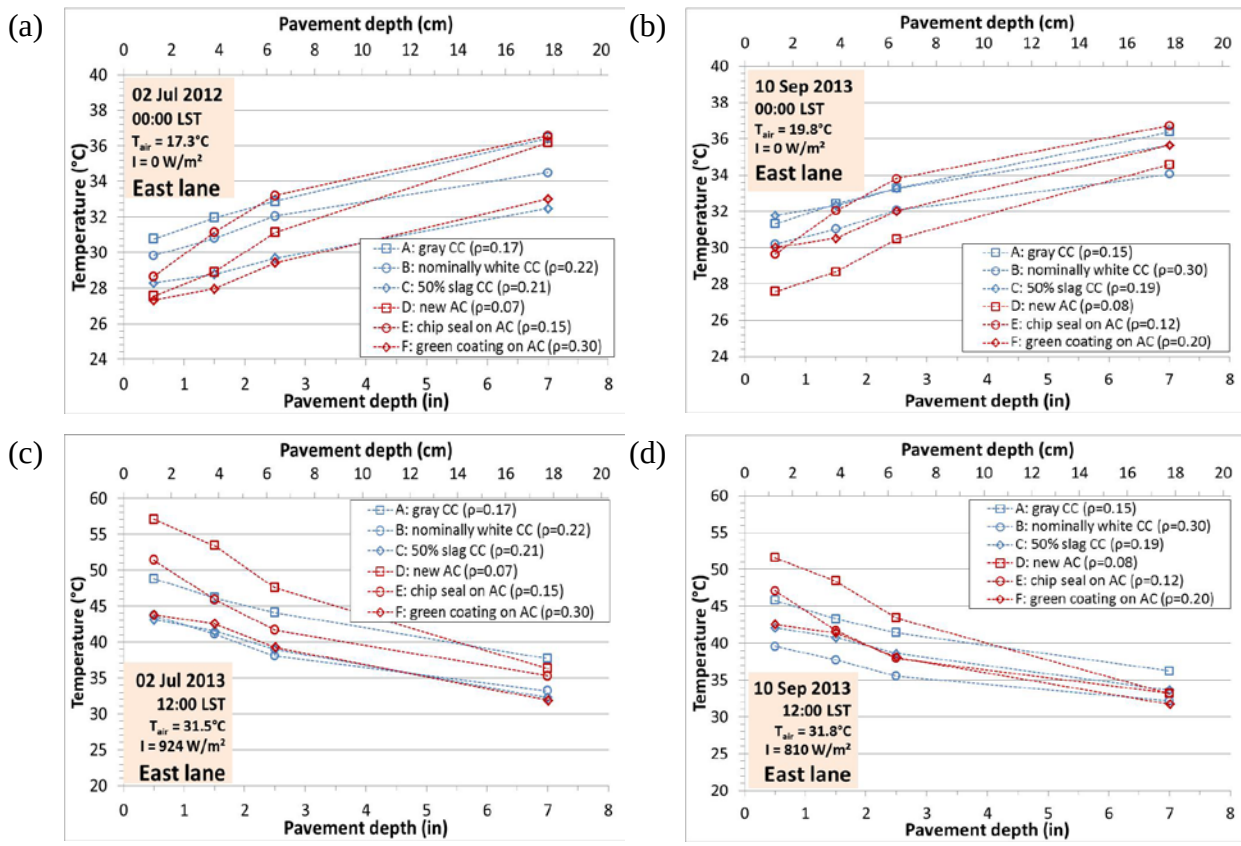


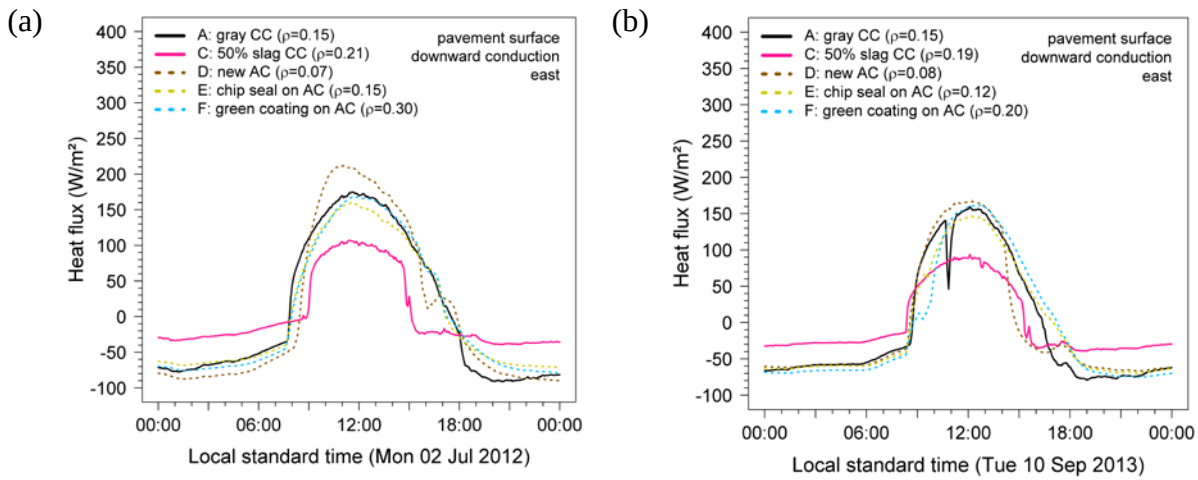
Figure 10 plots pavement temperature vs. depth from surface for the two representative days at midnight (panels a and b) and noon (panels c and d). At midnight, temperature increases with depth. At noon, the relationship is inverted. These relationships can be used to calibrate a model of pavement temperature versus depth.

Figure 10: Pavement Temperature vs. Pavement Depth on July 2, 2012, and September 10, 2013, at (a-b) Midnight and (c-d) Noon. Air Temperature (T_{air}) and Solar Irradiance (I) Provided for Context



The heat flux sensors embedded in the east lane 2.5 cm [1"] from the surface measured the conducted heat. The sensor in section B failed early in the study. Excluding the bad sensor, during the two representative days section D (new AC) was measured to have the greatest heat flux at noon (Figure 11). By 10 Sep 2013, although section D still had the highest downward conducted heat flux, the difference between heat fluxes in sections A, D, E and F was very small. At night, these sections had similar values. Section C experienced substantially less downward conduction during the day, and therefore less upward conduction at night.

Figure 11: Comparing Downward Conduction Heat Fluxes for the Two Representative Days



3.2.2.4 Heat Balance at the Pavement Surface

The reflected short-wave solar radiation is the product of solar irradiance I and the surface albedo ρ. The upward heat flow rate from the pavement to the atmosphere and surroundings is

$$q_{\text{up}} = \rho I + q_{\text{conv}} + q_{\text{rad}}, \tag{1}$$

where q_{conv} (W/m²·K) is the heat convected to the air and q_{rad} (W/m²·K) is the net long-wave (thermal infrared) radiation transferred from the pavement to its environment. The long-wave radiation was computed as

$$q_{\text{rad}} = \varepsilon \cdot \sigma \cdot \left(T_{\substack{\text{near}\\ \text{surf}}}{}^{4} - T_{\text{sky}}{}^{4} \right) \tag{2}$$

where ε, σ, $T_{\substack{\text{near}\\ \text{surf}}}$ and T_{sky} are respectively the surface thermal emittance, Stefan-Boltzmann constant, absolute pavement temperature at 1.3 cm [0.5"] from surface, and absolute far sky temperature. The far sky temperature was estimated by subtracting 10 K from the measured ambient air temperature. The convected heat was calculated from a heat flux balance at the pavement surface. The energy balance gives

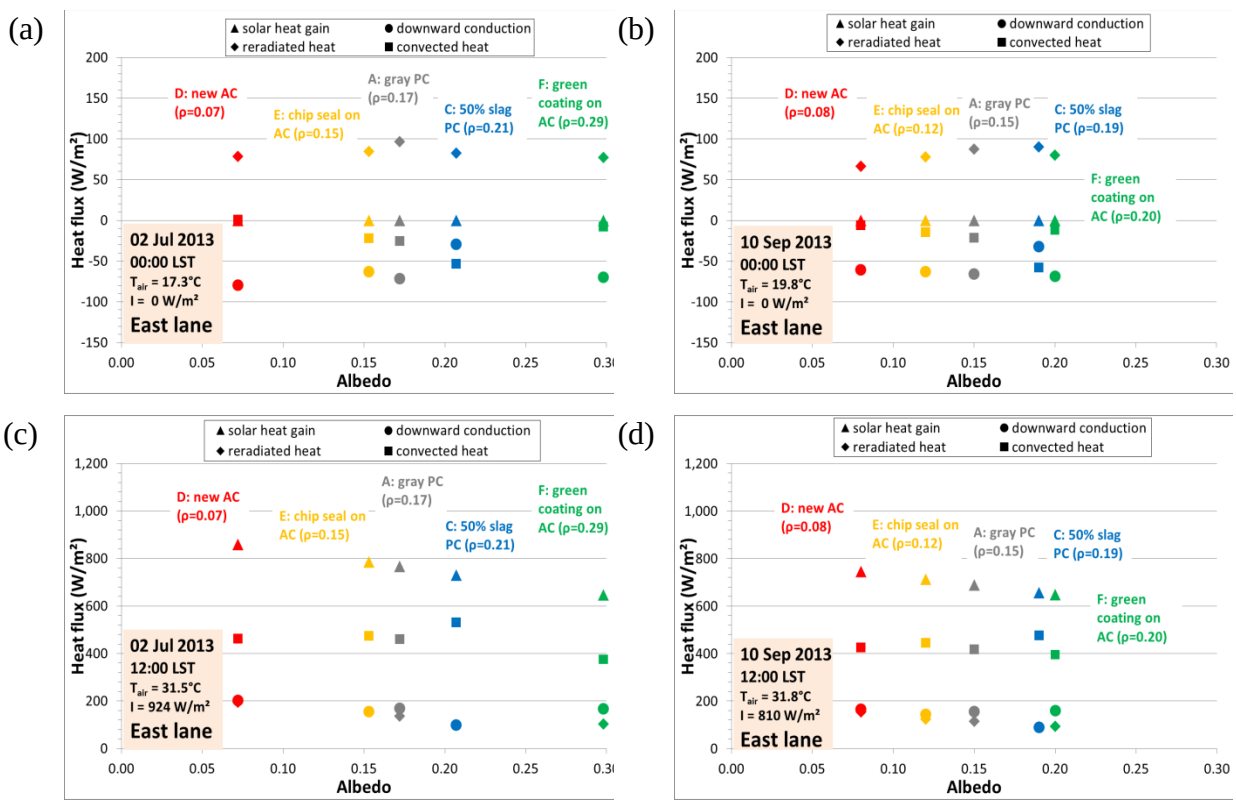
$$(1-\rho)\, I = q_{\text{cond}} + q_{\text{conv}} + q_{\text{rad}} \ . \tag{3}$$

The left-hand side in Eq. (3) is the rate of solar heat gain, where I is the solar irradiance and $(1-\rho)$ is the solar absorptance. The solar irradiance was obtained from the photodiode pyranometer installed at the top of the weather station tower. q_{cond} is the heat conducted downward. It was measured with heat flux sensors embedded in each pavement section. The convected heat flux was calculated by rearranging Eq. (3) as

$$q_{\text{conv}} = (1-\rho)\, I - q_{\text{cond}} - q_{\text{rad}} \,. \tag{4}$$

Figure 12 compares the sections' surface heat fluxes vs. albedo for the two representative days. The heat flux sensor embedded in section B was defective, so it is not include it in this analysis. At midnight (panels a and b), in addition to not having solar heat gain, the difference between air and pavement surface temperatures is smaller than at noon. Hence, the energy balance favors thermal radiation exchange with the far sky. Additionally, the heat fluxes were similar between sections. At noon (panels c and d), the solar heat gain was the dominant heat flux, and the magnitude decreased with higher albedo. Convected heat flux is the biggest form of heat loss from the surfaces. The noon figures also show slight decrease in conducted, convected and radiated heat loss with increases in albedo.

Figure 12: Heat Fluxes at the Pavement Surfaces for the Two Representative Days at Midnight (a-b) and Noon (c-d). Air Temperature (T_{air}) and Solar Irradiance (I) Provided for Context

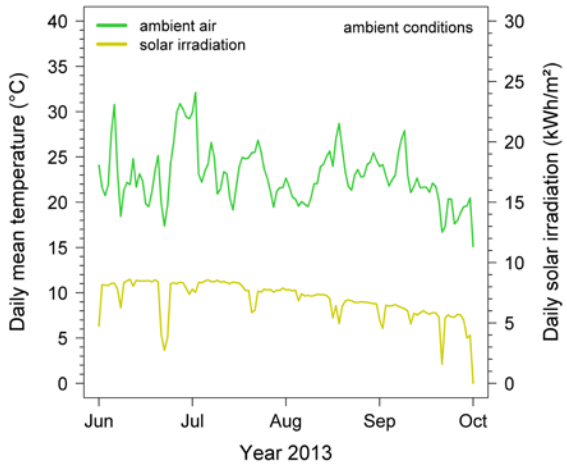


3.2.3 Daily Results

3.2.3.1 Solar Irradiation and Mean Air Temperature

Figure 13 shows the daily mean temperatures and solar irradiations for the four hottest months of 2013. Highest clear-day global horizontal irradiation was 8.5 kWh/m² (June). Dips in daily solar irradiation indicate cloudy days. Clear-day mean air temperature was highest in July, reaching up to 32 °C.

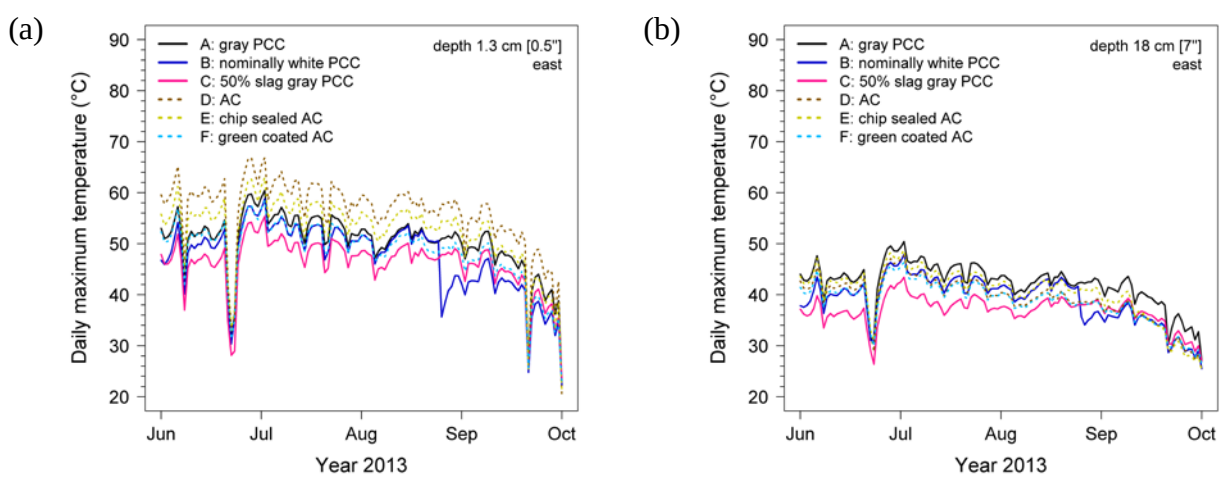
Figure 13: Daily Mean Ambient Air Temperature and Daily Solar Irradiation for the Four Hottest Months of 2013



3.2.3.2 Maximum Pavement Temperatures

Figure 14 compares the daily maximum temperatures between sections for depths at 1.3 cm [0.5"] (panel a) and 18 cm [7"] (panel b) throughout four summer months of 2013 (June – September). The asphaltic surfaces were the hottest at 1.3 cm [0.5"]. During daytime, section A has the longest exposure to direct sunlight, which could be the reason why it has the highest daily maximum temperature at a depth of 18 cm [7"] (panel b). On the other hand, sections D and E are the most shaded in the afternoon, possibly why they experience daily maximum temperatures lower than section A at the 18 cm [7"] depth.

Figure 14: Daily Maximum Temperatures During the Summer of 2013 at depths (a) 1.3 cm [0.5"] and (b) 18 cm [7"] From Pavement Surface



3.3 Conclusions and Recommendations

3.3.1 Conclusions

As described above, the Davis pavement study serves two purposes: (1) study the ability of various pavement types to reduce solar heat gain, and thereby stay cooler than conventional paving materials; and (2) to test the initial and long-term performances of new pavement technologies, with attention to both materials and installation practices.

To address its first purpose, this experimental study examined the time-dependent performance of surface albedo, and analyzed the impact it had on solar heat gain of the various pavement types. Thermocouples and heat flux sensors were embedded in the pavements to record the temperatures within the pavement typess and compared the heat gained through the surface. Measurements proved that higher-albedo pavements reduce surface and subsurface temperatures, and reduce daytime heat conducted downward. From a heat gain balance at the pavement surface, it was calculated that lower pavement temperatures decreased the heat convected to the air and heat reradiated as long-wave radiation to the atmosphere. At noon on 02 July 2012, measurements showed a reduction of near-surface temperature of about 6.6 °C per 0.1 increase in albedo. The reduction was 5.3 °C per 0.1 albedo increase on 10 Sep 2013. This suggests that if the albedocan beraised from 0.1, its current average, to a value of about 0.3, an average of 12 °C (22 °F) decrease in pavement temperature can be achieved. It follows that if the pavements can be kept cooler even when the sunlight is maximal, the air will be cooler. This can reduce the demand for air-conditioning energy and help mitigate the air-polluting effects of high air temperatures.

For the second purpose of the study, some of the pavements installed initially had albedos well below the expected values and underperformed with regard to soiling resistance. The team then tested other pavement technologies and surface treatment methods. Some of the problems encountered may be attributable to the unfamiliarity of the paving industry with cool pavements. These experiences may therefore help pavement technology manufacturers improve their current products and installation practices. For example, a mistake was made in section B, in which ordinary gray cement was mixed into the batch that was supposed to be 100% photocatalytic white cement. For section E, it was very difficult to find a commercially available light-colored aggregate for the chip seal. If there were a larger market for light-colored aggregate, then perhaps more quarries would open to fill this demand. The team also found that the green Emerald Cities coating placed on section F had an initial albedo 0.1 lower than expected because the formulation of the coated applied was different than the planned formula, and soiled rather quickly. The supplier is working on a new coating formulation for improved performance. Similarly, the white coating provided by StreetBond for section B is a product not traditionally applied to vehicle-transited surfaces. Naturally, the second attempt to install their coating benefited from the lessons learned from mistakes of their first attempt.

3.3.2 Recommendations

LBNL recommends that measurements continue to be made at the test site so that the effects of time and use can be quantified. The paving industry is just beginning to explore cool pavement technologies, and it is therefore currently difficult to obtain a wide variety of pavement options. But the benefits suggested by research should stimulate continued exploration of new technologies. It is also recommended that the Cool Pavement Demonstration be continued as an experimental site to allow us to test new products as they are developed, to gain experience using and monitoring potentially promising cool pavement technologies.

The project has identified some other areas for recommendations. Long-term albedo of cool coatings can be improved with further research on self-cleaning capabilities of products. In addition, recommendations from CTL Groups' study concluded that it is best to measure the albedo of cement concrete as part of the mixture design process to ensure that the mix ratios will result in the specified pavement albedo. In addition, manufacturers should continue to test all curing compounds and sealants under various climate and pavement use applications to ensure that these products do not negatively affect the albedo of the pavement after placement.

3.3.3 Benefits to California

LBNL have demonstrated several characteristics of cool pavements that qualify them as a potential mitigation measure for the urban heat island (UHI) effect in California. Pavement technologies with high albedos were shown to absorb less heat through the surface and achieve lower pavement temperatures at depths close to the surface. It is inferred from this research that high albedo pavements will result in lower air temperatures close to the pavement surface because less energy is emitted to the surrounding air through radiation and convection. It is important to continue studying cool pavement technologies to better understand their ability to reduce carbon dioxide equivalent emissions and measure their potential as a strategy to advance the emissions reduction goal set out by AB 32.

CHAPTER 4:
Cool Community Website Content

LBNL developed a cool roof website to serve as a one-stop source of cool roof information for consumers. In this task, that website was maintained and updated and new web content on cool community strategies for local government stakeholders was drafted. With useful resources online, California cities and residents are empowered to implement cool community policies, projects and cool roof designs. With increased use of these strategies, California will reduce its emissions and make progress toward AB 32 goals.

4.1 Approaches and Goals

In Cool Communities Phase 1, the team developed a cool roof website for consumers. The site is hosted on CoolCalifornia.org. ARB and other partners manage CoolCalifornia.org to "provide resources to all Californians in order to reduce their environmental impact and take action to stop climate change." The website includes information on the basic science and benefits of cool roofs as well as tools to help consumers select suitable cool roof products. Figure 15 shows the home page for the cool roof consumer website.

Figure 15: Home Page for the Cool Roof Website

Photo credit: CoolCalifornia.org

In Cool Communities Phase 2, the project team planned to maintain and update the existing content on CoolCalifornia.org as well as develop new content on cool community strategies— cool roofs, cool pavements and urban vegetation— for the website's local government audience.

4.1.1 Existing Cool Roof Consumer Website

The project team worked closely with CalTrans to solicit their feedback and comments on the existing web content. In addition, the entire website was reviewed to check for content that needed to be updated, most notably the cool roof product search wizard, the cool roof building codes section, and the utility rebate section. All of the existing codes and utility rebates were reviewed to identify changes.

4.1.2 New Cool Communities Web Content

Since local governments are responsible for broad decision-making about city infrastructure, which can span various land uses and surface types, content for urban vegetation, cool pavements and cool roofs was developed for this audience. The development of this new web content for cool community strategies mirrored the approach used for the cool roof content. The goal was to convey research to the local government audience in a way that clearly communicates the science and empowers them to implement cool community projects or policies.

The basic navigation of the web content is presented in Figure 16. To develop new content, journal publications and popular press articles, as well as websites and presentations from industry and stakeholder groups were reviewed. Interviews were also conducted with people who helped implement cool community strategies in their localities. Their experiences were then written up as case studies that are tailored to the local government audience, and requested that interviewees review the case studies to assure accuracy. The project team worked closely with staff from ARB to review all of new web content that was developed as part of this task.

Figure 16: The Cool Communities Web Content Is Divided Into Three Subsections: Cool Roofs, Cool Pavements, and Urban Vegetation

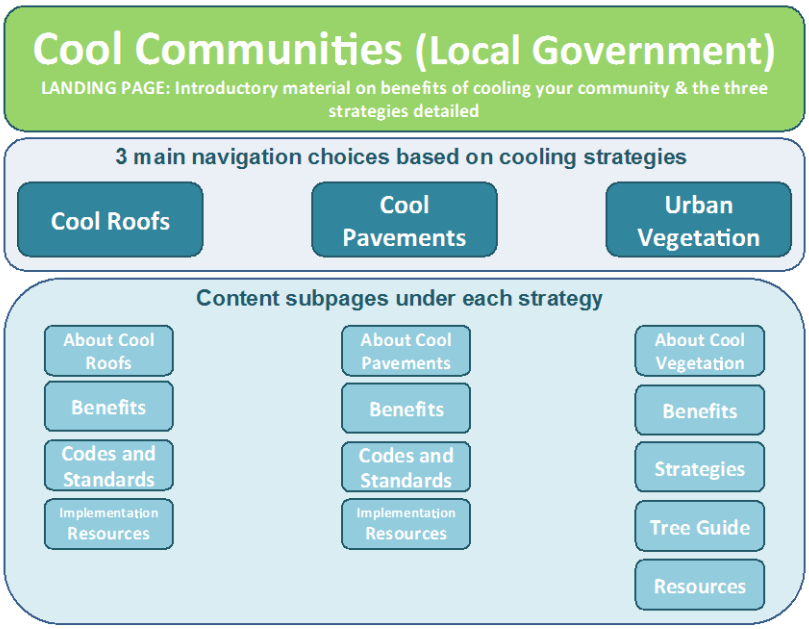


Photo credit: Lawrence Berkeley Lab – Heat Island Group

4.2 Outcomes

The team successfully incorporated many improvements to the existing cool roof consumer website. However, the team did encounter a problem with the cool roof product search wizard. The team also developed extensive web content on cool community strategies for the local government audience.

4.2.1 Existing Cool Roof Consumer Website

The team reviewed the cool roof consumer website and noted several changes needed to keep it updated with current information and links. Table 5 lists many of the updates that were made to the website. One of the big updates was to the California building code content. In 2013, the California Building Energy Efficiency Standard was updated, including new cool roof requirements for residential buildings, with new requirements to be effective January 1, 2014. These new requirements are included alongside the 2008 requirements, and after January 1, 2014 the website will be updated to remove the 2008 cool roof requirements.

Table 5: Changes to the Cool Roof Consumer Website Content

Section	Page	Content	Update/Change
How to Buy	Product Comparison	Product table	Aesthetic improvements
	Building Codes	Updated introductory text	
		CA Title 24 Building Energy Efficiency Standard	Updated to include 2013 minimum radiative requirements
My Savings	Rebates & Incentives	LA Department of Water & Power – Cool Roof Rebate Program	Updated to reflect new SRI requirements and rebate amounts
		Long Beach Residential Energy Efficiency Rebate Program	Fixed broken link
		Southern California Edison Advanced Upgrade Package	Changed link to Energy Upgrade California
		New federal tax credit for cool roofs	10% of cost up to $500 until December 31, 2013 for Energy Star asphalt and metal roofs
Taking Action	Local Initiatives	Sonoma County Community Climate Action Plan	Fixed broken link
		Town of Windsor	Fixed broken link
		Alphabetized list by municipality	

Section	Page	Content	Update/Change
About Cool Roofs	Technical Terms	Improved content and formatting	

The cool roof consumer website features a cool roof search wizard, intended as an interactive tool to guide consumers to select a suitable cool roof product. It is driven by images and uses filters to narrow down the results (Figure 17). Once the consumer narrows the selection with the filters and submits a search, he/she should be directed to the Cool Roof Rating Council's Rated Products Directory[2] where the results are listed. Unfortunately, the website was offline for debugging over several months (spring and summer 2011) while both ARB and the LBNL team tried to resolve the issues. Eventually, ARB's consultant was able to fix the problem and the cool roof search wizard was working again. However, in Spring 2012, the Cool Roof Rating Council (CRRC) launched a new website with a new database design for its Rated Products Directory. Since the search wizard is sensitive to changes on the CRRC website, these new changes have caused the tool not to work properly. ARB and LBNL have limited financial resources to address this recent technical issue but are actively trying to resolve it.

Figure 17: The Cool Roof Product Search Wizard Has Five Search Filters (slope, material, color, standards, rebates) With Multiple Choices for Each (e.g., tile or slates, shingles or shakes), or Viewers Can Chose "Any" for each filter

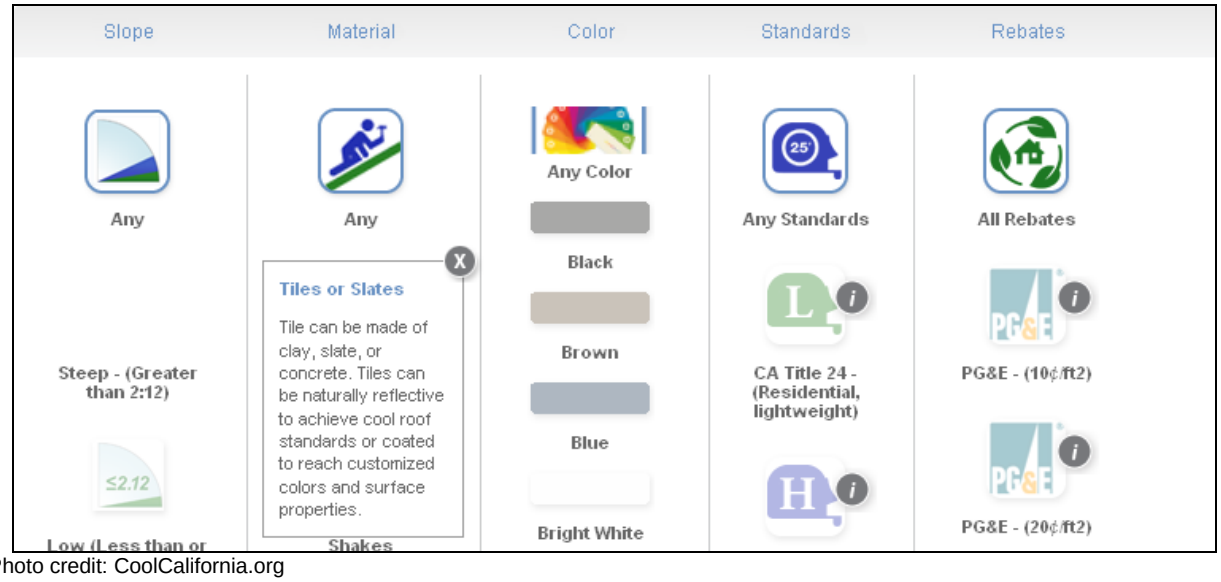


Photo credit: CoolCalifornia.org

4.2.2 New Cool Communities Web Content

Local communities and cities have been seeking resources with information on cool roofs, cool pavements and urban vegetation to aid their development of strategies for climate action and climate adaptation plans. With the information and resources on the website, they will know

2 http://coolroofs.org/products/results

how develop plans/policies as well as projects. The project team has developed content for 14 web pages for the cool communities portal on CoolCalifornia.org, which can be viewed in Attachment 3. Now that the web content is developed, LBNL has released the content to the ARB to put on the website. Because of funding constraints, LBNL collaborated withARB staff to upload this information instead of hiring a web programmer for assistance.

4.3 Conclusions and Recommendations

4.3.1 Conclusions

The Heat Island Group promotes the cool roof consumer website on flyers, in public presentations, and on its own website. The group often receives calls, especially during summers, from the public with inquiries about cool roofs, so the cool roof consumer website now provides a place to direct them to learn more about tailored solutions.

The new content for the local government stakeholders on cool communities will bring these resources to a new audience. There is growing interest in these strategies to help adapt to a changing climate, and easy-to-find resources will aid communities in thinking through these strategies and communicating them to their residents.

4.3.2 Recommendations

The ARB should upload the local government cool communities content to CoolCalifornia.org as soon as it is feasible. In addition, ARB and LBNL should continue to search for a solution to the issue with the cool roof search wizard. In the case that there is future funding available for website development, a maintenance fund should be set aside in order to address technical issues as they arise. Also, the consumer cool roof and local government cool communities websites should receive continued promotion to connect consumers and local governments with these resources. For the cool roof consumer website, outreach efforts should be targeted to audiences that implement roofing choices, namely roofing manufacturers, roofing contractors, and roofing supply companies. The current cool roof website audience consists primarily of homeowners who conduct research on roofing options prior to reroofing projects, so connecting them with more informed suppliers and service providers will facilitate the spread of cool roofs. For the new local government content on cool communities, outreach efforts should be targeted to local government coordinating organizations (e.g., Local Government Commission) that share resources and best practices among California localities. The content should also be given increased visibility by being presenting at local government events to spread the word on the new resources.

4.3.3 Benefits to California

To meet the goals set out in AB 32, California will need to employ many strategies. As described previously, "cool community" strategies including cool roofs, cool pavements, cool walls and urban vegetation have been identified as effective voluntary measures with potential statewide emission reductions of 4 million metric tons of carbon dioxide equivalent per year ARB 2008b). The increased use of cool community strategies can help to achieve these emission reduction targets. Web-based targeted resources for key stakeholders can drive interest in, and increase the voluntary use of, these strategies. This not only helps California meet its emission reduction goals and conserve energy, but produces co-benefits for residents, such as reduced utility bills, improved air quality and enhanced urban livability.

CHAPTER 5:
Cool Community Courses and Resources

LBNL developed cool community courses and resources for cool roof and cool pavement stakeholders. These outreach opportunities largely resulted from partnerships with other groups within LBNL as well as private and nonprofit organizations. These efforts were effective in spreading resources to targeted audiences as well as to the general public.

5.1 Approach and Goals

In *Cool Communities Phase 1*, the LBNL team developed training presentations and accompanying brochures/handouts on cool roofs and cool pavements. The authors partnered with industry groups and Pacific Gas & Electric to present on these topics to roofing contractors, and with California's Department of Transportation (CalTrans) to present to local government officials and design professionals.

In *Cool Communities Phase 2*, the LBNL team planned to expand its outreach on cool roofs and cool pavements by presenting materials in new forums, working with different groups to optimize outreach efforts, revising and updating its materials for future outreach opportunities, and developing a cool pavement showcase on LBNL premises.

Some of the key partners for this work were Graniterock, Climate Resolve, Acterra, and LBNL. A new partnership was created with Graniterock[3], a local company that supplies aggregate as well as ready-mix concrete and hot-mix asphalt. The partnership yielded an invitation for the LBNL team to present at the California Chip Seal Association's annual conference, as well as a co-sponsored cool pavement seminar for local government staff in the Bay Area.

Climate Resolve[4], a nonprofit that focuses on creating and communicating ideas to mitigate and adapt to climate change in Los Angeles, has also been a successful collaborator. Climate Resolve sought LBNL input on an initial report for cool roof and cool pavement strategies for Los Angeles, which precipitated their decision to focus on promoting cool surfaces as a strategy for both climate mitigation and climate adaptation. They subsequently invited members of the project team to present at their cool roofs conference called *Hot City, Cool Roofs*[5] and continue to consult on LBNL efforts to advance local government action towards adoption of cool surfaces in Los Angeles.

An active partner in the South Bay Area has been Acterra[6], a nonprofit organization focused on environmental education and action. Their Green@Home[7] program trains volunteers to go

3 http://graniterock.com

4 http://climateresolve.org

5 http://climateresolve.org/hot-city-cool-roofs/

6 http://acterra.org

7 http:// acterra.org/programs/greenathome/index.html

door-to-door to help residents understand options for simple energy-saving techniques and create home energy conservation plans. The LBNL team collaborated with Acterra to develop resources for South Bay residents and their volunteer trainers.

LBNL's Public Affairs Department and Facilities Division have also been integral partners to help us leverage resources. Public Affairs has invited the Heat Island Group for several years to host a booth at the LBNL's Open House event, where it has showcased the science behind cool surfaces to the general public. More recently, the Heat Island Group has also collaborated with the Facilities Division to turn a new parking lot into a cool pavement showcase.

5.2 Outcomes

5.2.1 Graniterock

In partnership with Graniterock, members of the Heat Island Group spoke at the California Chip Seal Association's annual conference in Sacramento on 9 February 2012. A cool pavement presentation was tailored for this audience to include more information on chip seal reflectance. The audience consisted of more than 230 attendees from local government public works departments, asphalt pavement manufacturers and pavement consultant groups from across the state. On 19 June 2012, the Heat Island Group welcomed more than 50 guests from Bay Area local governments to LBNL for a cool pavement seminar co-sponsored by Graniterock (Figure 18). The event featured an expert panel of presenters to discuss the benefits of roadway reflectivity, including improved nighttime visibility, durability and air quality. The event was recorded and uploaded it to the internet to create an online resource (footage: part 1[8], part 2[9]). A cool pavement brochure was developed (here[10]) in preparation for the event, which concluded with a tour of the new LBNL cool pavement showcase (see Section 5.2.4.2).

Figure 18: LBNL Partnered With Graniterock to Cosponsor a Cool Pavement Seminar for Bay Area Local Governments

Photo credit: Lawrence Berkeley Lab – Heat Island Group

8 http://youtube.com/watch?feature=player_embedded&v=Eg1IMfC2iT0.

9 http://youtube.com/watch?feature=player_embedded&v=WgDKPXa3AnU.

10 https://drive.google.com/file/d/0B_DMiLYGSPgdUHVNZVYzLXhNbTg/edit?usp=sharing.

5.2.2 Climate Resolve

Climate Resolve developed a report for the Mayor of Los Angeles describing "cool" strategies—cool roofs and cool pavements—for the city to consider. Climate Resolve contacted the Heat Island Group to provide resources and to review their report. As a result of this report, the organization decided to host a cool roof conference in Los Angeles and invited members of the Heat Island Group to participate and help develop the agenda. The *Hot City, Cool Roofs* conference was held on 8 March 2013, and highlighted LBNL work promoting cool roofs and pavements in California, including roof and pavement demonstration projects and more recent efforts to catalyze cool schoolyards. Following the conference, Mayor of Los Angeles, Antonio Villaraigosa, instructed local officials to include stricter cool roof requirements in the city's building code (here[11]). Since the conference, LBNL has continued to work with Climate Resolve to connect Los Angeles' government staff with resources on cool pavements and cool roofs. To date, this relationship has provided resources to Los Angeles Department of Water and Power for its cool roof rebate program as well as the Department of Public Works' Bureau of Street Services to advise on a cool pavement pilot project (see Section 6.2.3).

5.2.3 Acterra

Acterra's Green@Home program, established in 2007, has trained more than 260 volunteers in home energy conservation skills. To complement their existing home energy audit resources, Acterra invited the Heat Island Group to develop a residential cool roof handout. The one-page handout (here[12]) was included in packets and discussed with more than 60 homeowners in San Jose neighborhoods. In addition, the Heat Island Group made a presentation on cool roofs to 40 members of the Green@Home volunteer corps during an Acterra volunteer training event in Palo Alto on 16 July 2013.

5.2.4 Lawrence Berkeley National Laboratory

In partnership with LBNL's Public Affairs Department, the project team has participated in two Open House events over the past two years. In collaboration with the Lab's Facilities Division, the team has developed the cool pavement showcase as a public-facing exhibit of cool pavement solutions. As part of LBNL's Open House events on 15 October 2011 and 13 October 2012, the Heat Island Group staffed a booth that demonstrated cool science, including cool roofs, cool pavements and cool colors/pigments. Both the CoolCalifornia.org cool roof website and the updated Heat Island Group website (http://Heatisland.LBL.gov) were shared with the public during these events, and in 2012, the Open House featured the cool pavement parking lot showcase. LBNL welcomed more than 3000 guests from throughout the Bay Area for each event.

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11 http://heatisland.lbl.gov/news/los-angeles-strengthens-commitment-cool-roofs.

12 https://webspace.lbl.gov/xythoswfs/webui/_xy-e6881373_1-t_WZI1jLPt.

5.2.4.1 Cool Your School Curriculum Development

In collaboration with LBNL's Center for Science & Engineering Education, a 6th grade curriculum on cool science is being developed. It will include investigations into cool surfaces (playgrounds, roofs, and pavements), cool colors/pigments, and the effect of cool surfaces on buildings and the community. The *Cool Your School* program began piloting this curriculum in September 2012 at Longfellow Middle School in Berkeley, CA and continued with two additional pilots at King Middle School and Willard Middle School, both in Berkeley, CA. In total, eight teachers and 13 classes of students have been involved in the planning and piloting of this curriculum, allowing it to reach more than 320 students in total. For an overview of the program, here[13] is a slide presentation and here[14] is a video overview.

5.2.4.2 LBNL Cool Pavement Showcase

In June 2012, LBNL built a new asphalt concrete parking lot. After the initial construction, the Facilities Division at the Lab accepted an offer by the Heat Island Group to develop a cool pavement showcase. The parking lot provided an opportunity to feature cool pavement technologies that are applied directly to existing paved surfaces. The showcase demonstrates emerging technologies to local governments and design professionals. In addition, the showcase allows the LBNL team to evaluate how the coatings' albedo changes over time.

In June and July 2012, two manufacturers, Emerald Cities Cool Pavement[15] and Quest Construction Products[16], donated their products for the showcase. The initial six coatings (Figure 19) were on display for the cool pavement seminar in June 2012 and at the LBNL Open House event in October 2012. For the Open House event, a signpost (Figure 20) was created for the parking lot to explain the showcase and a booth next to the cool coatings was staffed by the Heat Island Group to engage the event's attendees.

Later in October 2012, the University of California Office of the President filmed a video on LBNL's demonstration and outreach work for cool pavements, highlighting the cool pavement showcase (here[17]). Since its release, the video was picked up by several outlets, including FastCoExist.com (here[18]) and Grist.org (here[19]).

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13 https://webspace.lbl.gov/xythoswfs/webui/_xy-e6881550_1-t_jlNC1vQl.

14 http://eetd.lbl.gov/video/15329/berkeley-labs-cool-your-school-program.

15 http://emeraldcoolpavements.com/.

16 http://quest-cp.com/.

17 http://youtube.com/watch?v=dmWHRwEO52Q.

18 http://fastcoexist.com/1681630/using-different-colored-streets-to-keep-our-cities-cool.

19 http://grist.org/list/weve-got-white-roofs-so-how-about-pastel-pavement/.

Figure 19: Four Emerald Cities Coatings (right) and Two StreetBond Coatings From Quest Construction Products (left) Became the First Components of LBNL's Cool Pavement Showcase in Summer 2012

Photo credit: Lawrence Berkeley Lab – Heat Island Group

Figure 20: Signpost to Mark the Cool Pavement Showcase, Prepared for the October 2012 LBNL Open House

Photo credit: Lawrence Berkeley Lab – Heat Island Group

In November 2012, it was announced that all six coatings would have to be covered for the next 18 months to provide a staging area for the construction of a new building at LBNL. The project team is currently working with LBNL Facilities to bring back the initial two cool coating donors, Emerald Cities Cool Pavement and StreetBond, to reapply their coatings once the construction is complete.

While the original six Cool Pavement Showcase sections were obstructed by construction staging, two new pavement coatings were added in an unaffected part of the parking lot in March 2013. Western Colloid[20] applied its Armor Top cool asphalt seal coat in two solar reflective colors (Stealth Gray and California Tan; Figure 21). Early measurements showed an albedo of about 0.20 for both samples, though this value is likely lower than the true initial values owing to heavy vehicle traffic and dirt from a nearby construction site.

Figure 21: Two Western Colloid Cool Coatings Were Added to the LBNL Cool Pavement Showcase in March 2013

Photo credit: Lawrence Berkeley Laboratory – Heat Island Group

To date, more than 40 non-LBNL guests have visited the site and another site visit by representatives from the San Mateo Transportation Department and the City of San Carlos is being planned. Representatives from CalTrans, which is considering cool pavement coatings for use in a city street redevelopment project, are also expected to visit the cool pavement showcase site in the coming months.

5.2.4.3 Consultation for LBNL Facilities on New LEED Project

The collaboration with LBNL's Facilities Division continued during its planning process for a new Leadership in Energy & Environmental Design (LEED) project at LBNL. Facilities wanted to earn a LEED Sustainable Sites credit by using cool pavements on at least half of the non-roof project area. LBNL's Facilities Division consulted the Heat Island Group for technical and product-related issues for this project, and this enabled the project managers to identify a range of suitable cool pavement surface treatment options. Procurement staff also received assistance

20 http://westerncolloid.com/asphalt-sealcoat-systems.html.

from the Heat Island Group to create a list of local installers of these products, so that the request for bid (RFB) could be issued directly to installers rather than through a general contractor. The general contractor that had previously issued a price quote for a cool pavement product only had knowledge of one such product. By issuing the RFB directly to installers, LBNL was able to avoid a significant markup from the general contractor and could also permit more vendors to compete on price. The resulting bid process awarded the project to a local installer for a quarter of the price that a general contractor had previously quoted for the project. The winning bidder installed the cool coating (Western Colloid's Armor Top) in October 2013.

5.2.5 Other Efforts

In addition to the work that was completed in collaboration with other groups or organizations, one-off opportunities arose to present on cool roofs and cool pavements. With a growing interest in cool pavements, LBNL was invited to present for two national webinars – the Green Parking Council[21] and Durability & Design[22] (part of the Journal of Architectural Coatings). Both the webinars were recorded and can be found online here[23] and here[24], respectively.

LBNL also developed background resources for stakeholders looking to learn more about cool pavement science and product options. The LBNL team compiled cool pavement resources and case studies into a Cool Pavement Primer (here[25]) to assist local governments and non-profit organizations throughout the country in making informed decisions regarding pavement investments. LBNL also compiled a table of currently available cool pavement material options to send to interested parties. This table is not exhaustive but presents information on an array of product types and representative manufacturers and includes estimates for initial albedo and cost per square foot (here[26]).

5.2.6 Media Coverage

In general, the project team's outreach efforts and research attracted a lot of media attention. With the support provided by this task, the research team was able to follow-up on many of these media leads and its work was featured in several news and popular press articles and videos. The media coverage helped convey the research on the benefits of cool surfaces to a general audience.

Table 6 lists the media coverage of Cool Communities research.

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21 http://greenparkingcouncil.org/.

22 http://durabilityanddesign.com/.

23 http://greenparkingcouncil.org/portfolio-item/cool-pavement/.

24 http://durabilityanddesign.com/webinars/?fuseaction=archive&action=view&webinarID=146.

25 https://drive.google.com/file/d/0B_DMiLYGSPgdb1pnSmFsVDdORDQ/edit?usp=sharing.

26 https://drive.google.com/file/d/0B_DMiLYGSPgdb1pnSmFsVDdORDQ/edit?usp=sharing.

Table 6: LBNL Cool Communities Research Was Featured in Several News Articles and Videos

Source	Type	Title/Link
Berkeley Lab News Center	Print	"Parking Lot Science: Is Black Best?" (here[27])
Daily Mail (UK)	Print	"Should we change the colour of our streets? Researchers design 'cool pavement' that could reduce the heat of a city" (here[28])
Durability + Design	Print	"Berkeley Lab Shines Light On Cool Pavement Coatings" (here[29])
University of California Office of Research	Video	"The urban heat island effect and how cool pavement can help" (here[30])
Fast Co.Exist	Print/Video	"Using Different Colored Streets To Keep Our Cities Cool" (here[31])
Grist.org	Print/Video	"We've got white roofs, so how about pastel pavement?" (here[32])
Take Part	Print/Video	"Bye-Bye, Blacktop—Why White Streets Will Chill Our Boiling Cities" (here[33])
San Francisco Chronicle	Print	"Cool steps help fight global warming" (here[34])
The Weather Channel	Video	"Reducing the Urban Heat Island" (here[35])
Beyond Zero Emissions (Australia)	Audio	"Haley Gilbert – LBNL – Talks Cool Communities" (here[36])
Beyond Zero Emissions (Australia)	Audio	"Benjamin Mandel – LBNL – Talks Cool Pavements" (here[37])

27 http://newscenter.lbl.gov/feature-stories/2012/09/13/parking-lot-science/.

28 http://dailymail.co.uk/sciencetech/article-2203314/Researchers-design-cool-pavement-reduce-heat-city.html.

29 http://durabilityanddesign.com/news/?fuseaction=view&id=8415&nl_versionid=2371.

30 http://vimeo.com/58386459.

31 http://fastcoexist.com/1681630/using-different-colored-streets-to-keep-our-cities-cool.

32 http://grist.org/list/weve-got-white-roofs-so-how-about-pastel-pavement/.

33 http://takepart.com/article/2013/04/03/new-player-urban-cooling-pastel-pavement.

34 http://sfgate.com/technology/dotcommentary/article/Cool-steps-help-fight-global-warming-4266070.php#ixzz2KXBOfTkb.

35 http://youtube.com/watch?v=U-7q55gDxqQ.

36 http://bze.org.au/media/radio/haley-gilbert-lbnl-130302.

5.3 Conclusions and Recommendations

5.3.1 Conclusions

Cool Communities Phase 2 successfully continued outreach efforts and developed new resources to aid stakeholders. Through collaborations and partnerships, the research team was able to leverage existing resources to expand its outreach. Table 7 includes a complete list of the outreach events for this task. In addition to the activities listed in the table, other activities not listed include the development of a new brochure, a cool roof factsheet, several recorded and web accessible presentations and a video on cool pavements.

With the addition of the cool pavement showcase, this task created new resource to help stakeholders engage with the various cool pavement technologies and witness firsthand the cooling effect of these technologies. The showcase was featured during the cool pavement seminar for local governments in June 2012 and the LBNL Open House in October 2012. The cool pavement showcase also attracted a lot of media attention, which helped it reach a wider audience through news and popular press articles, features and videos.

Table 7: During the Project Period, LBNL Staff Hosted and Presented at Several Outreach Events Listed in the Table Below

Event	Date	Location	LBNL Presenters	Sponsor	Attendees
LBNL Open House (2 events)	2011-10-15 2012-10-13	Berkeley, CA	Dr. Ronnen Levinson Dr. Melvin Pomerantz Dr. Paul Berdahl Pablo Rosado Benjamin Mandel Haley Gilbert	Lawrence Berkeley National Laboratory	Each year more than 3000 attendees
CA Chip Seal Association Annual Workshop	2012-02-10	Sacramento, CA	Dr. Melvin Pomerantz Haley Gilbert	CA Chip Seal Association	200
Cool Pavement Seminar for Local Government	2012-06-19	Berkeley, CA	Dr. Melvin Pomerantz Haley Gilbert	Graniterock & Heat Island Group at LBNL	50
Hot City, Cool Roofs	2013-03-08	Los Angeles, CA	Dr. George Ban-Weiss Benjamin Mandel Haley Gilbert	Climate Resolve	120
Green@Home training event	2013-07-16	Cupertino, CA	Benjamin Mandel	Acterra	40
Green Parking Council Webinar	2013-07-18	Online webinar	Benjamin Mandel Haley Gilbert	Green Parking Council	40
Durability & Design Education Series	2013-08-01	Online webinar	Benjamin Mandel Haley Gilbert	Durability & Design	60

37 http://bze.org.au/media/radio/benjamin-mandel-lbnl-130925.

5.3.2 Recommendations

Continued outreach efforts to stakeholders in California are highly recommended. There have been many positive responses from industry, state and local government entities, community organizations and the public to the outreach efforts detailed above. At the moment, the Heat Island Group serves as the main portal of information on both the science and implementation of these strategies. Continuing on the success of the first phase of Cool Communities, stronger alliances have been built with partners to leverage existing resources. It is crucial to continue these alliances and to add new partners to help with the adoption and implementation of cool community strategies.

Cool community resources should also be distributed and presented to additional networks (e.g., Local Government Commission, Coalition for Adequate School Housing, County Public Works Officers) to increase interest in these strategies. A survey of existing statewide and local government policies and programs should also be completed to identify opportunities where cool community strategies can help achieve policy/program objectives or targets. Results from the survey can then be used to target specific outreach to these groups to increase their awareness of cool community strategies and how the strategies can be implemented to achieve mutual benefits/goals.

5.3.3 Benefits to California

As described in the previous chapter, to meet the goals set out in AB 32, California will need to employ many strategies. Cool community strategies have been identified as effective voluntary measures with statewide potential emission reductions of 4 million metric tons of carbon dioxide equivalent per year (ARB 2008b). To achieve these potential emission reductions, the state of California needs to increase the use of cool community strategies. By developing targeted resources for key stakeholders, LBNL and its partners can connect resources to stakeholders, drive interest and increase the voluntary use of these strategies. This helps California meet its emission reduction goals and conserve energy, and produces co-benefits for residents, such as reduced utility bills, improved air quality and enhanced urban livability.

CHAPTER 6:
Codes and Technical Assistance

The benefits of cool community strategies increase with widespread adoption of cool roofs, cool pavements, and urban vegetation. While there has been an increase in the adoption of cool roofs on low-slope roofs for commercial buildings in California, there is still a need to target other stakeholder groups in California to increase the adoption of the strategies more broadly. To address this, the LBNL team developed new resources; counseled pavement manufacturers on the development of new cool pavement products; coordinated technical assistance to schools districts; provided technical review of papers, policies and resources; and guided communities and stakeholders through the steps of implementation for cool community policies and programs. These efforts led to the development of a cool schoolyard pilot program in Los Angeles Unified School District (LAUSD), proposal of a district-wide cool roof retrofit project for Sacramento City Unified School District (SCUSD), testing and development of three novel cool pavement products, statewide legislation for cool pavements, and statewide guidance on the implementation of cool community measures to mitigate human health exposure during extreme heat events.

6.1 Approach and Goals

In Cool Communities: Phase 2 the activity goal was to extend the reach and resources of the first Cool Communities project to new California stakeholders. This involved the development of model building code language for cool roofs and cool pavements, the formation of strategic partnerships to leverage outreach and technical assistance resources, and the provision of technical assistance to entities and individuals interested in adopting cool community strategies or promoting their beneficial use. To carry out this task, LBNL again turned to existing networks of partners and established new collaborations with and between stakeholders.

6.1.1 Model Universal Building Code Language

For this activity, the project team set out to develop universal language on cool roofs and cool pavements for building codes, city ordinances and climate action/adaptation plans. More often than not, local government entities reference existing policy language or boilerplate language. To take advantage of this, an objective of this activity was to draft language and guidance as a resource to facilitate the proper adoption of cool roof and pavement codes and policies. To begin this effort, a collaborative of organizations was formed that assessed current building codes and local/state policies for cool roofs and cool pavements. This collaborative would also eventually roll out the universal language to the various implementing entities (e.g., International Code Council, 100 Cool Cities' participants). The collaborative included the Cool Roof Rating Council[38], Global Cool Cities Alliance[39], The Energy Foundation[40], and the U.S. Environmental Protection Agency's Heat Island Program[41].

38 http://coolroofs.org/.

39 http://globalcoolcitiesalliance.org/.

6.1.2 Collaboration with School Stakeholders

There are close to 10,000 schools across California with annual energy expenses totaling $700 million (California Department of Education 2011; Energy Commission Consumer Energy Center). Clearly, school districts can greatly benefit from the adoption of cool community measures to reduce their energy costs. Given the size, complexity and operations of school districts, this stakeholder group requires unique resources and technical assistance to achieve energy savings reductions and thermal comfort improvements from the adoption of cool surfaces. The LBNL team developed strong partnerships with the California Governor's Office of Planning and Research (OPR), LAUSD and SCUSD to develop resources, construct pilot projects, and analyze potential energy savings.

6.1.2.1 Cool Schoolyards Initiative

Working in collaboration with the California Governor's OPR, LBNL began coordinating a group of school stakeholders that could identify the barriers and opportunities for the adoption of cool pavements at schools in California. The school stakeholder group included more than 50 participants representing pavement manufacturers, Department of Education facility officials, local school district representatives and LBNL researchers. LBNL also worked closely with LAUSD to develop a cool schoolyard pilot project. The pilot project was an important step in the rollout of cool schoolyards on a larger scale, as it can encourage innovation of products by manufacturers and provide an opportunity for school districts to learn the administrative process for implementation.

6.1.2.2 Sacramento City Unified School District (SCUSD) Cool Roof Analysis

Most Sacramento county schools were constructed with dark asphaltic roofing products and many are now in need of repair. The Facilities Division at SCUSD contacted LBNL to learn more about cool roof coating options. They had conducted preliminary research and recognized that a coating could extend the life of the existing roof, but also wanted to quantify the potential energy cost savings from converting their dark roofs to white roofs. The LBNL team collaborated with the Facilities Division at SCUSD to conduct a high-level analysis of the cost and emissions savings for 85 schools and more than 450,000 m2 of conditioned roof area. The analysis used estimates and emissions factors from Levinson and Akbari (2010) by zip code to assess the potential benefits of applying white roof coatings, adjusting the initial analysis to reflect the efficiency of SCUSD's HVAC system and current energy costs.

6.1.3 Cool Communities Policy Guide

The LBNL team consulted many state and local entities during the project period to review policies, provide guidance on cool community projects, and connect them with other experts or cool surface material manufacturers. Specifically, LBNL worked with ARB and California Department of Public Health to prepare for the Governor's Conference on Extreme Climate

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40 http://ef.org.

41 http://epa.gov/hiri/.

Risks and California's Future and review the California's Extreme Heat Adaptation Guidance Report & Recommendations.

In addition, the team partnered with agencies and organizations to explore the prospects for cool pavements in future plans for particular areas of California. LBNL teamed up with U.S. Environmental Protection Agency – Region 9 to offer guidance on how best to incorporate cool pavement technologies into a redevelopment and planning process for Complete Streets for four South Bay cities—San Carlos, South San Francisco, San Bruno, and Daly City. The cities are part of the Grand Boulevard Initiative and are developing plans for the section of El Camino Real that runs through these cities. In addition, LBNL helped the Los Angeles Department of Public Works, Bureau of Street Services take steps toward developing a cool pavement pilot project. The Bureau is planning several pilot cool pavement cul-de-sacs in the city, so turned to LBNL for help connecting with manufacturers and guidance on the design of the pilot.

For both of these pilot opportunities, the team shared technical resources and industry contacts. LBNL's involvement has facilitated the flow of information and expedited the learning process, so that potential barriers were identified and addressed early on.

6.1.4 Cool Pavement Product Development

In California, there is growing awareness and interest in cool pavements, but limited options has delayed their deployment. In order to bring a wider variety of cool pavement products to market, LBNL offered assistance to manufacturers to aid development of cool pavement products covering a variety of product types. The team tested the albedo of various cool pavement technologies, including cool asphalt seal coats, a rubberized cool seal coat, and cement overlays to assess their viability as cool community solutions. In all, samples of varying colors and textures for seven cool pavement products manufactured by seven distinct vendors were tested. LBNL also advised these companies on albedo targets to meet voluntary cool pavement requirements both locally, in the California Green Building Standards Code (CalGreen), and nationally, in the U.S. Green Building Council's LEED program. The sample albedo results ranged from 0.06 to 0.62, and four products were found to have albedo above 0.30, which meets CalGreen and LEED minimum requirements.

This testing and consultation process familiarized LBNL with several cool pavement suppliers. From this experience, the team has been able to introduce manufacturers to interested cool pavement stakeholders throughout California, most notably LAUSD and the General Services Division of the City of Los Angeles.

6.1.5 Technical Review of Related Publications/Resources

Again, to leverage limited resources, LBNL supported efforts by various partner organizations by providing technical review of cool community aligned publications and resources. The newly formed Global Cool Cities Alliance[42] (GCCA) is a national and international non-profit, advocating for the use of cool surfaces in cities to promote energy efficiency, improved human health and comfort, and global cooling. The team advised on and reviewed their new *Cool Roofs*

42 http://globalcoolcities.org/.

and Cool Pavements Toolkit[43], which provides program managers and policy makers a primer and implementation guide on cool roofs and pavements. The team also provided substantial technical review of a new report by the Natural Resources Defense Council and University of California Los Angeles' Emmett Center on Climate Change and the Environment titled, "Looking up: How Green Roofs and Cool Roofs Can Reduce Energy Use, Address Climate Change, and Protect Water Resources in Southern California"[44]. The report quantifies the local benefits of cool roofs for Los Angeles, makes policy recommendations, and presents a good methodology for California local governments to follow when quantifying high-level benefits of cool roofs in their cities.

6.2 Outcomes

6.2.1 Model Universal Building Code Language

Before beginning to draft model code language, the collaborative first pulled together a compendium of cool community policies, codes, and programs throughout the United States. This compendium contains information on the type of policy in place (i.e., codes and standards, plans and ordinances, rebates and incentives, voluntary programs, or information/demonstration), the mitigation strategies promoted in the policy, as well as the targeted audience (i.e., commercial, residential, municipal). This compendium allowed us to quickly review existing policies across the U.S and direct interested stakeholders to existing, successful policies and/or programs. After initial development of the compendium, the LBNL team handed it over to the GCCA, which used it to develop its Cool Roofs and Cool Pavements Toolkit: Knowledge Base[45]. Expanding on the information provided on current building codes in the cool community policy compendium, LBNL developed a second resource, a cool codes summary worksheet (here[46]), which lists the history of cool roof and cool pavement code language and requirements for American Society for Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) 90.1, ASHRAE 90.2, ASHRAE 189.1, EnergyStar, International Energy Conservation Code (IECC), International Green Construction Code (IGCC), LEED, CalGreen and California Building Energy Efficiency Standard (Title 24). This is a convenient resource to help stakeholders understand the history and progression of cool codes in the U.S. and in California.

Next the collaborative developed model universal building language for cool roofs (here[47]). This language clarifies definitions, building and roof types, applicable climate zones, and testing and measurement standards for cool roof code adoption. The collaborative is now working with building code experts at the New Buildings Institute and with an independent consultant, Craig Conner, to adapt the language for various national building codes (IECC, IGCC, ASHRAE 90.1

43 http://coolrooftoolkit.org/.

44 http://cdn.law.ucla.edu/SiteCollectionDocuments/Centers and Programs/Emmett Center on Climate Change and the Environment/Looking_Up_June_2012.pdf.

45 http://coolrooftoolkit.org/knowledge-base/.

46 https://docs.google.com/file/d/0B_DMiLYGSPgdVnlveWw3bWlNMTg/edit?usp=sharing.

47 https://docs.google.com/file/d/0B_DMiLYGSPgdWkNuYXFXWWVpb2c/edit?usp=sharing.

+ 189.1). In addition to the model code guidance for cool roofs, the LBNL team provided technical guidance to the Energy Commission and its consultants on the 2013 California Building Energy Efficiency Standards; to the U.S. Environmental Protection Agency on its comments for the IgCC; to the GCCA, U.S. Department of Energy, and building code consultant, Craig Conner, on comments for the IECC; to California Assembly Member Skinner's staff on *Department of Transportation: paving materials 2012* (AB 296); and to the U.S. Green Building Council on Version 4 of the LEED voluntary building program. LBNL team member Ronnen Levinson was also invited to serve on (and joined) the technical advisory group of LEED's sustainable sites credit, which includes measures for both cool roofs and cool pavements.

6.2.2 Collaboration With School Stakeholders

6.2.2.1 Cool Schoolyards Initiative

The idea for the cool schoolyard initiative originated from a meeting with the California Governor's OPR to discuss options for implementing cool surfaces in California. In December 2011, the project team met with Ken Alex and Sandy Goldberg from OPR, Kathleen Moore and Monique Ramos from the School Facilities and Transportation Services Division of California's Department of Education, and Jeff Vincent of UC Berkeley's Center for Cities and Schools, to discuss cool surfaces for school playgrounds. The discussions provided several good leads for technical assistance in support of the Department of Education and OPR's interest in implementing cool playground surfaces.

LBNL and OPR agreed to co-host a roundtable discussion with pavement manufacturers, Department of Education facility officials, local school district representatives and LBNL researchers to better understand the barriers and opportunities for the adoption of cool pavements at schools. In preparation for the meeting, the LBNL team developed a background primer on cool schoolyards (here[48]), and completed a review of currently available cool pavement options. In July 2012, OPR and LBNL co-hosted the cool schoolyard stakeholder meeting with 40 participants from school district administration and operations offices, state and local government agencies (ARB, California Department of Public Health, and Bay Area Air Quality Management District), the California Department of Education, several cool pavement manufacturers, landscape architects and LBNL research staff. The meeting was very successful and LBNL developed a summary table of the barriers and opportunities along with their associated action items (here[49]). The group found that the barriers to cool schoolyards are sensitivity to higher first costs and general lack of familiarity with cool pavement products. The opportunities identified included developing demonstration projects and dissemination of educational/outreach resources through the stakeholders' networks.

After the meeting in July 2012, LAUSD contacted LBNL to help the district navigate the options for cool pavement coatings. LAUSD is the second largest school district in the United States with more than 1000 school facilities. Working with LAUSD provided LBNL an opportunity to

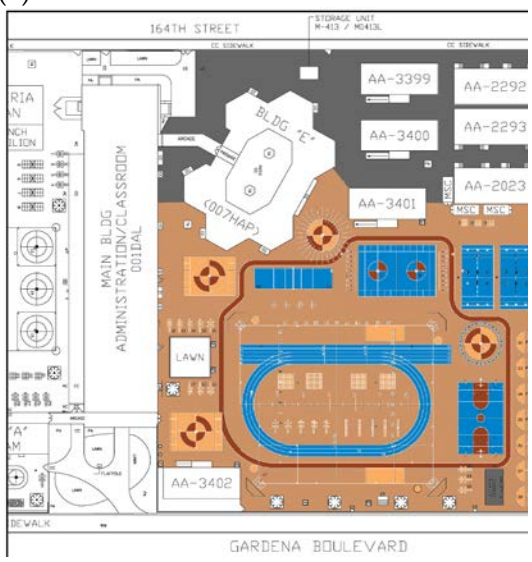
48 https://docs.google.com/file/d/0B_DMiLYGSPgddldHeUdGdDBCcTA/edit?usp=sharing.

49 https://docs.google.com/file/d/0B_DMiLYGSPgdczBjWm1oWFVrTm8/edit?usp=sharing.

document the district's experiences to then pass along to other school districts in California. Collaboration was initiated with Chad Fenwick, Advisor to Physical Education, and Roshini Das, Sustainability Specialist in the Facilities Services Division. They wanted to first investigate several cool coating technologies and then co-host a meeting with the district's school operations and maintenance staff to introduce the technologies. LBNL provided content for presentations and organized several meetings with manufacturers for the school district to learn more about the various coating technologies. The district was keen to find products that offered a range of cool colors to brighten schoolyards, as well as find products that could be applied by their in-house facilities staff. After hearing the presentation and meeting with several pavement coating manufacturers, LAUSD's New Products Committee selected several candidate products to submit for approval to the District's Office of Environmental Health & Safety. To date, two products have been approved by the Office of Environmental Health & Safety for use in the district. Since district regulations only permit design standards with a minimum of three product options, the goal is to construct three pilot projects with three different products. During the summer of 2013, construction was completed on the first pilot with StreetBond at Gardena Elementary School in Gardena, California. Figure 22 demonstrates the cool schoolyard design (panel a), the pre-existing blacktop (panel b), the completed project (panel c) and the application of the cool coating by the district staff (panel d). Currently, the district is planning the second pilot project with Plexipave and the authors are working with the district to identify the final product for the third pilot.

Figure 22: Image (a) Is the Proposed Design of the Gardena Elementary School Cool Schoolyard and (b) Shows the Preexisting Blacktop Area That Was Coated in the Summer of 2013. Image (c) Is the Completed Project, and (d) Was Taken During the Application of the Cool Coating

(a)



(b)

(c)

(d)

Photo credit and graphic source: StreetBond Coatings From Quest Construction Products

In addition to the pilot project in LAUSD, one of the cool schoolyard cool pavement companies, Western Colloid, applied their cool seal coat at four schools in Palmdale Unified School District. They completed the application in August 2013 (Figure 23).

Figure 23: One of the Cool Schoolyard Initiative Members, Western Colloid, Worked With Palmdale Unified School District in Southern California to Apply Its Cool Seal Coat on Four Schools in the District

Photo credit: Western Colloid

6.2.2.2 Sacramento City Unified School District Cool Roof Analysis

LBNL collaborated with SCUSD to quantify the potential benefits of retrofitting 85 school buildings with white roof coatings over the existing dark roofs. The high-level analysis estimated energy and CO_2 savings for the school district. By installing white coatings on their schools, SCUSD could save more than $670,000 annually. These cost savings, as well as emissions reductions, are summarized in Table 8. The table below highlights the estimated potential for total annual cost savings for SCUSD by ZIP code and conditioned roof area. The columns on the left display the potential for emission reduction from conserved energy in the District. SCUSD will present these findings and analysis to their School Board in the coming year to request funding for cool roof retrofits of their District's buildings.

Table 8: LBNL Analysis Determined That SCUSD Can Save Approximately $670K Annually on Energy Costs for Its 85 Buildings

ZIP code	Number of schools	Total conditioned roof area (1000 m^2)	Total annual energy-cost saving ($K)	Total annual CO_2 reduction (t)	Total annual NO_x reduction (kg)	Total annual SO_2 reduction (kg)	Total annual Hg reduction (mg)
95811	1	3	4.9	13	11	8	34
95816	3	16	23.4	62	53	39	162
95817	2	8	11.5	30	26	19	79
95818	8	52	76.6	202	174	129	529
95819	5	20	29.8	79	68	50	206
95820	10	62	92.2	243	210	155	637
95822	17	72	106.0	280	242	178	732
95823	6	46	68.1	180	155	114	470
95824	10	52	77.5	204	177	130	535
95826	6	26	37.9	100	86	64	262
95827	5	37	54.5	144	124	92	377
95828	1	3	4.9	13	11	8	34
95831	7	41	61.1	161	139	103	422
95832	4	15	22.7	60	52	38	157
		Total:	**671.3**	**1,771**	**1,529**	**1,126**	**4,635**

The District has already begun to demonstrate support of the cool roof retrofits. Stemming from analysis with SCUSD on cool roof building energy savings, a 6th grade class from A.M. Winn Elementary School submitted a cool roof retrofit project to the district-wide Project Green competition. The students presented their recommendations and were selected to receive $100,000 for a new cool roof (Figure 24). Read more online here[50].

Figure 24: A.M. Winn 6th Grade Project Green Team Presented Their Green School Recommendation, Cool Roofs, to a Panel of Experts and Were Selected as Finalists to Receive $100K for a New Cool Roof on their School

Photo credit: Ron Rudd, SCUSD

6.2.3 Cool Communities Policy Guide

The LBNL team consulted many state and local entities during the project period to review policies, provide guidance on cool community projects and to connect them with other experts or cool surface material manufacturers.

Through partners at ARB and the California Department of Public Health, the team advised on the development of the agenda for the *Governor's Conference on Extreme Climate Risks and California's Future*[51]. The conference featured a presenter from Fresno County's Public Health Department who spoke of the need for local governments to adopt cool community measures to adapt to and lessen the impact of extreme heat events. In addition, one of the video segments from the conference highlighted Misha Sarkovich from Sacramento Municipal Utility District, who described the benefits of shade trees and solar reflective roofs for cool cities. In addition, LBNL reviewed and commented on California's Extreme Heat Adaptation Guidance Report & Recommendations. The report and recommendations include several cool community measures

50 http://rosemont.patch.com/groups/schools/p/am-winn-elementary-wins-100k-for-upgrade.

51 http://gov.ca.gov/ecrcf.php.

to alleviate, and adapt to, extreme heat events. The report and recommendations were finalized in October 2013 and posted to the California Climate Change Portal here[52].

LBNL also teamed up with U.S. Environmental Protection Agency – Region 9 to offer guidance on how best to incorporate cool pavement technologies into a redevelopment and planning process for Complete Streets redesign as part of the Grand Boulevard Initiative[53]. LBNL spoke with the design lead to educate them on the benefits of cool pavements and coordinated several meetings with cool pavement manufacturers to find best products for the street design. The technical assistance for cool pavements was recently highlighted in a memorandum to CalTrans from the Complete Streets Project Team for the Grand Boulevard Initiative (here[54]). The memo is the first step for the cities to have their proposed design approved by CalTrans. Since the plan includes many new design features, like cool pavements, CaTtrans is required to review and approve the proposed design. The design for the project includes plans for cool pavements (albedo > 35%) on the street sections that run through the city centers.

LBNL has also assisted the Los Angeles Department of Public Works, Bureau of Street Services initiate a cool pavement pilot project. The Bureau is currently planning several pilot cool pavement cul-de-sacs in the city. The project team helped identify several potential cool pavement technologies, including a novel cool slurry seal product that is applied in a similar fashion to their existing slurry seal. The manufacturer is now working with LBNL and Los Angeles' Bureau of Street Services to develop the product to meet the performance, application, and albedo requirements for Los Angeles. The goal is to develop a product soon so construction on the pilots could begin in spring/summer 2014.

6.2.4 Cool Pavement Product Development

The project team tested the albedo of various types of cool pavement technologies from seven manufacturers. As summarized above in Section 6.1.4, four products (two cement concrete overlays and two coatings) meet the minimum albedo requirements specified in LEED and CalGreen. For products with lower SR, the team worked subsequently with manufacturers to help them improve their products' albedos and in one case tested subsequent reformulations. While that vendor's results showed slight improvements, its product has not yet demonstrated CalGreen/LEED eligibility. New formulations of additional products will be tested in the near future

6.2.5 Technical Review of Related Publications/Resources

As was described in section 6.1.5, LBNL has supported efforts to assist various partner organizations by providing technical review of cool community aligned publications and resources. GCCA's new Cool Roofs and Cool Pavements Toolkit has been broadly shared with cool community stakeholders across the globe. The toolkit has also been helpful for LBNL to communicate background information and resources to program managers and policy makers

52http://climatechange.ca.gov/climate_action_team/reports/Preparing_California_for_Extreme_Heat.pdf.

53 http://grandboulevard.net/projects/complete-streets.html.

54 https://docs.google.com/file/d/0B_DMiLYGSPgdM1lNdTVzZGl0ejg/edit?usp=sharing.

in California. The toolkit now also features a knowledge base that was populated with the policies, codes and programs LBNL identified in the codes compendium. In addition, a report by Natural Resources Defense Council and University of California Los Angeles' Emmett Center on Climate Change and the Environment titled "Looking up: How Green Roofs and Cool Roofs Can Reduce Energy Use, Address Climate Change, and Protect Water Resources in Southern California" has been a good resource for policy makers and non-profit organizations in southern California. It has also highlighted the opportunity for cities to include a strategy of both cool roofs and green roofs to advance city sustainability efforts. These two resources will help LBNL better communicate with new city stakeholders in California on why and how cool community strategies should and can be adopted.

6.3 Conclusions and Recommendations

6.3.1 Conclusions

The LBNL outreach efforts described in Chapter 5 have helped drive interest in the topic of cool communities in California. In contrast, the technical assistance and guidance activities described in Chapter 6 have aided key stakeholders in turning their interest into actual cool community programs, policies, and projects. Through these activities, the team was able to provide more tailored support to these stakeholders. For example, the work with the cool schoolyard initiative allowed the project team to educate this unique stakeholder group on the potential of cool pavements for schools. By doing so, LBNL helped the stakeholder group understand the benefits of cool pavements and the range of available products. In addition, the project team was able to guide the pavement manufacturers to understand the specific needs of school districts. Similar support is being provided to the City of Los Angeles. With the interest driven by initial outreach efforts, Los Angeles invited LBNL to explore ideas and products for a cool pavement pilot project. If successful, the pilot project could lead to widespread adoption across the city.

Initially, this activity was loosely defined so the team could take advantage of opportunities that came about during the project period. This flexibility paired with the expertise of LBNL's team has been successful and led to innovative projects, policies and research that addressed gaps in currently available resources and increased the adoption/implementation of cool community strategies throughout the state.

6.3.2 Recommendations

From the initiation of the project to its conclusion, the number of inquiries from the public, policy makers, manufacturers and other stakeholder groups has grown significantly. Although the number of cool community projects has increased across the state, there is a continued need to provide technical assistance. LBNL found this to be especially true of organizations and stakeholder groups that have difficulty sifting through the existing resources and understanding product claims. These groups require tailored resources that help them make the most responsible decisions for their unique applications, projects or policies.

In addition, the development of more cool pavement pilot projects can help demonstrate proof of concept and lessen or eliminate uncertainties that prevent wider adoption of cool pavements.

To complement pilot projects, manufacturers of cool pavement products need continued technical guidance to develop products that can meet more diverse applications and structural demands in cities and communities.

6.3.3 Benefits to California

As described in the previous chapters, to meet the goals set out in AB32, California will need to employ many strategies. Cool community strategies have been identified as effective voluntary measures with statewide potential emission reductions of 4 million metric tons of carbon dioxide equivalent per year (ARB 2008b). To achieve these potential emission reductions, The state of California needs to increase the use of cool community strategies. The authors continue to have success with spreading the word about the benefits of these strategies and with tailored technical assistance and guidance; the authors find that this interest is turning into projects. The continued voluntary adoption of cool community strategies will help California meet is emission reduction goals and conserve energy, but also produce co-benefits for residents, such as reduced utility bills, improved air quality and enhanced urban livability.

CHAPTER 7:
Benefits of Cool Community Measures

This study uses a meteorological model to predict potential changes to urban surface air temperature that could be attained by large-scale adoption of cool roofs and pavements in Bakersfield. The authors model two cases: a base scenario representative of the present urban area with roof albedo determined through high resolution aerial imagery, and a modified "cool" scenario representative of the potential urban albedo after large-scale adoption of cool roofs and cool pavements. The temperature differences between the two scenarios represent the upper bound of potential average seasonal temperature changes.

7.1 Approaches and Goals

7.1.1 Introduction

A cool roof can directly reduce indoor temperature or the air conditioning use in a building. Citywide adoption of cool roofs and pavements has the potential to lower ambient urban air temperature. Lower ambient urban air temperatures from the large-scale adoption of cool roofs would further reduce air conditioning needs and provide general public health benefits during summer heat waves. Building energy use may increase during the winter as cool surfaces could reflect sunlight that would otherwise help offset heating demands.

The effects of cool roofs on individual buildings can be measured in demonstration projects. However, there are few examples of large urban areas that have adopted cool roofs and pavements to the extent that the average albedo of the whole urban area increased significantly. In general, however, predictions of temperature reduction due to large-scale surface albedo changes are limited to numerical modeling efforts as demonstration projects are too expensive. Campra et al. (2008) measured and Campra and Millstein (2013) modeled surface temperature changes in a region in Southern Spain that experienced significant surface brightening due to changes in agricultural practices, and were able to show surface air temperature reductions relative to neighboring regions that did not have surface brightening. Several modeling efforts have been aimed at predicting city-wide cool roof benefits for both surface air temperatures. Additional studies have assessed the possibility of enhancing global surface albedo through adoption of cool surfaces across urban areas in order to reduce surface and atmospheric heating. Akbari et al. (2009), Menon et al. (2010), and Millstein and Menon (2011), for example, have investigated the continental and global effects on radiative forcing and meteorology of increasing urban surface reflectivity. A number of studies have predicted effects at the city level, including those by Taha (2008), Lynn et al. (2009), and Zhou and Shepherd (2009). This work follows the general approach of many of these previous studies as the authors use a state-of-the-art meteorological model (the Weather Research and Forecasting (WRF) model 3.4.1) and change only the gridded urban albedo values between the scenarios.

One aspect of this work that differentiates it from past modeling studies is the careful development of initial values for roof albedo. Typically, albedo is input as an average reflectivity for each grid cell developed either from a satellite product or as a function of the

land-use type (also a function of a satellite product). Either way, the typical albedo input data does not have the geographical resolution to quantify individual roof albedos. In contrast, this work applies aerial imagery (1 m2 resolution) to develop model inputs that accurately describe the current roofing stock. Furthermore, this detailed input data allows estimation of potential albedo enhancement that is spatially resolved throughout the city of Bakersfield. For example, using the aerial imagery data one can resolve buildings that already have a highly reflective roof, and avoid assuming the albedo of those roofs can be increased significantly. Using the aerial imagery to create a base case scenario allows one to limit the total potential albedo increase based on the current building stock and accurately represent the variation of that stock across different neighborhoods within Bakersfield.

7.1.2 WRF Setup

WRF version 3.4.1 (Skamarock 2008) was used with a nested two-way model configuration centered at Bakersfield, CA., The innermost nest was resolved to 1.3 × 1.3 km grid cells. The largest nest, resolved to 36 × 36 km, covered all of California. Boundary and initial conditions were forced with North American Regional Reanalysis (NARR) data (Mesinger et al. 2006). Longwave and shortwave radiation was modeled within WRF using Rapid Radiative Transfer Model (RRTMG). The surface layer modeling was based on the Eta similarity while the land-surface was modeled using the Noah Land Surface Model. The planetary boundary layer was modeled using the Mellor-Yamada-Janjic scheme. A cumulus parameterization (Grell 3D) was used in the two coarsest grids, but not at the grids resolved to 4 or 1.3 km. Surface albedo, for non-urban cells and urban cells outside of Bakersfield, was characterized using monthly dependent Moderate Resolution Imaging Spectroradiometer (MODIS) based values.

7.1.3 Incorporating High-Resolution Aerial Imagery

The aerial imagery provided information about roof reflectivity but not reflectivity of other surfaces. Geographic Information Systems (GIS) software was used to isolate building outlines in the aerial imagery and develop average reflectivity estimates for each individual roof in Bakersfield, California. Roofs were divided into two types, flat and sloped, which are considered representative of commercial and residential roofs, respectively. For each grid cell, a weighted average (by roof area) albedo value for sloped and flat roofs was created. Raw roof albedo values were calibrated by comparing the observed albedo of recently installed roofs to the known reflectivity values of the specific roofing products. The comparison indicated that raw roofing albedo values needed to be multiplied by a calibration factor of 1.5 to match the known reflectivity values.

The albedo for each urban grid cell was calculated based on a combination aerial imagery and MODIS imagery:

$A^* = (A_f \times F_f) + (A_s \times F_s) + (A_p \times F_p) + (A^\circ \times F^\circ)$

where

A^* = Final albedo value for an urban Bakersfield grid cell

A_f = Weighted average albedo of all flat roofs in the cell

F_f = Fraction of grid cell area covered by flat roofs

A_s = Weighted average albedo of all sloped roofs in the cell

F_s = Fraction of grid cell area covered by sloped roofs

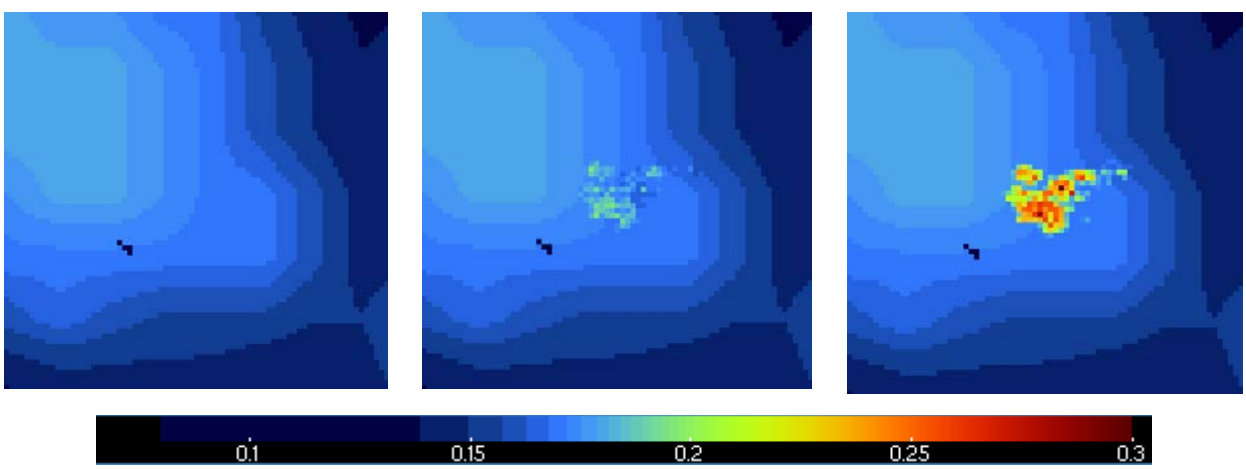
A_p = Albedo of paved area, assumed to be 0.14

$F_p = (A_f + A_s) \times (R_p/_r)$, where $R_p/_r = (0.35/0.25)$ is the average fraction of pavements in urban area divided by the average fraction of roofs in urban area (note, this ratio is not based on data specific to Bakersfield but follows the methods described Akbari et al (2009).

A° = MODIS based albedo value for the grid cell

$F^\circ = 1 - (F_f + F_s + F_p)$

Figure 25: Surface Albedo Based on, From Left to Right, MODIS Only, MODIS + Aerial Imagery, MODIS + Aerial Imagery + Cool Roof and Pavement Substitution



This formulation is not perfect, as ideally, one would want a value for the $(A^\circ \times F^\circ)$ term that did not already incorporate the roof and pavement area in A°. However, the initial MODIS data shows no difference in average albedo for the urban region of Bakersfield compared to surrounding cells, indicating that the there would be little difference between estimating A° with or without roof and pavement area.

Figure 25 shows base case MODIS albedo, the base case albedo after it has been updated to include the aerial imagery data, and the cool case albedo.

A "cool" scenario was developed to investigate the effects on temperature of switching all current roofs and pavements to cool technology. In the cool scenario, idealized albedo values, 0.60, 0.35, and 0.30, were substituted for the flat (Af) and sloped (As) roof and the pavement (Ap) albedo, respectively. These idealized values represent typical aged albedo of reflective materials used for roofs and pavements. In this manner, each roof in Bakersfield, as measured by the high-resolution imagery, was effectively replaced by a "cool" roof. Additionally, although the pavement area was not directly measured, the total pavement area available for replacement in each grid cell was bounded by the total building area [as shown above: $Fp = (Af + As) \times (Rp/r)$].

Each scenario was modeled as a series of 20 weeklong episodes. The first week of February, June, August, and December were modeled for the years 2005 – 2009. Winter averages were generated based on December and February outputs and summer averages were generated based on June and August outputs.

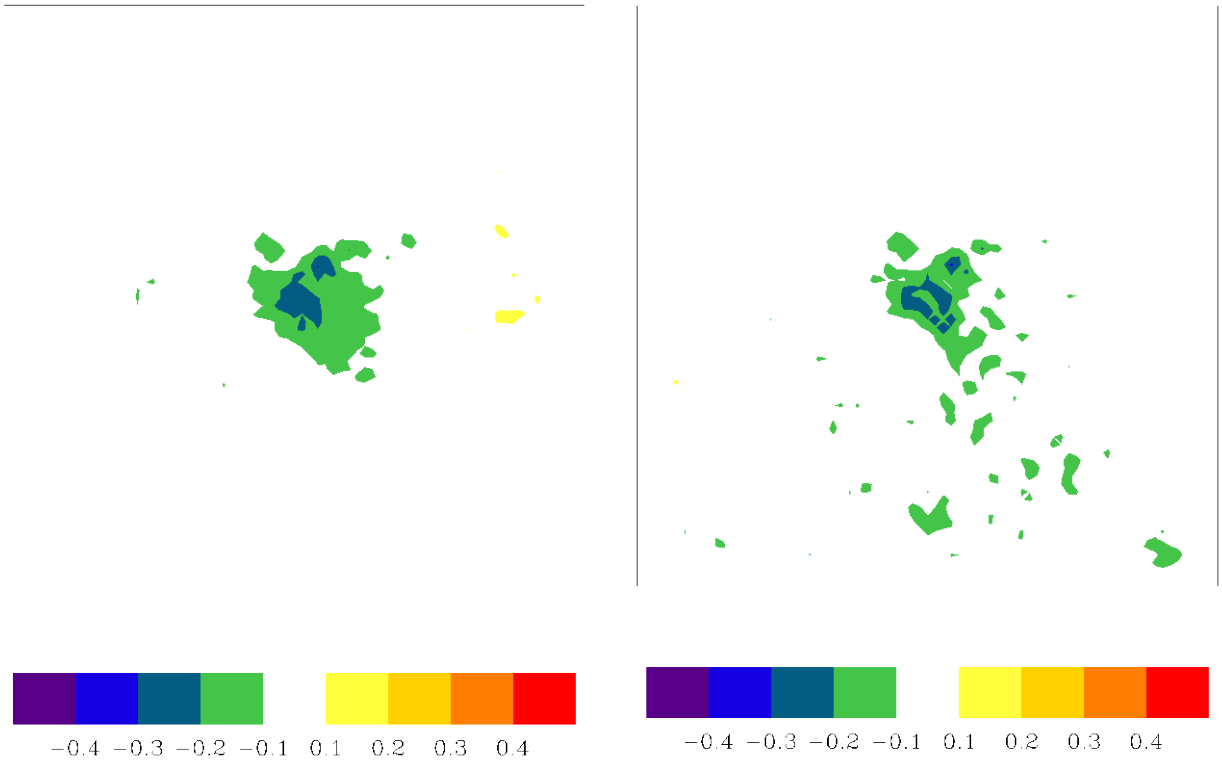
7.1.4 Modeled and Observed Temperatures

The addition of cool roofs and pavements reduced afternoon air temperatures across the Bakersfield urban area (Figure 27). Maximum temperature reductions of 0.3°C were modeled over the downtown Bakersfield area, while smaller temperature reductions (0.1 – 0.2°C) were found in Bakersfield's residential neighborhoods. Interestingly, the magnitude of temperature reductions was constant across both summer and winter seasons. However, the spatial distribution of temperature changes varied between the seasons. During the summer season, afternoon temperature reductions extended downwind (to the southeast) of Bakersfield in a turbulent pattern. During the winter, average temperature reductions were limited to Bakersfield due to the lack of a consistent direction to the afternoon winds

Temperature changes modeled here are smaller than the changes predicted by similar studies of increasing albedo in other California cities. For example, Taha (2008) modeled larger temperature reductions in Sacramento than this study reports in Bakersfield. Two differences in study design help to account for the lower predicted temperature changes described here. This work predicts the effects of adopting cool roofs and pavements, while Taha (2008) predicts the effects of adopting cool roofs, walls, and pavements. The albedo changes modeled in Taha (2008) are significantly larger than the albedo changes modeled here. Additionally, Taha (2008) modeled instantaneous temperature differences between the scenarios (i.e. the temperature difference at one hour of one day), whereas this work models the average temperature change for each hour of the day over 60 model days for each season, as opposed to changes that might be seen on a single hot day. There are also differences in the representation of the urban areas between Taha (2008) and this work; for example, Taha (2008) employed an urban canopy model whereas, the WRF default description of urban characteristics, other than surface albedo, was applied in this work. The temperature changes reported here would be suitable as inputs to calculate energy use changes that occur over an annual cycle. However, the averaged

temperature changes might not be representative of temperature reductions that occur during heat waves.

Figure 26: Afternoon (15:00 LST) Temperature Differences (cool minus base) AVERAGED OVER ALL EPISODES (2005 through 2009)



Average winter temperature change (°C)

Average summer temperature change (°C)

7.2 Conclusions and Recommendations

7.2.1 Conclusions

The WRF model was used to predict air temperature changes from widespread adoption of cool roofs and pavements in Bakersfield, California. Aerial imagery was used to develop estimates of albedo for each individual roof in Bakersfield. The transition to cool surfaces was modeled by increasing the albedo of each individual roof up to the typical albedo value of an aged 'cool' roofing material selected by roof type, flat or sloped. Total pavement area was constrained as a function of the total roof area measured in the aerial imagery, and pavement albedo was assumed to increase from 0.14 to 0.30 after cool pavements were introduced. Temperature decreased most over downtown Bakersfield, by roughly 0.3 °C, during the afternoon in the summer and the winter seasons. Afternoon temperature reductions between 0.1 °C and 0.2 °C were seen through the rest of the Bakersfield city limits. Summer and winter temperature reductions were similar in magnitude. During the summer season, temperature reductions were seen in central Bakersfield and downwind of Bakersfield to the southeast.

7.2.2 Recommendations

The widespread addition of cool roofs and pavements would likely reduce afternoon temperatures in Bakersfield. These temperature reductions would lower air conditioning usage and likely decrease the rate ozone formation in downtown Bakersfield. Similar benefits would be expected in other California cities that are alike in size and meteorology to Bakersfield. However, the average temperature reductions found in this study are relatively small compared to expected warming from climate change, thus, additions of cool roofs and pavements offers only partial mitigation of future urban temperature increases. This analysis was designed to capture average temperature changes and it is possible that average temperature reductions are an underestimate of temperature reductions that occur during the hottest days of year. There is growing interest in California to prepare for and mitigate extreme heat events so the authors recommend continued research to model the effect of cool community strategies during extreme heat events in California.

7.2.3 Benefits to California

Cool roofs and pavements offer benefits to California cities such as Bakersfield, and California as a whole, by reducing air temperature and building energy demand during hot summer days. Though there may be some heating penalty in Bakersfield during the winter as a consequence of using more reflective roofs and pavements, it is not determined in this chapter whether the benefits outweigh costs or other penalties associated with the reflective technologies examined here.

GLOSSARY

Term	Definition
AB32	Global Warming Solutions Act passed in 2006 in California
AB296	Department of Transportation: paving materials passed in 2012 in California
AC	Asphalt concrete
ASHRAE	American Society of Heating, Refrigerating & Air Conditioning Engineers
ARB	California Air Resource Board
°C	Degrees Celsius
cm	Centimeter
COP	Coefficient of performance
CRRC	Cool Roof Rating Council
CO_2	Carbon dioxide
Energy Commission	California Energy Commission
°F	Degrees Fahrenheit
ft^2	Square feet
g	Gram
GCCA	Global Cool Cities Alliance
GHG	Greenhouse gases
GIS	Geographic Information Systems
HVAC	Heating, Ventilation and Air Conditioning
IECC	International Energy Conservation Code
IGCC	International Green Construction Code
IR	Infrared
K	Kelvin
kJ	Kilojoule

kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
LAUSD	Los Angeles Unified School District
LEED	Leadership in Energy and Environmental Design
LBNL	Lawrence Berkeley National Laboratory
LST	Local standard time
m	Meter
m^2	Square meter
MODIS	Moderate Resolution Imaging Spectroradiometer
NARR	North American Regional Reanalysis
NO_x	Nitrogen oxide
OPR	California Governor's Office of Planning and Research
PCC	Portland cement concrete
PV	Photovoltaic
R-*n*	Thermal resistance of n ft^2 °F h/BTU
RFB	Request for Bid
RRTMG	Rapid Radiative Transfer Model
RSI-n	Thermal resistance of n m^2 K/W
SCUSD	Sacramento City Unified School District
SO_2	Sulfur dioxide
SR	Solar reflectance, also expressed as albedo
TiO_2	Titanium dioxide
UC Davis	University of California at Davis
UHI	Urban heat island
W	Watt
WRF	Weather Research and Forecasting model

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APPENDIX A:
Measured Temperature Reductions and Energy Savings From a Cool Tile Roof on a Central California Home

Measured temperature reductions and energy savings from a cool tile roof on a central California home

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Abstract

Temperatures, heat flows, and energy uses were measured for a year in two similar single-family, single-story homes built side by side in Fresno, California. The "cool" house had a reflective cool concrete tile roof (initial albedo 0.51) with nearly twice the thermal capacity of the standard dark asphalt shingle roof (initial albedo 0.07) on the "standard" house.

Cool-roof energy savings in the cooling and heating seasons were computed two ways. Method A divides by HVAC efficiency the difference (standard – cool) in ceiling + duct heat gain. Method B measures the difference in HVAC energy use, corrected for differences in plug and window heat gains. Methods A and B agreed well in the cooling season only.

Based on the more conservative Method B, annual cooling (compressor + fan), heating fuel, and heating fan site energy savings per unit ceiling area were 2.82 kWh/m^2 (26%), 1.13 kWh/m^2 (4%), and 0.0294 kWh/m^2 (3%), respectively. Annual space conditioning (heating + cooling) source energy savings were 10.7 kWh/m^2 (15%); annual energy cost savings were 0.886 \$/m^2 (20%). Annual conditioning CO_2, NO_x, and SO_2 emission reductions were 1.63 kg/m^2 (15%),

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0.621 g/m^2 (10%), and 0.0462 g/m^2 (22%). Peak-hour cooling power demand reduction was 0.88 W/m^2 (37%).

Keywords

cool roof; energy savings; solar reflectance; thermal mass; residential building; temperature reduction; ceiling heat flow; asphalt shingle; concrete tile

1 Introduction

The number and size of air conditioned homes in hot climates has risen significantly over the past 20 years, increasing U.S. residential cooled floor area by 71% [1]. Boosting the albedo (solar reflectance) of a building's roof can save cooling energy in summer by reducing solar heat gain, lowering roof temperature, and decreasing heat conduction into the conditioned space and the attic ducts. It may also increase the use of heating energy in winter. Prior research has indicated that net annual energy cost savings are greatest for buildings located in climates with long cooling seasons and short heating seasons, especially those buildings that have distribution ducts in the attic [2][3][4][5][6][7].

Solar-reflective "cool" roofs decrease summer afternoon peak demand for electricity [3][8][9], reducing the strain on the electrical grid and thereby lessening the likelihood of brownouts and blackouts. Reducing peak cooling load can also allow the installation of a smaller, less expensive air conditioner. This is referred to as a "cooling equipment" saving [9]. Smaller air conditioners are also typically less expensive to run, because air conditioners are more efficient near full load than at partial load.

Roofs can cover a substantial fraction of the urban surface. For example, when viewed from above the tree canopy, roofs comprise about 19 – 25% of each of four U.S. metropolitan areas—Chicago, IL; Houston, TX; Sacramento, CA; and Salt Lake City, UT [10]. Citywide installation of cool roofs can lower the average surface temperature, which in turn cools the outside air. A meta-analysis of meteorological simulations performed in many U.S. cities found that each 0.1 rise in urban albedo (mean solar reflectance of the entire city) decreases average outside air temperature by about 0.3 K, and lowers peak outside air temperature by 0.6 to 2.3 K [11]. Cool roofs thereby help mitigate the "daytime urban heat island" by making cities cooler in summer. This makes the city more habitable, and saves energy by decreasing the need for air conditioning in buildings. Cooler outside air can also improve air quality by slowing the temperature-dependent formation of smog [12][13].

Replacing a hot roof with a cool roof immediately reduces the flow of thermal radiation into the troposphere ("negative radiative forcing"), offsetting the global warming induced by emission of greenhouse gases [14][15][16]. Most recently, Akbari et al. [17] estimated that increasing by 0.01 the albedo of 1 m^2 of urban surface provides a one-time (not annual) offset of 4.9 – 12 kg CO_2. Substituting 100 m^2 of cool white roofing (albedo 0.6) for standard gray roofing (albedo 0.2) would provide a one-time offset of about 20 - 48 t CO_2.

The direct cooling benefits of increasing the albedo of a residential roof have been simulated or measured by several workers. For example, Akbari et al. [3] simulated with the DOE-2 building energy model the annual cooling and heating energy uses of a variety of building prototypes in 11 U.S. cities. They found that raising the albedo of an RSI-3.3 asphalt-shingle roof by 0.30

reduced the annual cooling energy use of a single-story home by 6 – 15%, and increased annual heating energy use by 0 – 5%.

Parker and Barkaszi [18] measured daily cooling energy uses in summer before and after applying white roof coatings to nine single-story Florida homes. Savings ranged from 2 – 40% and averaged 19%. In a home with RSI-3.3 ceiling insulation, increasing the albedo of an asphalt shingle roof by 0.44 (to 0.59 from 0.15) reduced daily cooling energy use by 10%, and lowered peak cooling power demand by 16%.

Miller et al. [19] measured cooling energy uses in three pairs of Northern California homes. Each pair of homes had color-matched standard (lower albedo) and cool (higher albedo) roofs. The first pair had brown concrete tile roofs with albedos of 0.10 (standard) and 0.40 (cool); the second, brown metal roofs with albedos of 0.08 (standard) and 0.31 (cool); and the third, gray-brown shingle roofs with albedos of 0.09 (standard) and 0.26 (cool). After adjusting for widely disparate occupancy patterns, summer daily cooling energy savings were estimated to be about 9% in the homes with the cool tile and cool metal roofs; savings for the cool shingle roof were unclear.

High thermal capacity and/or subsurface natural convection ("above-sheathing ventilation") in the roof system can further cool the building [20][21][22][23]. For example, Miller et al. [24] measured the summer daily heat flows through an SR 0.13 flat tile roof on double battens and through an SR 0.09 shingle roof, each installed over a modestly insulated (RSI-0.9) ceiling in a test assembly. The heat flow through the tile roof was only half that through the shingle roof,

even though the solar absorptance (1 – solar reflectance) of the tile was only 4% lower than that of the shingle.

Two of the most popular roofing product categories in the western U.S. residential roofing market are fiberglass asphalt shingles (hereafter, "shingles") and clay or concrete tiles (hereafter, "tiles"). Surveys by *Western Roofing Insulation & Siding* found that shingles and tiles comprised 50% and 27% of 2007 sales, respectively, and 63% and 14% of projected 2013 sales [25][26]. Substituting a light-colored tile for a dark asphalt shingle reduces the roof's solar heat gain, roughly doubles its thermal capacity [27], and provides above-sheathing ventilation. In a mild-winter climate where heating is needed primarily in the morning, this substitution may even decrease heating energy use in winter. This is possible because increasing the roof's thermal capacity keeps the attic warmer overnight, while high roof albedo has little consequence after sunset.

The present study compares two side-by-side, single-story, single-family houses in Fresno, California. Fresno is located in the state's Central Valley, a hot climate in which homes use air conditioning from approximately May to October. The first house has a standard dark asphalt shingle roof, and the second a cool concrete tile roof; they are otherwise quite similar in construction and use. The homes serve as show models and are open to the public every day from 09:00 to 17:00 LDT. By monitoring temperatures, heat flows, and energy consumption in these air-conditioned houses, we investigate the extent to which over the course of a year the cool roof reduces (a) roof and attic temperatures; (b) conduction of heat into the conditioned space and into HVAC ducts in the attic; (c) cooling and heating energy uses; and (d) peak-hour

power demand. We also compare measured cooling energy savings to cooling energy savings calculated from heat flow and temperature measurements, in order to evaluate whether a simplified experimental configuration without power meters can be used in future cool roof experiments.

2 Theory

While the tested homes share similar floor and elevation plans, differences other than roof construction, such as those in plug load (appliances and lights), fenestration (window area, orientation, construction, and coverings), and occupancy, can influence building conditioning energy use. Here, we derive two ways to isolate the energy savings attributable to the cool roof.

2.1 Heat balance

The conditioned space (hereafter, "room") can gain or lose heat through its envelope (ceiling, wall, floor, and windows), and gain heat from internal sources, including plug loads (appliances, lighting) and people. Conditioned air can also gain or lose heat as it flows through the attic ductwork from the air conditioner or furnace to the room. Denoting the rates of heat gain (power) in the room and ductwork as q_{room} and q_{duct}, the building's combined heat load is

$$q_{\text{load}} \equiv q_{\text{room}} + q_{\text{duct}} \,. \tag{1}$$

The rate q_{HVAC} at which the furnace or air conditioner must remove heat to regulate room air temperature (positive in the cooling season, negative in the heating season) is

$$q_{\text{HVAC}} = q_{\text{load}} \,. \tag{2}$$

We disaggregate q_{room} in gains from the ceiling, plug load, windows, and other sources (e.g., walls, floor, infiltration and occupants), such that

$$q_{\text{room}} = q_{\text{ceiling}} + q_{\text{plug}} + q_{\text{window}} + q_{\text{other}} \,. \tag{3}$$

The rate of heat gain through the ceiling, q_{ceiling}, is the product of ceiling area and the ceiling heat flux (power/area). The rate of plug load heat gain, q_{plug}, equals the plug load electric demand. The rate of heat gain through the windows, q_{window}, can be estimated from solar irradiance and the area, construction, orientation, and coverings of windows.

The rate of heat gain through attic ductwork is

$$q_{\text{duct}} = \dot{m}\, c_{\text{p}} \left[\delta T_{\text{supply}} + \delta T_{\text{return}} \right] \tag{4}$$

where $\dot{m}$ and c_p are the mass flow rate and specific heat capacity of the duct air, δT_{supply} is the temperate rise (outlet – inlet) along the supply duct, and δT_{return} is the temperature rise along the return duct. Note that neglecting minor thermal storage in the duct work, duct heat gain vanishes when the HVAC system is off ($\dot{m}$ =0). If duct temperature rises have not been measured, q_{duct} can be estimated as

$$q_{\text{duct}} = \overline{U} A_{\text{duct}} \frac{\theta_{\text{out}} - \theta_{\text{in}}}{\ln\left(\theta_{\text{out}} / \theta_{\text{in}}\right)} \tag{5}$$

where $\overline{U}$ is the thermal transmittance of the duct wall, A_{duct} is duct surface area, inlet temperature depression $\theta_{\text{in}} = T_{\text{attic air}} - T_{\text{inlet}}$, and outlet temperature depression $\theta_{\text{out}} = T_{\text{attic air}} - T_{\text{outlet}}$ [28]. In the supply duct, T_{inlet} can be estimated from room air temperature and HVAC equipment specifications of temperature drop across the evaporator (often approximately 10 °C) and rise across the furnace; in the return duct, T_{inlet} can be approximated by room air temperature. Air temperature at the outlet of either duct can be estimated from

$$\frac{T_{\text{outlet}} - T_{\text{attic air}}}{T_{\text{inlet}} - T_{\text{attic air}}} = \exp\left(-\frac{\overline{U}\,A_{\text{duct}}}{\dot{m}\,c_p}\right). \tag{6}$$

The rate of HVAC heat removal during the cooling season is

$$q_{\text{cooling}} \equiv q_{\text{HVAC, cooling}} = C \times P_{\text{cooling}} \tag{7}$$

where C is the coefficient of performance (COP) of the cooling equipment (compressor and fan) and P_{cooling} is its electric power demand. Similarly, the rate of HVAC heat removal in the heating season is

$$q_{\text{heating}} \equiv q_{\text{HVAC, heating}} = -\eta \times P_{\text{heating}} \tag{8}$$

where η is the annual fuel utilization efficiency (AFUE) of the furnace and P_{heating} is its rate of fuel energy consumption. Note that while P_{cooling} includes electric fan power, P_{heating} does not.

COP can be computed from Seasonal Energy Efficiency Ratio (SEER) by applying the SEER-to-EER conversion given by Hendron and Engebrecht [29] and the unit conversion EER = COP × 3.412 BTU h^{-1} W^{-1} to obtain

$$C = \frac{\left(-0.02 \times \mathrm{SEER}^{2} + 1.12 \times \mathrm{SEER}\right)}{3.412}. \tag{9}$$

2.2 Energy savings

Consider two buildings, one with a standard roof and the other with a cool roof, that are otherwise matched in size and shape, and in particular have the same ceiling and duct areas. Defining $\Delta x \equiv x_{\mathrm{standard}} - x_{\mathrm{cool}}$,

$$\Delta q_{\mathrm{HVAC}} = \Delta q_{\mathrm{load}}. \tag{10}$$

The difference in heat load can be disaggregated as

$$\Delta q_{\mathrm{load}} = \Delta q_{\mathrm{room}} + \Delta q_{\mathrm{duct}} = \Delta q_{\mathrm{ceiling}} + \Delta q_{\mathrm{plug}} + \Delta q_{\mathrm{window}} + \Delta q_{\mathrm{other}} + \Delta q_{\mathrm{duct}}. \tag{11}$$

If the duct wall is well-insulated, or the duct air flow rate is high, the air temperature drop from inlet to outlet of each duct will be small. This can be tested by checking whether expression on the right hand side of Eq. (6) is close to unity. If further (a) the supply ducts in each building share the same inlet temperature, wall thermal transmittance, and wall area; (b) the same is true of the return ducts, and (c) both HVAC systems are on, then it follows from Eq. (5) that

$$\Delta q_{\mathrm{duct,\ supply}} = \overline{U}_{\mathrm{supply}} A_{\mathrm{supply}} \Delta T_{\mathrm{attic\ air}} \tag{12}$$

and

$$\Delta q_{\text{duct, return}} = \overline{U}_{\text{return}} \; A_{\text{return}} \; \Delta T_{\text{attic air}} \; . \tag{13}$$

This permits estimation of $\Delta q_{\text{duct}} = \Delta q_{\text{duct, supply}} + \Delta q_{\text{duct, return}}$ without measuring or calculating duct inlet and outlet temperatures.

If the buildings' HVAC systems share the same COP C and AFUE η , then

$$\Delta q_{\text{cooling}} = C \times \Delta P_{\text{cooling}} \tag{14}$$

and

$$\Delta q_{\text{heating}} = -\eta \times \Delta P_{\text{heating}} \; . \tag{15}$$

The HVAC power savings (standard building – cool building) in the cooling and heating seasons are

$$\Delta P_{\text{cooling}} = \Delta q_{\text{cooling}} \, / C = \Delta q_{\text{load}} \, / C \tag{16}$$

and

$$\Delta P_{\text{heating}} = - \Delta q_{\text{heating}} \, / \eta = - \Delta q_{\text{load}} \, / \eta \; , \tag{17}$$

respectively.

To distinguish conditioning power savings attributable to the roof from those that result from differences in plug, window, or other heat loads, we define the cool-roof cooling power savings in the cooling season as

$$\Delta P_{\text{cooling, roof}} \equiv \left(\Delta q_{\text{ceiling}} + \Delta q_{\text{duct}}\right)/C \tag{18}$$

and the cool-roof heating power savings in the heating season (potentially negative) as

$$\Delta P_{\text{heating, roof}} \equiv -\left(\Delta q_{\text{ceiling}} + \Delta q_{\text{duct}}\right)/\eta \ . \tag{19}$$

This first approach—"**Method A**"—estimates cool-roof cooling and heating power savings from measured ceiling heat gain and calculated duct heat gain.

Our second approach—"**Method B**"—calculates cool-roof cooling and heating power savings from measured HVAC power savings after correcting for differences in plug, window, and other heat loads. If $\Delta q_{\text{other}} = 0$, combining Eqs. (11), (16) and (18) yields the cooling (compressor + fan) power savings attributable to the cool roof,

$$\Delta P_{\text{cooling, roof}} = \Delta P_{\text{cooling}} - \frac{\Delta q_{\text{plug}} + \Delta q_{\text{window}}}{C} \ , \tag{20}$$

while combining Eqs. (11), (17) and (19) yields the heating fuel energy savings rate attributable to the cool roof,

$$\Delta P_{\text{heating, roof}} = \Delta P_{\text{heating}} + \frac{\Delta q_{\text{plug}} + \Delta q_{\text{window}}}{\eta} \ . \tag{21}$$

Since P_{heating} excludes electric fan power, and AFUE η also neglects fan power, neither method includes cool-roof fan power savings in the heating season. We estimate this value as

$$\Delta P_{\text{fan, heating, roof}} = \Delta P_{\text{fan, heating}} \times \frac{\overline{\Delta P}_{\text{heating, roof}}}{\overline{\Delta P}_{\text{heating}}} . \tag{22}$$

where bar denotes mean over the heating season.

If the envelope of each home is well insulated, room heat gains (or losses) that occur while the HVAC system is off will warm or cool the room's surfaces and air, influencing the conditioning load when the HVAC system later operates. Therefore, daily, cooling season, and heating season site energy savings are each evaluated by integrating power savings over all hours in the day or season, including those times in which the HVAC system is off. That is, site energy savings

$$\Delta E \equiv \int \Delta P \, dt . \tag{23}$$

This assumption appears safe in the cooling season, because the mid-morning period during which there is typically a substantial ceiling heat gain without HVAC operation is immediately followed by late-morning to early-evening HVAC operation. In the heating season, this assumption may overestimate cool-roof heating energy penalties, because the HVAC system operates primarily in the early morning, nearly 12 hours after the sun has set and during a period where the cool roof will have minimal impact on the attic/duct heat balance.

Cool-roof energy savings are assumed to be zero on days when HVAC systems are off in both homes.

2.3 Other savings

The following savings are all annual.

2.3.1 Source energy savings

If substituting a cool roof for a standard roof yields cooling (compressor + fan) site energy savings $\Delta E_{\text{cooling, roof}}$, heating fuel site energy savings $\Delta E_{\text{heating, roof}}$, and heating fan site energy savings $\Delta E_{\text{fan, heating, roof}}$, the source energy savings will be

$$\Delta s = r_{\text{e}} \left(\Delta E_{\text{cooling}} + \Delta E_{\text{fan, heating, roof}} \right) + r_{\text{g}} \, \Delta E_{\text{heating}} \ . \tag{24}$$

where r_{e} and r_{g} are the source-to-site energy ratios for electricity and natural gas, respectively.

2.3.2 Energy cost savings

The energy cost savings will be

$$\Delta c = d_{\text{e}} \left(\Delta E_{\text{cooling}} + \Delta E_{\text{fan, heating, roof}} \right) + d_{\text{g}} \, \Delta E_{\text{heating}} \ . \tag{25}$$

where d_{e} and d_{g} are the prices of electricity and natural gas, respectively.

2.3.3 Emission reduction

The reduction in emission of pollutant i will be

$$\Delta p_i = f_{\text{e},i} \left(\Delta E_{\text{cooling}} + \Delta E_{\text{fan, heating, roof}} \right) / \eta_{\text{t}} + f_{\text{g},i} \, \Delta E_{\text{heating}} \ . \tag{26}$$

where $f_{\mathrm{e},i}$ is its electricity emission factor (mass of pollutant i per unit electricity supplied to the grid), $f_{\mathrm{g},i}$ is its natural gas emission factor (mass of pollutant i per unit gas energy consumed), and η_{t} is the grid's transmission efficiency.

2.3.4 Peak-hour power demand reduction

Utilities may define hours of peak electrical demand. For example, the California Public Utilities Commission classifies noon – 6 pm LDT, Monday – Friday, May – October as peak demand hours for nonresidential users [30]. The peak-hour demand reduction on a given day is the ratio of cooling energy saved during those hours to the time interval spanned.

3 Experiment

3.1 Overview

Temperatures, heat flows, and HVAC (compressor + fan) energy uses are compared over the course of 12 months in two adjacent and similar homes in California's Central Valley, one with a standard roof and the other with a cool roof. Monthly rates of natural gas use for heating are obtained from utility statements.

Cool roof energy savings in the cooling and heating seasons are computed via both Method A (difference in ceiling + duct heat gain, divided by COP or AFUE) and Method B (difference in HVAC energy use, corrected for differences in plug and window heat gains). Seasonal and annual site energy savings, source energy savings, energy cost savings, and emission reductions are calculated with local source-to-site energy ratios, energy prices, and emission factors. Peak-hour power demand reduction is also computed.

3.2 Construction

Two side-by-side, single-story, single-family homes built by Granville Homes in Fresno, CA in summer/fall 2010 have been made available for this study. The buildings are oriented with the front door facing east and the length of the home running east-west. Hence, one side of each roof faces south and the other north, each at a pitch of about 20°. The houses are similar in floor plan and elevation plan (ESM Figure A-1) with the main difference being that one has a standard roof ("standard home") and the other has a cool roof ("cool home"). The homes serve as show models and are open to the public every day from 09:00 to 17:00 LDT. Lighting as well as other appliances are scheduled to turn on during business hours. Each home has additional plug loads drawn by a flat screen TV and a sound system, though the TV and sound system in the standard home were not operated in winter.

The standard home has an asphalt shingle roof (CertainTeed Autumn Blend) measured following ASTM C1549 [31] to have an initial SR of 0.07 (Figure 1). Shingles are glued and nailed on an underlayment covering the roof deck (ESM Figure A-2a).

The cool home has a flat concrete tile roof (Eagle Roofing model 4258, CRRC PID 0918-0008) rated with initial SR 0.51 and three-year-aged SR 0.47 [32].[2] Each row of flat tiles rests on a horizontal batten and on a lower row of tiles, allowing air to circulate between the tiles and underlayment (ESM Figure A-2b). Air enters at the eave and is exhausted at the ridge.

[2] The albedos reported for each roofing product are beam-normal, air mass 1.5 solar outputs of a Devices & Services Solar Spectrum Reflectometer. Because this metric tends to overestimate the solar reflectance of spectrally selective surfaces, the true albedo of the cool tile roof is likely 0.03 – 0.05 lower than rated [33][34].

The homes are built with the AC compressor placed at the back of the house next to the wall facing west; the furnace and ventilation fan are placed in the attic, approximately at the center of the floor plan. The ducts (RSI-1.1) run through a prefabricated truss support system located in the attic, supplying every room of the home. Each home is also equipped with a return grill, located outside the master bedroom. For attic ventilation, squared static gable vents are located on the west side of both attics, facing the backyard. Eave and profile-specific attic vents (O'Hagin's Inc., Rohnert Park, CA) provide additional attic ventilation. Each attic floor is covered with blown cellulose insulation of thermal resistance 3.3 $m^2 \cdot K \cdot W^{-1}$ (RSI-3.3) [19 $ft^2 \cdot °F \cdot h \cdot BTU^{-1}$ (R-19)]. Wall insulation is also RSI-3.3 (R-19), and the ventilation duct insulation is RSI-1.1 (R-6). Windows are double-paned. Table 1 further details each home's roof, attic, envelope, and HVAC system.

3.3 Instrumentation and data acquisition

Sensors and dataloggers were installed between 27 August and 14 December 2010. Each home has been instrumented to measure external and internal temperatures, ceiling heat flux, and electricity use, while a roof-mounted station on the standard house records weather.

In a clear summer day in Fresno, the south face of a 20° pitch roof receives more direct irradiance than the north face at mid-day, when the sun is south-southeast to south-southwest, but less irradiance in the early morning (sun east-northeast) and early evening (sun west-northwest). On a clear winter day, the south face receives more direct irradiance all day, because the sun stays in the southern hemisphere (ESM Figure A-3). For example, at solar noon on the summer solstice (June 21), when the solar altitude is 77°, the north face of a 20° tilt roof

receives 16% less direct sunlight than the south face. At solar noon on the winter solstice (solar altitude 30°), the north face receives 78% less direct sunlight than the south face [35]. Since this can make the north face of the roof cooler than the south face, sensors were placed on both the north and south sides of each house to assess building temperatures, and to explore the downward propagation of north-south temperature differences.

Table 2 summarizes the type and location of all sensors installed.

3.3.1 Roof

To measure the roof top temperature of the standard home, a thermistor was placed under a shingle on each side of the house (north and south), approximately at the center of each side (Figure 2a). On the cool roofed home the roof top temperature was measured with a thermistor placed near the surface of a tile on each side of the roof (Figure 2b). To do so, a small hole was drilled at the back of the tile extending nearly to the top of the tile; the thermistor was embedded and epoxied inside this hole. This shielded the sensor from direct sunlight, wind and outside air.

3.3.2 Attic

Each attic was instrumented with vertical arrays of thermistors on both the north and south side. At each side, a sensor was attached to the underside of the roof deck to measure the roof bottom, another was suspended at mid-attic height, and a third was attached to the attic floor (Figure 2). The vertical profile was positioned mid-way along the home's east-west axis. A heat flux sensor was taped on the south side of the attic floor close to the thermistor under the insulation to measure the heat flux through the ceiling.

3.3.3 Room

Inside each home are two sensors, each of which measures both temperature and relative humidity. These are located at ceiling level near the ceiling-mounted return grill. Two additional thermistors were installed inside of each home. One was placed on the ceiling's surface below the heat flux sensor, and the other next to the thermostat of the HVAC system. The latter is used to measure room air temperature.

3.3.4 Weather station

A weather station was mounted on a tower fixed at the top of the west end wall of the standard roof home and extends 1.5 m above roof line. The tower has a combined and self-contained temperature and relative humidity transmitter. The sensors of the transmitter are shielded by a cylindrical PVC rain and sun guard to prevent wetting of the humidity sensor and keep direct sunlight from shining on the sensors. A three-cup anemometer and a precision potentiometric wind vane are mounted at the top of the tower. A blue-enhanced photodiode pyranometer was also installed at the top of the tower to measure global horizontal solar irradiance.

3.3.5 Electric power monitoring devices

Three split-core current transformers (accuracy ±1%) were connected to the power meter of each home, measuring currents drawn by the AC compressor, ventilation fan, and entire house. The transformers are directly connected to a digital energy meter which reports power demand.

3.3.6 Data acquisition system

Two data loggers, one in each home, are used to acquire measurements. Each one has a multiplexer to increase the number of inputs. The data loggers are connected to the internet for data transfer. They are both located in the master bedroom walk-in closet, inside the panel that contains the internet wiring for each home. The data loggers are programmed to scan instantaneous readings every 30 seconds; data is transmitted hourly.

3.4 Estimation of window heat gain

Monthly window heat fluxes (energy/area) were evaluated with the Sustainable By Design window heat gain tool [36], using window solar heat gain coefficients (SHGC) and orientations reported in building plans. The SHGC of each window and its covering (curtain or blind) was estimated using WINDOW software [37] assuming surface-normal solar incidence. Each monthly heat gain (energy per area) was then multiplied by window area and divided by its time interval (seconds in a month) to calculate its contribution to the rate of window heat gain, Q_{window} (power/area).

3.5 Building operation

From January to April 2011, the team tested the operation of the homes, the instrumentation and the retrieval of data. Measurements have been recorded and analyzed since May 2011, but in July 2011, the AC in the standard home started leaking refrigerant from a loose valve. This forced its compressor to overwork to satisfy the cooling demand. The problem was identified and addressed in April 2012.

During the cooling season of 2012 (May - October), the indoor air temperature in each home was set to 25°C. During the heating season (November 2012 - April 2013), indoor temperatures were set to 20°C from 7:00 LST to 23:00 LST and 13°C at other times.

3.6 Study period

This study analyzes nearly a full year of measurements collected from May 2012 through April 2013, during which time the HVAC system was monitored to ensure proper operation. About 7% of the data in this 12-month period—12 days in early January and 13 days in late April—was lost when communications were interrupted. In calculation of cumulative energy savings, daily energy savings for the 12 missing days in January are interpolated, while daily energy savings for the 13 missing days in late April are set to zero.

3.7 Local source-to-site energy ratios, energy prices, and emission factors

Method A and Method B site energy savings are converted to source energy savings and energy cost savings using the source-to-site energy ratios and site energy prices in Table 3. They are also converted to CO_2, NO_X, and SO_2 emission reductions using the emission factors in Table 4 and a grid efficiency assumed to be 90%.

Peak-hour demand reduction in the cooling season is calculated as the mean rate of cooling energy savings during peak-demand hours, defined by the California Public Utilities Commission for nonresidential users as noon – 6 pm LDT, Monday – Friday, May – October [30]. (While the utility does not yet apply time of use rates to its residential customers, any peak-demand hour savings benefits the grid).

4 Results

4.1 Representative summer and winter days

4.1.1 Weather

July 6, 2012 and January 21, 2013 were selected as representative sunny days in summer and winter, respectively. The maximum and minimum outside air temperatures on July 6, 2012 were similar to the average maximum and minimum values on July 6 from 1995 through 2011. However, the maximum outside air temperature on January 21, 2013 (sunny) exceeded the historical average for that day of year, because winter days in Fresno are often cloudy or rainy [38][39]. On the summer day, about two weeks after the summer solstice, outside air temperature ranged from 14.3°C (04:53 LST) to 36.3°C (15:14 LST); global horizontal solar irradiance peaked at 875 W/m^2 (12:07 LST), with 14.6 hours from sunrise to sunset and 7.45 kWh/m^2 of solar irradiation. On the winter day, about one month after the winter solstice, outside air temperature ranged from 1.3°C (06:05 LST) to 24.3°C (14:16 LST); solar irradiance peaked at 511 W/m^2 (12:03 LST), with 10.1 hours from sunrise to sunset and 3.05 kWh/m^2 of solar irradiation (Figure 3).

4.1.2 North and south side building temperatures

On a clear summer day, the south face of the roof receives less direct solar irradiance than the north face in the early morning and early evening, but more in the middle of the day. On a clear winter day, the south face roof receives more direct irradiance throughout the day (see Section 3.3).

Figure 4 shows the temperature differences on the summer and winter days between the south and north sides of the standard home. On the summer day, the difference (south – north) was about -5 to +6°C at the roof top, -3 to +4°C at the roof bottom, -1 to +1°C at the attic air, and 0 to 2°C at the attic floor.

On the winter day, roof top and roof bottom differences were much larger, ranging from -1 to +24°C at the roof top and 0 to 13°C at the roof bottom. Winter-day attic air temperature differences were close to zero. The south-north attic floor temperature differences on that day were up to 4°C because the south-side attic floor temperature sensor was close to a supply register, while its north-side counterpart was not. (Proximity to a supply register has little effect on attic floor temperature in summer, when the cold supply air falls, but strong influence in winter, when the warm supply air rises.)

Similar results were observed in the cool home on the summer and winter days (ESM Figure A-4).

The north and south side temperature measurements suggest that (a) as expected, it is important to measure roof top and roof bottom temperatures on all faces of a sloped roof; (b) while good practice, measuring attic air and attic floor temperatures at more than one point is not strictly necessary; and (c) attic floor temperature sensors should be placed away from supply registers.

4.1.3 Maximum building temperatures, ceiling heat gain, and duct heat gain

The cool home's higher roof albedo lowers its maximum attic air temperature, ceiling heat gain rate, and duct heat gain rate, which can reduce need for cooling energy in summer, and increase need for heating energy in winter.

For example, on the summer day, maximum roof top, roof bottom, and attic air temperatures in the cool home were 13.8, 14.3, and 10.5°C lower than in the standard house. In the standard home, the roof top, roof bottom, and attic air temperatures reached their maxima at 12:42, 13:35, and 14:37 LST; in the cool home, the corresponding maxima were attained 68, 64, and 47 min later (Figure 5; Table 5). Maximum rates of ceiling, duct, and ceiling + duct heat gain in the cool home were 1.50, 0.89, and 2.4 kW lower than in the standard house (Figure 6; Table 5).

On the winter day, maximum roof top, roof bottom, and attic air temperatures in the cool home were 11.0, 10.6, and 6.9°C lower than in the standard house. In the standard home, the roof top, roof bottom, and attic air temperatures reached their maxima at 13:06, 14:19, and 14:47 LST; in the cool home, the corresponding peaks were attained 65, 64, and 37 min later. Maximum ceiling, duct, and ceiling + duct rates of heat gain in the cool home were 0.83, 1.33, and 1.17 kW lower than in the standard house.

On each day, the lags between peak temperatures in the cool and standard houses (e.g., time of roof top peak temperature in the cool house – time of roof top peak temperature in the standard house) are expected consequences of the higher thermal capacity of the tile roof. Differences in maximum temperatures (standard – cool) are greater on the summer day than

on the winter day because they occur in the afternoon, when there is more sunlight in summer than in winter. The same remarks also apply to ceiling.

4.1.4 Minimum building temperatures, ceiling heat gain, and duct heat gain

The cool home's higher roof thermal capacity raises its minimum attic air temperature, ceiling heat gain rate, and duct heat gain rate, which can increase need for cooling energy in summer, and reduce need for heating energy in winter.

On the summer day, minimum roof top, roof bottom, and attic air temperatures in the cool home were 2.1, 2.4, and 2.4°C *higher* than in the standard house; these minima were reached in the early morning, when cooling power demand is low. In the standard home, the roof top, roof bottom, and attic air temperatures reached their minima at 04:53, 05:09, and 05:17 LST; in the cool home, the corresponding minima were attained 14, 34, and 32 min later (Figure 5; Table 6). Minimum rates of ceiling, duct, and ceiling + duct heat gain in the cool home were 0.44, 0, and 0.44 kW *higher* than in the standard house (Figure 6; Table 6).

On the winter day, minimum roof top, roof bottom, and attic air temperatures in the cool home were 0.4, 2.1, and 2.3°C *higher* than in the standard house. In the standard home, the roof top, roof, and attic air temperatures reached their minima at 05:15, 05:19, and 05:18 LST; in the cool home, the corresponding minima were attained 57, 21, and 24 min later. Minimum rates of ceiling, duct, and ceiling + duct heat gain in the cool home were 1.32, -0.12, and 1.20 kW *higher* than in the standard house.

On each day, the minimum roof top, roof bottom, and attic air temperatures in the cool house are greater than those in the standard house because the tile roof is slower than the shingle

roof to cool to the outdoor air and night sky. The differences in minimum temperatures (cool – standard) on the summer day (2.1 to 2.4°C) are comparable to those on the winter day (0.7 to 2.3°C) because the minima occur long after sunset.

4.1.5 HVAC operation

Figure 7 shows the HVAC fan power demand in the standard and cool houses on the summer and winter days. The difference (standard – cool) in attic air temperature is overlaid on each graph because difference in attic air temperature drives differences in ceiling and duct heat gains.

On the summer day, the HVAC systems (cooling) are completely off from about 22:30 LST (late night) to 11:30 LST (just before noon), and cycle on/off at other times. On the winter day, the HVAC systems (heating) are completely off from 23:00 LST (late at night) to 05:30-06:00 LST (early morning), from 07:00 to 09:00 LST (mid-morning), and from 11:00 to 20:30 – 22:00 LST (late morning to late night), running continuously from about 1.5 hours in the early morning and cycling on/off for another 4 – 5 hours in the mid-morning and late evening.

The HVAC performance observed on the summer day supports the premise of including all hours of day when integrating cooling power savings, because the period of non-operation in which there is a substantial difference in attic air temperature (about 08:00 – 11:00 LST) is immediately followed by about 7 hours of operation. The winter-day HVAC operation suggests that including all hours of day when integrating heating power savings may overestimate the heating energy penalty, because the primary heating period (early morning, following the

nighttime setback of the thermostat) begins about 10 hours after the attic air temperature difference falls to a small nighttime value.

4.2 Daily solar irradiation and maximum outdoor air temperature

Clear-day global horizontal solar irradiation was up to three times greater in summer in Fresno than in winter, ranging from 2.6 kWh/m^2 (December) to 7.8 kWh/m^2 (June). Dips in daily solar irradiation indicate that cloudy days were more common in the heating season (Nov – Apr) than in the cooling season (May – Oct) (Figure 8).

Clear-day maximum outdoor air temperature was up to 32°C higher in summer than in winter, ranging from about 11°C (December) to 43°C (June) (Figure 8).

4.3 Seasonal reductions in daily mean temperatures and heat gains

Seasonal mean reductions (standard – cool) in roof top, roof bottom, and attic air temperatures in the cooling season were about 3.4°C, 3.7°C, and 2.4°C, roughly twice those the heating season (Table 7). Ordinarily, one would expect to find the greatest temperature difference between standard (lower albedo) and cool (higher albedo) roofs at roof top, where sunlight is absorbed. In this experiment, above-sheathing ventilation cooling the deck of the cool tile roof may have made the temperature difference (standard – cool) at roof bottom (underside of roof deck) larger than that at roof top (just below tile surface). Daily maximum and mean roof top, roof bottom, and attic air temperatures are detailed in ESM Figure A-5.

Cooling-season mean rates of whole-ceiling and duct heat gain in the standard home were about 310 W and 130 W lower in the cool home than in the standard home. However, heating-season mean rates of ceiling and duct heat gain were about 46 W and 32 W *greater* in the cool

home than in the standard home (Table 7). The higher heating-season mean ceiling and duct heat gains in the cool home are attributed to the higher thermal capacity of the cool tile roof, which keeps the attic air under the cool roof warmer at night and early morning than that under the standard roof (ESM Figure A-5f). In fact, the daily mean ceiling heat gain is greater in the cool house than in the standard house on most days between early November and late February, or roughly two thirds of the heating season (Figure 9a).

Daily mean plug load heat gains were about the same in each house during the cooling season, but substantially higher in the cool house than in the standard house during the heating season, simply because the television and stereo in the standard house were turned off in winter (Figure 9c).

Estimated daily mean window heat gains in the cool home always exceeded those in the standard home (Figure 9d). Window heat differences were smallest in December and January, the months with least insolation (Figure 8).

4.4 Daily and cumulative energy savings in the cooling and heating seasons

Figure 10 shows in each season (cooling, heating) the daily and cumulative values of cool-roof energy savings per unit ceiling area.[3]

In the cooling season, Method A reports ceiling and duct heat gain savings divided by COP, while Method B subtracts from HVAC (compressor plus fan) electricity savings the difference (standard – cool) in plug load and window heat gains divided by COP. Cool-roof energy savings

[3] Ceiling area means the area of the ceiling of the top floor of the building.

are assumed to be zero on days when HVAC systems are off in both homes. Method A and Method B agree well in the cooling season, with an especially close match from May through July (Figure 10a,b). Cumulative cooling energy predicted by Method A (2.89 kWh/m^2) are 2% higher than those calculated from Method B (2.82 kWh/m^2) (Figure 10b), which is very close.

Figure 11 compares Method A and Method B daily energy savings for each day and each week of the cooling season. Agreement is especially good on a weekly basis.

In the heating season, Method A switches sign, since the HVAC supplies, rather than removes, heat [Eq. (17)], while Method B *adds* to fuel savings the difference in plug load and window heat gains divided by AFUE. Method A over-predicts Method B in the heating season, especially from November through January (Figure 10c,d). Cumulative fuel energy savings from Method A (3.34 kWh/m^2) are three times greater than those from Method B (1.13 kWh/m^2) (Figure 10d).

Figure 12 shows per unit ceiling area the daily and cumulative values of cool-roof fan energy savings in the heating season. For each method (A,B), cool-roof fan energy savings are estimated by scaling daily fan energy savings by ratio of cool-roof heating fuel energy savings to raw heating fuel energy savings. Cumulative heating-season cool-roof fan energy savings from Method A (0.077 kWh/m^2) are 2.7 times higher than those from Method B (0.029 kWh/m^2).

Note that Methods A and B each yield *positive* fuel and fan energy savings in the heating season, which we attribute to the higher thermal capacitance of the tile roof.

4.5 Daily peak-hour cooling power demand reduction

Figure 13 shows daily values of peak-hour cooling power demand reduction, calculated on each weekday in the cooling season (May through October) as the mean value of cool-roof power demand reduction from 12:00 LDT to 18:00 LDT (11:00 LST – 17:00 LST). The seasonal mean demands reduction predicted by Method A (1.06 W/m^2) is about 20% higher than that calculated by Method B (0.88 W/m^2).

4.6 Seasonal and annual cumulative conditioning site energy, source energy, energy cost, and emission savings

Table 8 summarizes Method A and Method B values of seasonal and annual site energy, source energy, energy cost, and emission savings, all per unit ceiling area. Since the earlier analysis showed substantial differences in heating-season fuel and fan energy savings, the following reports the more conservative Method B savings, which are based on measured energy savings adjusted for measured differences in plug load heat gain and estimated differences in window heat gain. Each parenthetical value is relative to use, cost, or emission in the standard home.

- **Annual cooling (compressor + fan) site energy savings** are 2.82 kWh/m^2 (26%).
- **Annual heating (furnace) fuel site energy savings** are 1.13 kWh/m^2 [0.0386 therm/m^2] (4%).
- **Annual heating (furnace) fan site energy savings** are 0.0294 kWh/m^2 (3%).
- **Annual conditioning (cooling + heating) source energy savings** are 10.7 kWh/m^2 (15%).
- **Annual conditioning energy cost savings** are 0.886 \$/m^2 (20%).

- **Annual conditioning CO_2 emission reduction** is 1.63 kg/m^2 (15%).
- **Annual conditioning NO_x emission reduction** is 0.621 g/m^2 (10%).
- **Annual conditioning SO_2 emission reduction** is 0.0462 g/m^2 (22%).
- **Peak-hour cooling (compressor + fan) power demand reduction** is 0.88 W/m^2 (37%).

Using the mean ceiling area of the two homes in this study (188 m^2), annual cooling, heating fuel, and heating fan site energy savings were 530 kWh, 212 kWh (7.25 therm), and 5.53 kWh, respectively. Annual conditioning source energy savings were 2010 kWh; annual energy cost savings were $167. Emission reductions were 307 kg CO_2, 117 g NO_x, and 8.69 g SO_2; peak-hour power demand reduction was 165 W.

5 Discussion

5.1 Cooling and heating energy savings

Following Method B, the cool home with the reflective tile roof (initial SR 0.51; thermal capacity 40 kJ/m^2·K) used 26% less annual cooling (compressor + fan) energy, 4% less annual heating fuel energy, and 3% less annual heating fan energy than the standard home with the dark shingle roof (initial SR 0.07; thermal capacity 22 kJ/m^2·K).

The Fresno fractional annual cooling energy savings (26%) were 2.6 times the 10% daily cooling energy savings that Parker and Barkaszi [18] measured after applying a white coating to an RSI-3.3 asphalt shingle roof on a Palm Bay, Florida home, even though (a) all three homes (Fresno cool, Fresno standard, Palm Bay) had RSI-3.3 roof insulation; (b) the roof albedo increase in

Fresno (0.44) was the same as that in Palm Bay; and (c) based on the TMY3 typical meteorological year, the cooling-season (May – Oct) mean global horizontal solar irradiance in Fresno is only about 25% greater than that in Melbourne, FL (near Palm Bay) [40]. Similarly, fractional peak-hour cooling power demand savings in Fresno were 37%, or 2.3 times the 16% savings measured in Palm Bay at 17:00 – 18:00 LDT.

The improved fractional cooling energy savings (26% vs. 10%) and fractional peak demand reduction (37% vs. 16%) observed in Fresno likely result from the tile roof's high thermal capacity (80% greater than that of the shingle roof) and above-sheathing ventilation. This is qualitatively consistent with the 50% ceiling heat flux reduction measured by Miller et al. [24] when comparing an SR 0.13 flat tile roof on double battens to an SR 0.09 shingle roof.

The slightly positive fractional annual heating energy savings in Fresno (4%) differs in sign from the fractional annual heating energy savings (e.g., -5% in Los Angeles; -2% in Phoenix) simulated by Akbari et al. [3] for a 0.30 increase in the albedo of an RSI-3.3 asphalt shingle roof. Here the improvement likely results from the tile roof's high thermal capacity, which increases the overnight temperature of the attic air.

5.2 Importance of corrections to measured energy savings

Figure 9 shows that differences (standard – cool) in daily mean rates of ceiling, plug load, duct, and window heat gain were generally comparable in magnitude (-0.5 kW to +0.5 kW). This confirms the importance of correcting measured HVAC savings for differences in window and plug load heat gain, as shown in Method B equations (20) and (21).

5.3 Estimating cooling energy savings from temperature and heat flux measurements

The close agreement between Methods A and B in the cooling season suggest that Method A can be used to estimate cooling energy savings without measuring HVAC or plug load power demand. A minimalist and quite economical *cooling season* experiment would require in each building only seven temperature sensors—roof top, attic air, room air, supply duct inlet, supply duct outlet, return duct inlet, and return duct outlet—and one ceiling heat flux sensor. While not strictly needed to measure energy savings, multiple roof top temperature sensors would be warranted if the roof is not flat.

If the HVAC's cooling COP and fan-on air flow rate are known from equipment specifications, duct heat gain rate and Method A cooling power savings can be computed from Eqs. (4) and (18), respectively. For calculation of duct heat gain rate, the fan can be assumed on if the supply duct outlet air temperature is far from the room air temperature, and off otherwise.

6 Summary

Temperatures, heat flows, and energy were measured for a year in two side-by-side, single-story, single-family homes in Fresno, California. One house had a reflective concrete tile roof (initial SR 0.51; thermal capacity 40 kJ/m^2·K), and the other a standard dark asphalt shingle roof (initial SR 0.07; thermal capacity 22 kJ/m^2·K). The flat tiles were mounted on battens, creating an air gap between tile and deck; the shingles were nailed directly to deck. The buildings were otherwise similar in construction and occupancy, with some differences in heat gains from plug loads and windows.

On a representative summer day (6 Jul 2012), maximum roof top, roof bottom, and attic air temperatures in the cool home (tile roof) were 13.8, 14.3, and 10.5°C lower than in the standard house (shingle roof). Maximum rates of ceiling, duct, and ceiling + duct heat gain in the cool home were 1.50, 0.89, and 2.4 kW lower than in the standard house. Minimum roof top, roof bottom, and attic air temperatures in the cool roof home were 2.1, 2.4, and 2.4°C *higher* than in the standard house, likely resulting from the higher thermal capacitance of the tile roof.

On a representative winter day (21 Jan 2013), maximum roof top, roof bottom, and attic air temperatures in the cool home were 11.0, 10.6, and 6.9°C lower than in the standard house. Maximum ceiling, duct, and ceiling + duct rates of heat gain in the cool home were 0.83, 1.33, and 1.17 kW lower than in the standard house. Minimum roof top, roof bottom, and attic air temperatures in the cool home were 0.4, 2.1, and 2.3°C *higher* than in the standard house.

The north and south side temperature measurements suggest that (a) as expected, it is important to measure roof top and roof bottom temperatures on all faces of a sloped roof; (b) while good practice, measuring attic air and attic floor temperatures at more than one point is not strictly necessary; and (c) attic floor temperature sensors should be placed away from supply registers.

In the cooling season (May – October), the mean rates of ceiling and duct heat gain in the standard home were about 310 W and 130 W lower in the cool home than in the standard home. However, mean rates of ceiling and duct heat gain in the heating season (November –

April) were about 46 W and 32 W *greater* in the cool home than in the standard home, likely resulting from the higher thermal capacity of the cool roof.

Seasonal mean reductions (standard – cool) in roof top, roof bottom, and attic air temperatures in the cooling season were about 3.4°C, 3.7°C, and 2.4°C, roughly twice those the heating season. Above-sheathing ventilation cooling the deck of the cool tile roof may have made the temperature difference (standard – cool) at roof bottom (underside of roof deck) larger than that at roof top (just below tile surface).

Cool-roof energy savings in the cooling and heating seasons were computed two ways. Method A divides by HVAC's COP the difference (standard – cool) in ceiling + duct heat gain. Method B measures the difference in HVAC energy use, corrected for differences in plug and window heat gains. Methods A and B agreed well in the cooling season, but not in the heating season. Therefore, all savings are reported based on Method B, which yielded more conservative savings in winter.

Relative to the standard home, annual cooling (compressor + fan), heating fuel, and heating fan energy savings at the site were 2.82 kWh/m^2 (26%), 1.13 kWh/m^2 (4%), and 0.0294 kWh/m^2 (3%), respectively. Annual conditioning source energy savings were 10.7 kWh/m^2 (15%); annual energy cost savings were 0.886 \$/m^2 (20%). Annual conditioning CO_2 , NO_x, and SO_2 emission reductions were 1.63 kg/m^2 (15%), 0.621 g/m^2 (10%), and 0.0462 g/m^2 (22%). Peak-hour cooling (compressor + fan) power demand reduction was 0.88 W/m^2 (37%). For the studied homes with 188 m^2 ceilings, annual cooling, heating fuel, and heating fan site energy savings were 530 kWh, 212 kWh (7.25 therm), and 5.53 kWh, respectively. Annual conditioning source energy savings

were 2010 kWh; annual energy cost savings were $167. Emission reductions were 307 kg CO_2, 117 g NO_x, and 8.69 g SO_2; peak-hour power demand reduction was 165 W.

Fractional annual cooling energy savings (26%) were 2.6 times the 10% daily cooling energy savings measured in a previous study that used a white coating to increase the albedo of an asphalt shingle roof by the same amount (0.44). Fractional peak-hour cooling power demand savings (37%) were 2.3 times the 16% savings observed in the earlier study. Since both studies used RSI-3.3 roof insulation, these improved savings likely resulted from the cool tile's roof high thermal capacity (80% greater than that of the shingle roof) and above-sheathing ventilation.

The slightly positive fractional annual heating energy savings likely resulted from the tile roof's high thermal capacity, which increased the overnight temperature of the attic air.

Acknowledgements

This work was supported by the California Energy Commission (CEC) through its Public Interest Energy Research Program (PIER). It was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We wish to thank Michael Spears and Woody Delp, and the Windows and Envelope Materials Group (Lawrence Berkeley National Laboratory); Victor Gonzalez, Tony Seaton, Terry Anderson, Darius Assemi, Mike Bergeron and Karl Gosswiller (Granville Homes Inc.); Ming Shiao and Richard Snyder (CertainTeed Corp.); Annette Sindar and Greg Peterson (Eagle Roofing Products); Danny Parker (Florida Solar Energy Center); and Hashem Akbari (Concordia University).

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Tables

Table 1. Home construction and HVAC equipment.

Property	Standard Home	Cool Home
Living floor area (also ceiling area) (m^2)	187	189
Number of stories	1	Same
Ceiling height (m)	2.74	3.05
Ratio of distribution duct inner surface area to ceiling area	35% [a]	Same
Frame construction	Wood	Same
Roof		
Roofing product		
Type	Asphalt shingle	Concrete tile
Make and model	CertainTeed Autumn Blend Presidential Shake	Eagle Roofing flat tile - Bel Air / 4258 Ridgecrest-Color Bonded / Color-Tan, Cream
CRRC product ID	N/A	0918-0008
Initial albedo	0.07	0.51
Mass per deck area (kg/m^2) [lb/ft^2]	17.3 [3.55]	47.4 [9.70]
Thermal capacity per deck area ($kJ/m^2 \cdot K$) [b]	21.8	39.8
Waterproofing layer and deck	43 lb/100 ft^2 black felt over 0.5" CDX plywood sheathing	Same
Rise to run [slope]	4:12 [18.4°]	5:12 [22.6°]
Air gap height under roofing product (cm)	No gap	1.9 – 4.4
Attic		
Total ventilation area (m^2)	1.66	1.62
Gable end vent – qty. × area (m^2)	2 × 0.25	4 × 0.17
Eave vent – qty. × area (m^2)	20 × 0.04	19 × 0.04
O'Hagin Dormer vent – qty. × area (m^2)	6 × 0.06	3 × 0.06
Radiant barrier	None	Same
Insulation		
Thermal resistance ($m^2 \cdot K/W$) [$ft^2 \cdot °F \cdot h/BTU$]		
Roof	3.3 [19]	Same
Exterior wall	3.3 [19]	Same
Ducts	1.1 [6]	Same
Windows		
Construction	Double-pane, low-E	Same
Thermal transmittance ($W/m^2 \cdot K$)	1.9 – 2.0	1.6 – 1.7
Area (m^2)		
South	3.25	4.74
East	1.86	3.40
West	11.9	11
North	9.38	2.32
Total	26.3	21.5

HVAC system		
Air conditioner[c]		
Make and model	Lennox 14ACX-042-230-11	Lennox 14ACX-048-230-11
SEER (BTU/W·h)	14	Same
Estimated COP (Wh/Wh)	3.5	3.5
Nominal cooling capacity (kW) [ton]	12.3 [3.5]	14 [4]
Gas furnace[d]		
Make and model	Lennox G51MP-48C-090	Same
Annual Fuel Utilization Efficiency (AFUE) (%)	92.1	Same

[a] Estimated following ASHRAE Standard 152P, Method B, based on the number of supply and return registers [41].

[b] Assumes specific heats of 1.26 kJ/ m^2·K (asphalt shingle) and 0.84 kJ/ m^2·K (lightweight concrete) [42].

[c] Lennox Merit Series 14ACX Units [43].

[d] Lennox G51MP Series [44],

Table 2. Instrumentation.

Measurement(s)	**Sensor(s)**	**Location(s)**
Outdoor air temperature and relative humidity	NeuroLogic Research, Model 1200A, protected by Model 40 Rain and Sun Guard	On weather station tower at the top of west end wall of standard home
Global horizontal solar irradiance	Blue-enhanced photodiode pyranometer (LI-COR LI-200SA)	On weather station tower at the top of west end wall of standard home
Wind speed and direction	Three-cup anemometer (Weather Instruments, Model A70-SL), potentiometric wind vane (Model A70-DL)	On weather station tower at the top of west end wall of standard home
Roof surface temperature × 4	Omega thermistors, model TH-44006-40-T	Standard and cool homes, north and south sides: under shingle of the standard roof; inside hole drilled into the backs of tile.
Attic temperature × 12	Omega thermistors, model TH-44006-40-T	Standard and cool homes, north and south sides: roof bottom (surface); attic air (midway between roof bottom and attic floor); attic floor (surface).
Room temperature × 4	Omega thermistor, model TH-44005-120-T	Standard and cool homes: center of ceiling surface; air near thermostat.
Return air temperature and relative humidity × 2	Pure Choice Inc., model The Nose Monitor	Standard and cool homes: ceiling level air near the two return grilles.
Ceiling heat flux (power/area) × 2	Hukseflux, HFP01-100-PT	Standard and cool homes, south side: attic floor beneath the cellulose insulation
Electricity use × 6	Continental Control Systems LLC, Watt Node Logger WNC-3Y-208-FT10 pulse counter transducer with split-core	Standard and cool homes: AC compressor; ventilation fan; total building power

	current transformers (CCS, CTS Series)	
Data logger × 2	Echelon, iLon SmartServer 2.0	Standard and cool homes
Logger expansion × 2	Control Solutions, AddMe II™, AM2-MX30, 30-point Lon Works I/O node	Standard and cool homes

Table 3. Source-to-site energy ratios and site energy prices in Fresno, CA.

	Electricity	**Natural gas**
Source-to-site energy ratio	3.34[a]	1.047[a]
Site energy price ($/kWh)	0.298[b]	0.0325[c]

[a] US average [45].

[b] Average Tier 3 (131% to 200% of baseline) electricity price in Fresno from March – October 2012 [46].

[c] Average Tier 1 (up to 100% of baseline) natural gas price in Fresno (November 2012 – April 2013) [46], converted from $/therm at 29.3 kWh/therm.

Table 4. Year-2009 total and non-baseload output emission factors per unit electricity supplied to the grid in US EPA eGRID subregion WECC California [47]; and non-regional natural gas combustion site emission factors per unit fuel energy consumed [48].

	CO_2 (kg/kWh)	**NO_x (g/kWh)**	**SO_2 (g/kWh)**
Total electricity	0.299	0.190	0.0826
Non-baseload electricity	0.451	0.146	0.0143
Natural gas	0.180	0.141	0.000887

Table 5. Local standard times and values of maximum roof top, roof bottom, attic air, and attic floor temperatures, and maximum rates of ceiling, duct, and ceiling + duct heat gains, in standard and cool homes on the representative summer day (6 July 2012) and the representative winter day (21 Jan 2013). Also shown is the time lag (cool – standard) and difference in value (standard – cool) between each pair of maxima.

	Summer day maxima						**Winter day maxima**					
	Standard		**Cool**		**Standard - cool**		**Standard**		**Cool**		**Standard - cool**	
	LST	Value	LST	Value	Lag (min)	Value	LST	Value	LST	Value	Lag (min)	Value
Roof top temp (°C)	12:42	69.9	13:50	56.2	68	13.8	13:06	40.7	14:11	29.7	65	11.0
Roof bottom temp (°C)	13:35	59.3	14:39	45.0	64	14.3	14:19	35.1	15:23	24.5	64	10.6
Attic air temp (°C)	14:37	51.1	15:24	40.7	47	10.5	14:47	29.6	15:24	22.8	37	6.9
Attic floor temp (°C)	15:48	28.6	17:04	28.3	76	0.3	06:47	27.0	06:50	23.4	3	3.7

Ceiling heat gain rate (kW)	14:52	2.65	15:13	1.15	21	1.50	15:03	0.98	16:30	0.15	87	0.83
Duct heat gain rate (kW)	14:07	2.97	15:25	2.08	78	0.89	14:47	-0.06	15:24	-1.39	37	1.33
Ceiling + duct heat gain rate (kW)	14:07	5.49	15:10	2.24	63	2.4	15:03	-0.09	16:30	-1.26	87	1.17

Table 6. Local standard times and values of minimum roof top, roof bottom, attic air, and attic floor temperatures, and minimum rates of ceiling, duct, and ceiling + duct heat gains, in standard and cool homes on the representative summer day (6 July 2012) and the representative winter day (21 Jan 2013). Also shown is the time lag (cool – standard) and difference in value (standard – cool) between each pair of minima.

	Summer day minima						**Winter day minima**					
	Standard		**Cool**		**Standard - cool**		**Standard**		**Cool**		**Standard - cool**	
	LST	Value	LST	Value	Lag (min)	Value	LST	Value	LST	Value	Lag (min)	Value
Roof top temp (°C)	04:53	10.0	05:07	12.1	14	-2.1	05:15	-3.2	06:12	-2.8	57	-0.4
Roof bottom temp (°C)	05:09	13.4	05:43	15.7	34	-2.4	05:19	0.1	05:40	2.1	21	-2.1
Attic air temp (°C)	05:17	14.3	05:49	16.7	32	-2.4	05:18	1.1	05:42	3.4	24	-2.3
Attic floor temp (°C)	06:05	23.7	06:18	24.1	13	-0.5	05:19	16.6	05:42	17.3	23	-0.7
Ceiling heat gain rate (kW)	05:49	-0.88	06:10	-0.45	21	-0.44	05:39	-3.48	06:16	-2.16	37	-1.32
Duct heat gain rate (kW)	NA	0	NA	0	NA	0	06:46	-4.08	06:55	-4.20	9	-0.1
Ceiling + duct heat gain rate (kW)	05:49	-0.88	06:10	-0.45	21	-0.4	05:39	-7.49	06:40	-6.29	61	-1.28

Table 7. Seasonal mean reductions (standard – cool) in daily maximum and daily mean temperatures and heat gain rates.

	Cooling season (May – Oct)		**Heating season (Nov – Apr)**	
	Max	Mean	Max	Mean
Roof top temperature (°C)	13.0	3.4	10.8	1.7
Roof bottom temperature (°C)	13.5	3.7	10.2	1.9
Attic air temperature (°C)	9.8	2.4	6.9	1.0
Ceiling heat gain rate (W)	1370	311	805	-46
Duct heat gain rate (W)	819	129	0	-32
Ceiling + duct heat gain rate (W)	2190	440	805	-78

Table 8. Daily, seasonal, and annual mean values of energy savings, energy cost savings, emission reduction, and peak-hour demand reduction per unit ceiling area. Method B fractional savings (relative to standard house) are shown in parentheses.

Savings per unit ceiling area	**Cooling season (May – Oct)**		**Heating season (Nov – Apr)**		**Annual**	
	Method A	Method B	Method A	Method B	Method A	Method B
Daily site cooling energy (Wh/m²)	15.7	15.3				
Daily site heating fuel energy (Wh/m²)			18.5	6.24		
Daily site heating fan energy (Wh/m^2)			0.426	0.162		
Seasonal or annual site electrical energy (kWh/m^2)	2.89	2.82 (26%)	0.0772	0.0294 (3%)	2.97	2.85
Seasonal or annual site fuel energy (kWh/m^2)	0.00	0.00	3.34	1.13 (4%)	3.34	1.13
Seasonal or annual source energy (kWh/m^2)	9.65	9.42	3.76	1.28	13.4	10.7 (15%)
Seasonal or annual conditioning energy cost ($/m²)	0.861	0.840	0.131	0.0454	0.993	0.886 (20%)
Seasonal or annual CO_2 (kg/m^2)	1.45	1.41	0.641	0.218	2.09	1.63 (15%)
Seasonal or annual NO_x (g/m^2)	0.468	0.456	0.484	0.164	0.95	0.62 (10%)
Seasonal or annual SO_2 (g/m^2)	0.0459	0.0448	0.00419	0.00147	0.0501	0.0462 (22%)
Peak-hour site electrical demand (W/m²)	1.06	0.88 (37%)				

Figures

(a) (b)

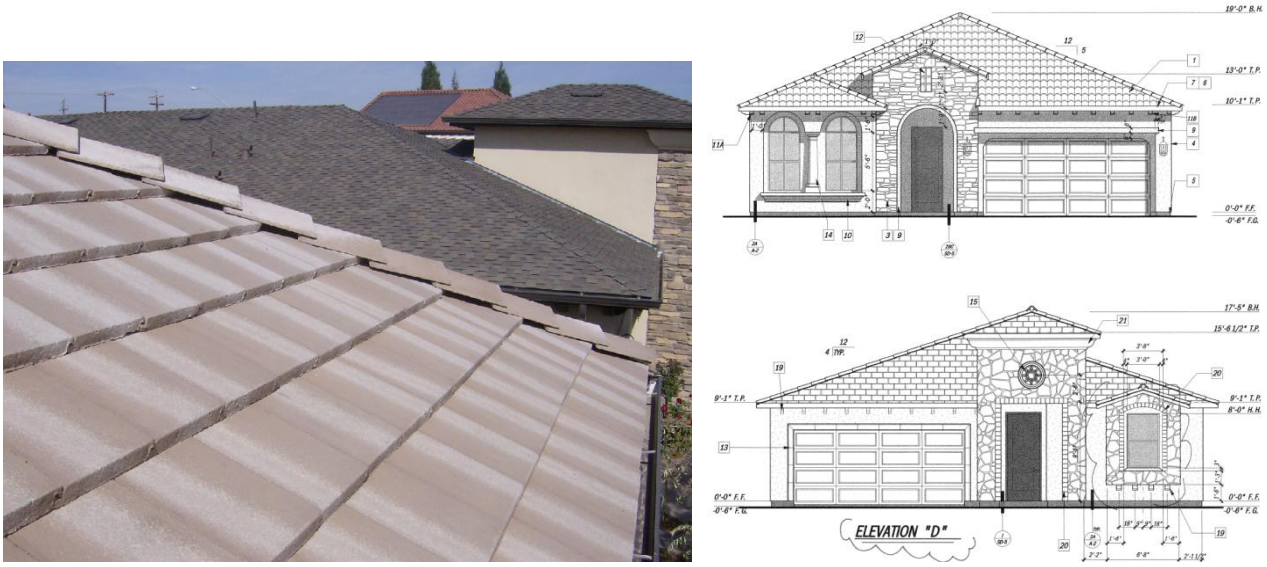


Figure 1. Image and plans of adjacent single-family homes in Fresno, CA, showing (a) cool concrete tile roof (foreground) and standard asphalt shingle roof (background); and (b) plans of home with cool roof (top) and home with standard roof (bottom).

(a) (b)

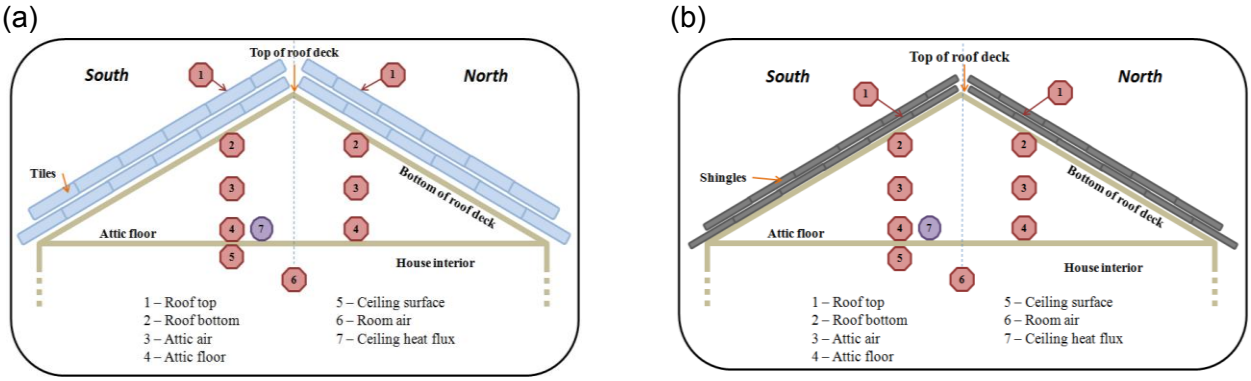


Figure 2. Temperature and heat flux sensor locations in (a) the cool home and (b) the standard home.

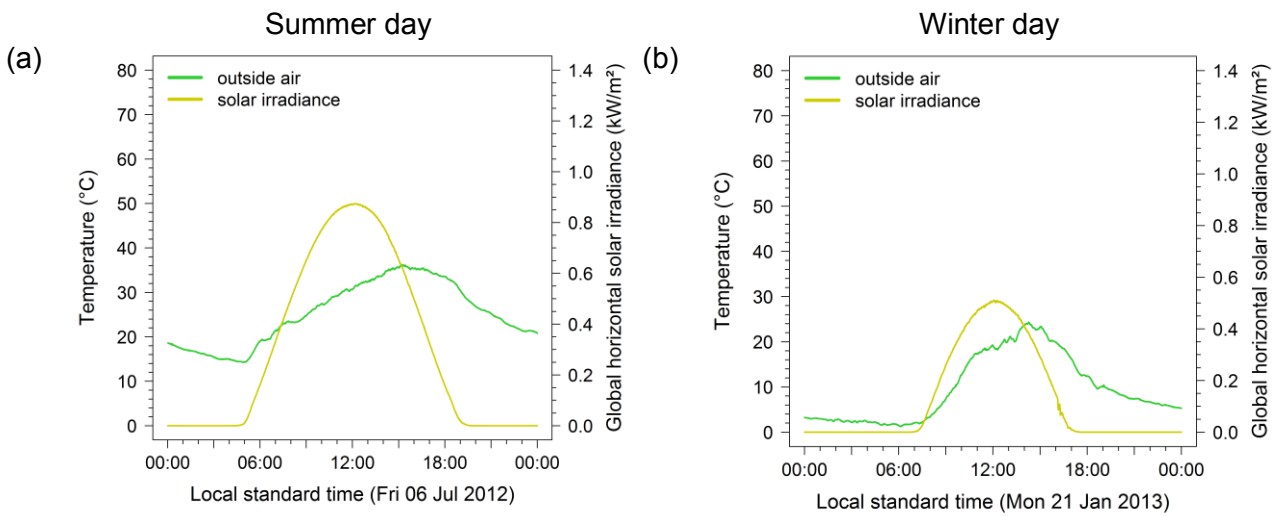


Figure 3. Outside air temperature and global horizontal solar irradiance on (a) a sunny summer day (6 July 2012) and (b) a sunny winter day (21 January 2013).

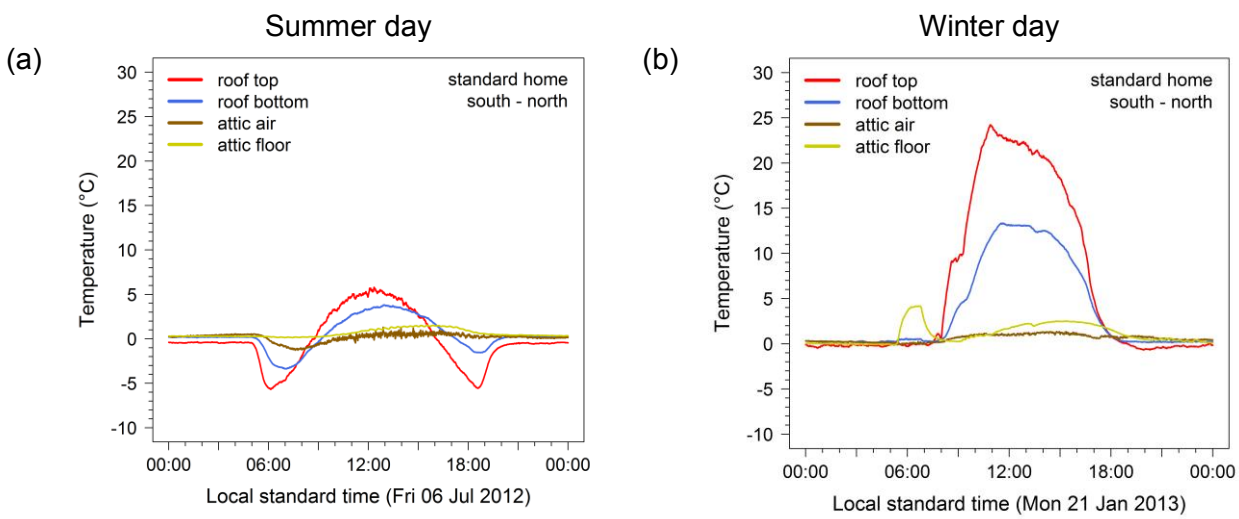


Figure 4. Roof top, roof bottom, attic air, and attic floor temperature differences between south and north sides of the standard home on (a) the summer day and (b) the winter day. As expected, it is important to measure roof top and roof bottom temperatures on all faces of a sloped roof.

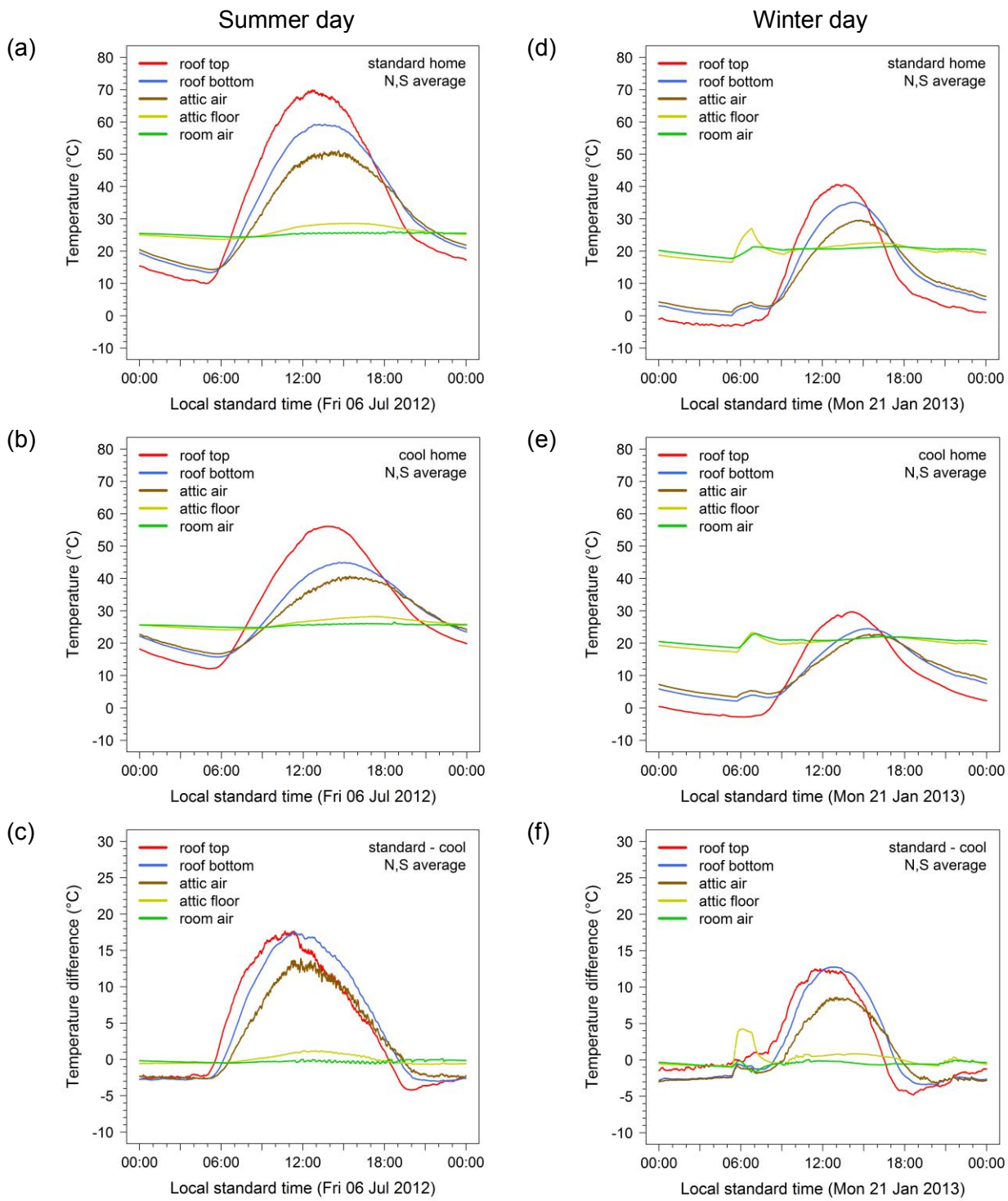


Figure 5. Roof top, roof bottom, attic air, attic floor, and room air temperatures and temperature differences on (a-c) the summer day and (d-f) the winter day. Label "N, S average" applies to roof and attic temperatures.

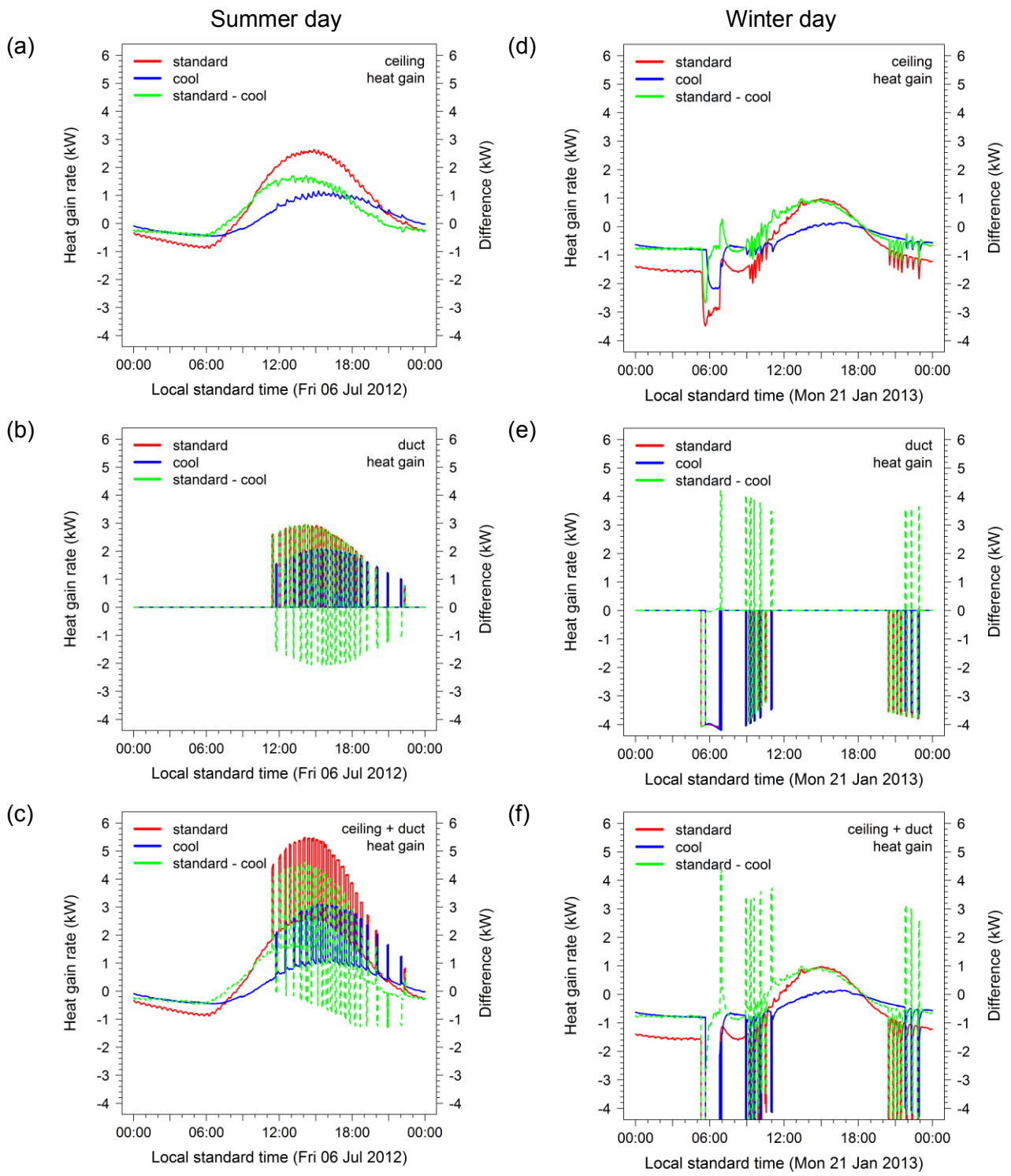


Figure 6. Rates of ceiling, duct, and ceiling + duct heat gain on (a-c) the summer day and (d-f) the winter day.

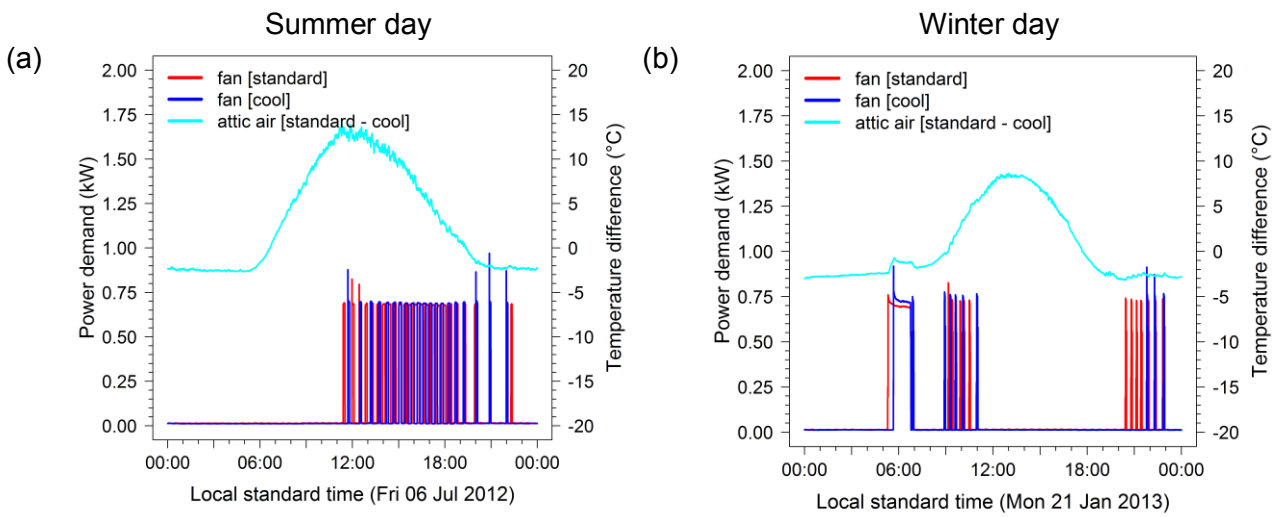


Figure 7. HVAC fan power demand on (a) the summer day and (b) the winter day.

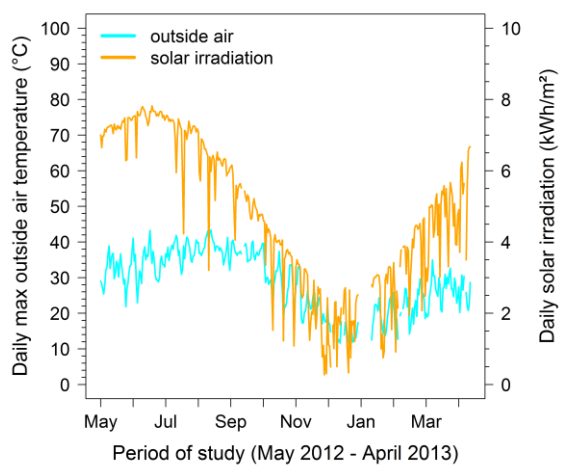


Figure 8. Daily maximum outside air temperature and daily solar irradiation over the period of study.

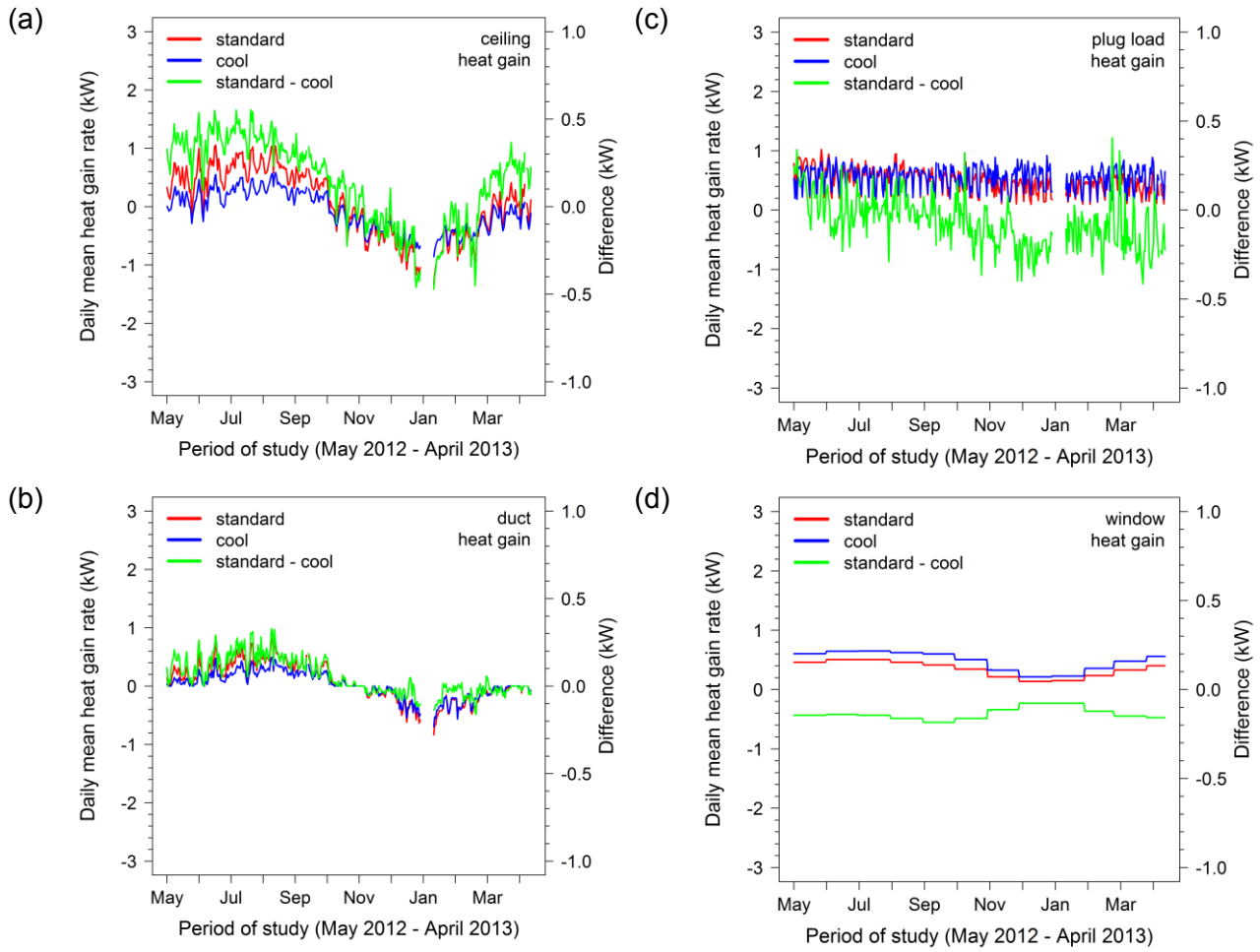


Figure 9. Daily mean rates of (a) ceiling, (b) duct, (c) plug load and (d) window heat gain.

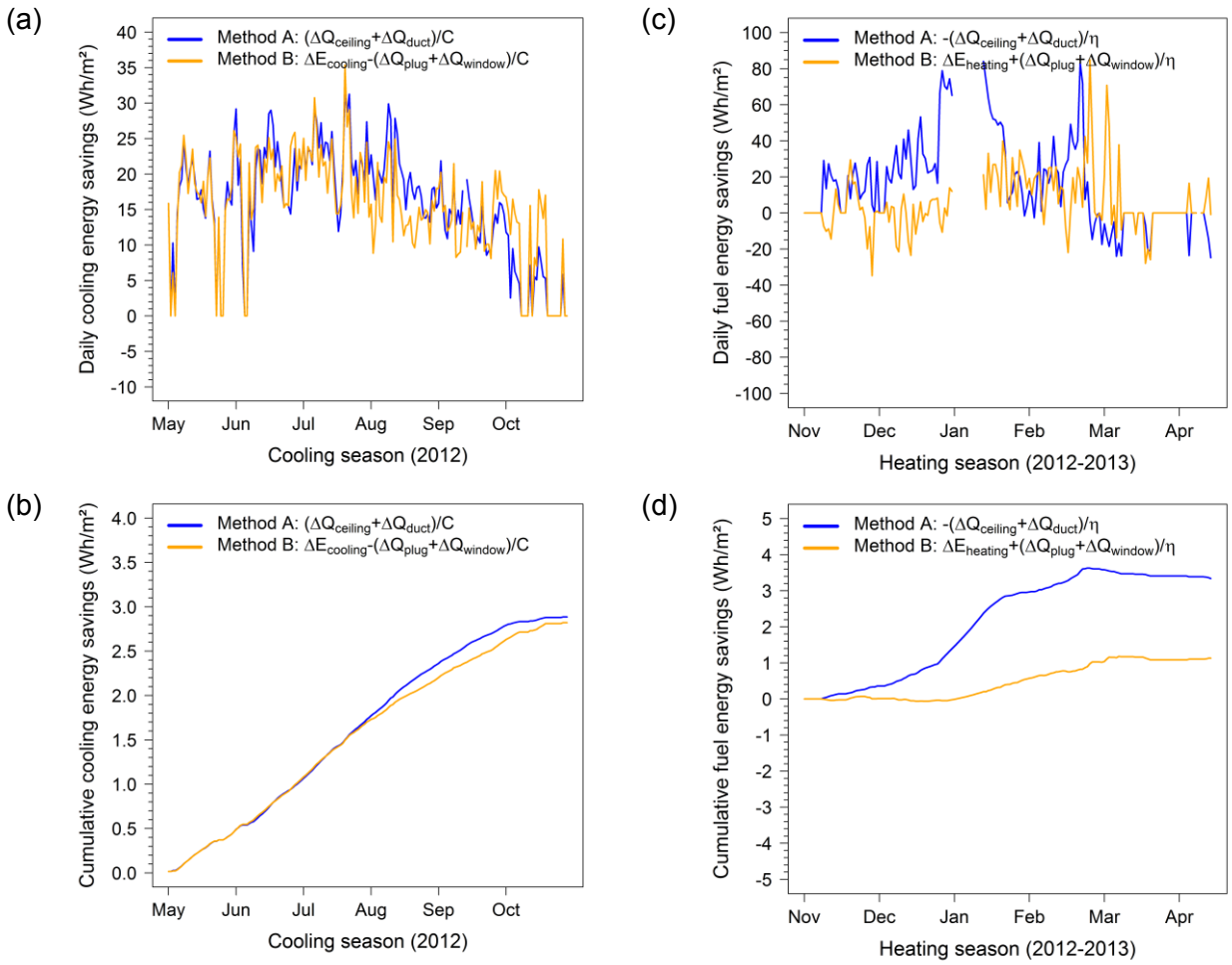


Figure 10. Values per unit ceiling area of (a) daily and (b) cumulative cooling (compressor + fan) energy savings in the cooling season; and (c) daily and (d) cumulative fuel energy savings in the heating season.

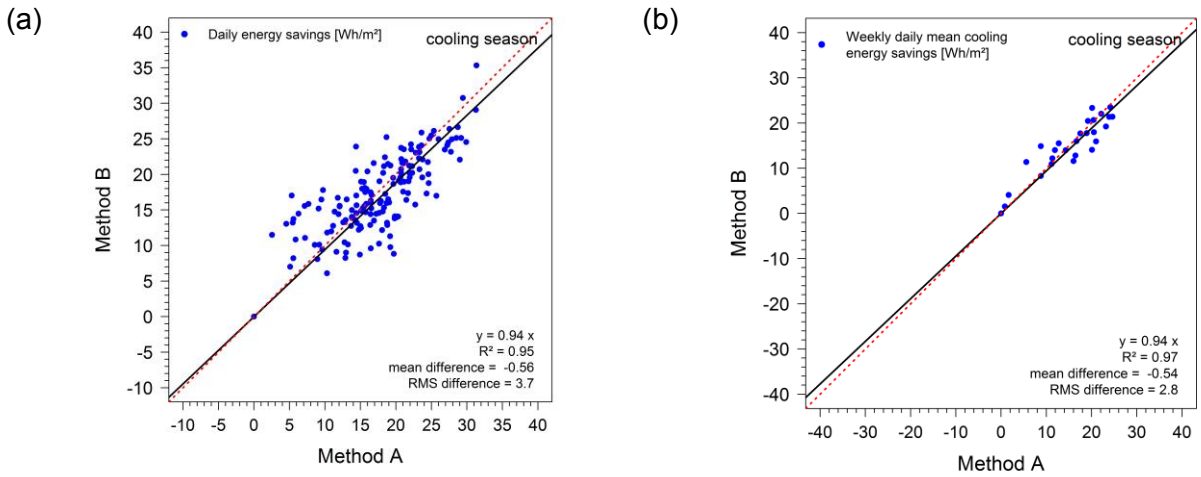


Figure 11. Cooling season comparisons of Method A and Method B estimates of (a) daily and (b) weekly mean values of daily cool-roof energy savings per unit ceiling area.

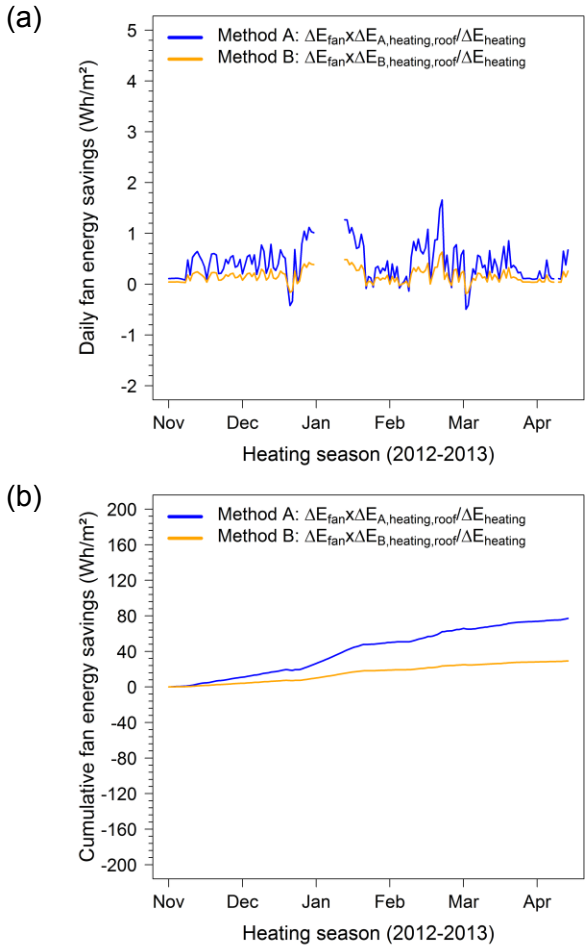


Figure 12. Values per unit ceiling area of (a) daily and (b) cumulative fan energy savings in the heating season.

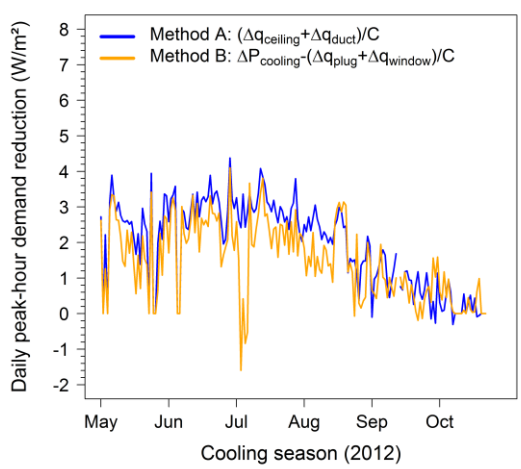
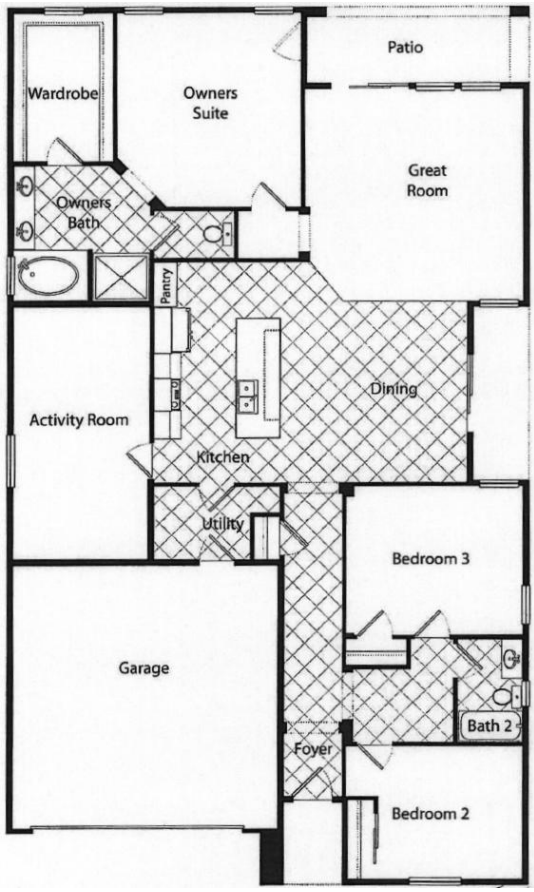


Figure 13. Daily peak-hour cooling power demand reduction in the cooling season.

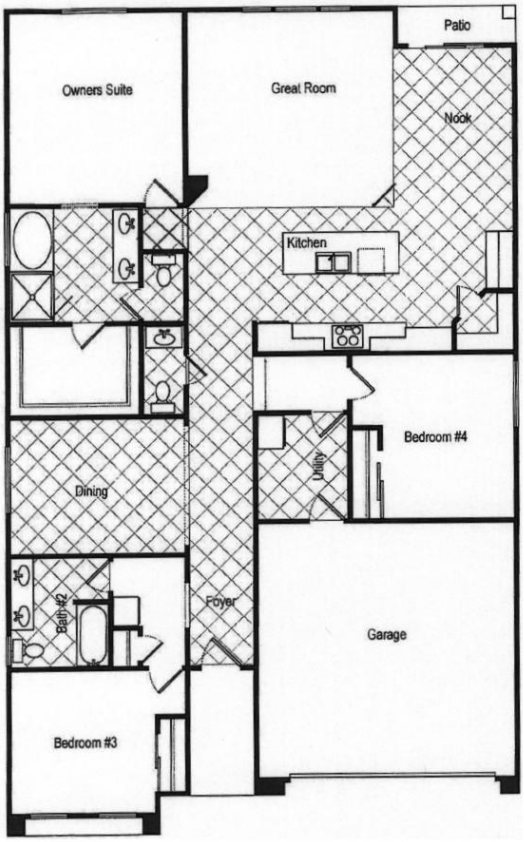
A. Electronic supplementary material

Figures

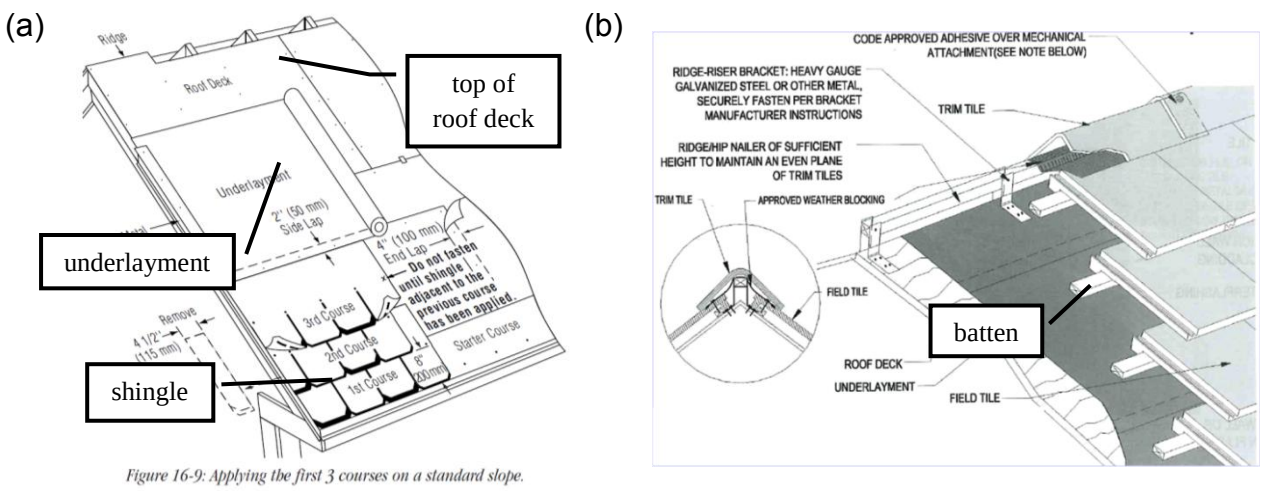
(a)



(b)

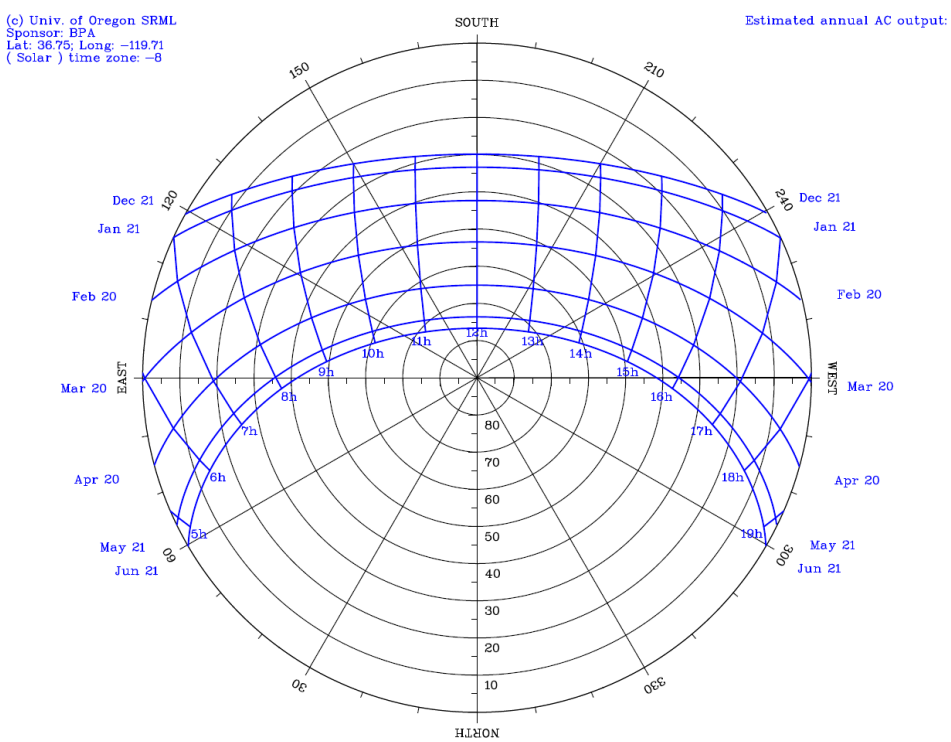


ESM Figure A-1. Floor plans for (a) the standard home and (b) the cool home.

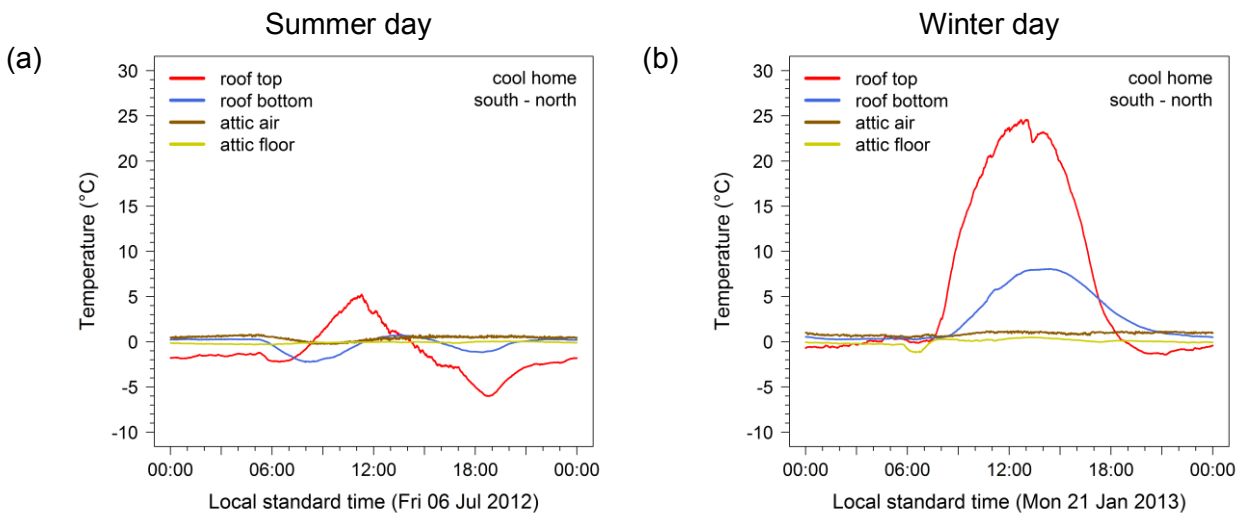


(a) (b)

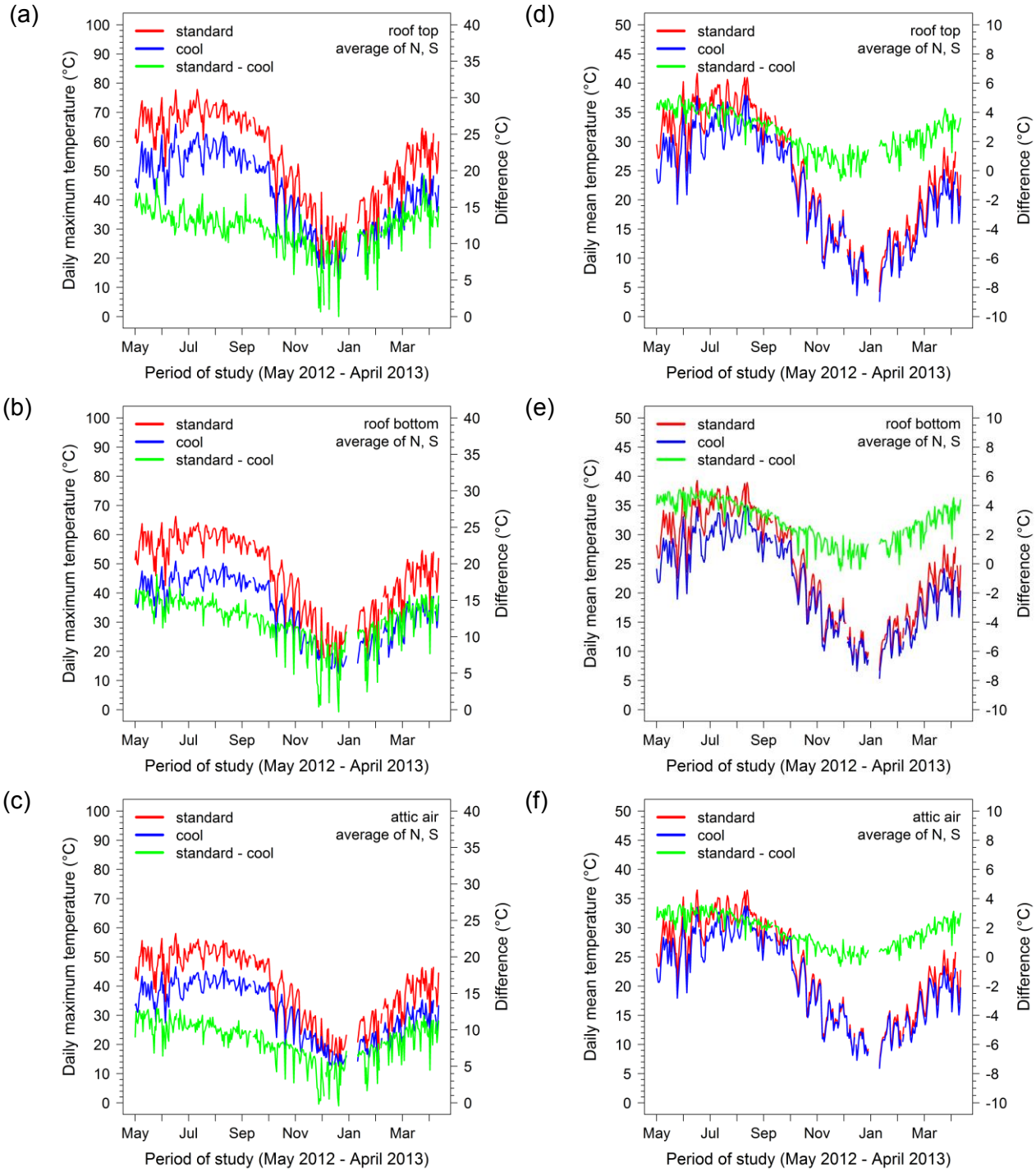
ESM Figure A-2. Diagram of (a) shingle roof installation [49] and (b) layers on flat tiles assembly over roof deck [50].



ESM Figure A-3. Sun path chart for Fresno, CA [51].



ESM Figure A-4. Roof top, roof bottom, attic air, and attic floor temperature differences between south and north sides of the cool home on (a) the summer day and (b) the winter day.



ESM Figure A-5. Daily (a - c) maximum and (d - f) mean temperatures at roof top, roof bottom, and attic air.

APPENDIX B:
Evaluation of LBNL Light Reflective Concrete Pavement Sections CTLGroup Project No. 056256

December 12, 2012

Tom Tietz
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USA

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Office: (714) 694-0800

Evaluation of LBNL Light Reflective Concrete Pavement Sections
CTLGroup Project No. 056256

Dear Mr. Tietz:

As requested, CTLGroup has evaluated nine cylinders, obtained from three experimental concrete pavement sections. The pavement sections are located in Davis, CA and are part of a surface reflectivity study being conducted by Lawrence Berkeley National Lab (LBNL). The pavement sections have lower than expected solar reflectivity values and our evaluation was initiated to determine the cause and possible mitigation strategies. Solar reflectance testing was conducted on three cores from each of the three concrete pavement test sites in accordance with ASTM C1549 to determine the as-received values as well as improved values after different cleaning methods. These cores were specifically selected from each pavement test site to broadly represent an area of average solar reflectivity, an area of poor reflectivity, and an area of higher than normal reflectivity. After the reflectivity testing, the core specimen having average reflectivity from each concrete section was evaluated petrographically in accordance with ASTM C856 to assess the general condition of the concrete at a microstructural level and to determine, to the extent possible, why the concrete in question appears darker than expected.

Solar Reflectance Testing

The cylinders were received by CTLGroup personnel in Skokie, IL on November 1, 2012. As authorized by you, CTLGroup measured the solar reflectance in general accordance with ASTM C1549 – 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer*.

The sample sets were labeled as "Traditional PCC" (Cores 1, 2, and 3) "Photocatalytic Cement[1]" (Cores 4, 5, and 6) and "Slag Cement[2]" (Core 7, 8, and 9). The specimens were stored at room temperature until they were tested and were not cleaned prior to testing. The age of the specimens at the time of testing is unknown. The specimens were approximately 4-in. by 8-in. cylinders. The top surface of each specimen is slightly rough and textured.

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[1] Note that the mixture designs provided by CEMEX state the cementitious binder in this test site is a blend of 50% white cement containing a photocatalytic titanium dioxide and 50% Type II/V portland cement.
[2] The cementitious binder for this concrete is reported in the CEMEX mixture design to be 50% slag cement and 50% Type II/V portland cement.

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On November 5, 2012, the solar reflectance of the top surface of each of the specimens was measured in three locations. The air mass on the solar spectrum reflectometer was set at 1.5, which approximates the length a beam of sunlight travels through the atmosphere over the conterminous United States. The measured solar reflectance for each specimen, average solar reflectance, and standard deviation are reported in the attached data sheets in Appendix A. The average specimen reflectivity results and the overall computed pavement are summarized in Table 1.

Table 1: As-received solar reflectance testing results.

	Specimen	Specimen Solar Reflectance	Solar Reflectance Index (SRI)*
Traditional PCC	1	0.16	
	2	0.18	
	3	0.22	
	Average	0.19	18
Photocatalytic Cement	4	0.23	
	5	0.30	
	6	0.24	
	Average	0.26	27
Slag Cement	7	0.27	
	8	0.20	
	9	0.24	
	Average	0.24	24

*Assuming a convection coefficient of 12 W/m²·°C (for medium wind speed) and an emittance of 0.9, which is appropriate for non-metallic opaque building materials.

The solar reflectance *index* (SRI) was also calculated according to ASTM E1980 – 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces*, assuming a convection coefficient of 12 W/m²·°C (for medium wind speed) and an emittance of 0.9, which is appropriate for non-metallic opaque building materials.[3] The SRI for each pavement section is also shown in Table 1, based on an assumption that the three cylinders were obtained randomly from the pavement surface, which was not the case.

After initial testing, the core with the lowest measured reflectivity from each pavement section underwent two levels of cleaning. The samples were first cut in half to preserve one side to represent the as-received condition. The other half of each sample was first manually scrubbed with a nylon brush under running water for two and half minutes and another set of solar reflectance measurements were taken along with pictures for comparison. Following this treatment, the scrubbed sample halves were lightly sandblasted with two passes over the surface and measurements and pictures were again taken. The measurements taken on the as-received and cleaned surfaces are summarized in Table 2.

[3] *LEED Reference Guide for Green Building Design and Construction for the Design, Construction and Major Renovations of the Commercial and Institutional Buildings Including Core & Shell and K-12 School Projects,* 2009 edition, page 112.

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Table 2: Solar Reflectance Testing on Cleaned Samples

	Solar Reflectance	Solar Reflectance Index (SRI)*
Traditional PCC (Core 1)		
As-Received[4]	0.15	13
Scrubbed with Brush and Water	0.23	23
Lightly Sandblasted	0.30	32
Photocatalytic Cement (Core 4)		
As-Received[4]	0.25	25
Scrubbed with Brush and Water	0.30	32
Lightly Sandblasted	0.35	38
Slag Cement (Core 8)		
As-Received[4]	0.21	20
Scrubbed with Brush and Water	0.32	34
Lightly Sandblasted	0.35	38

*Assuming a convection coefficient of 12 W/m²·˚C (for medium wind speed) and an emittance of 0.9, which is appropriate for non-metallic opaque building materials.

Both cleaning methods increased the reflectivity of the surface, raising the calculated SRI values of the cylinders. Figures 1, 2, and 3 are composite photos created to allow easy comparison of the Cores 1, 4, and 8 as received, after scrubbing with brush and water, and after lightly sandblasting.

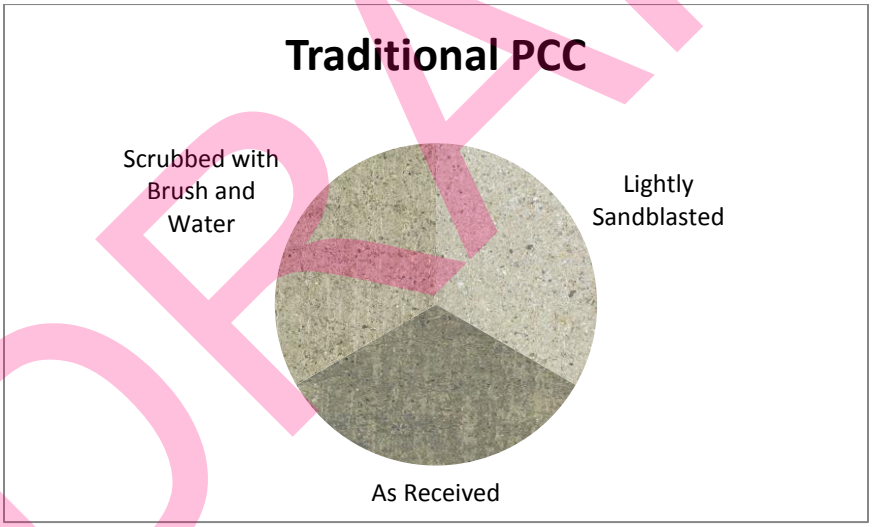

Figure 1: Traditional PCC (Core 1) composite photograph.

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[4] Note that the "initial" reading in Table 2 varies slightly from that reported for the core as a whole in Table 1 as it was conducted on only half the core after sawing and rinsing, which slightly altered the surface reflectivity.

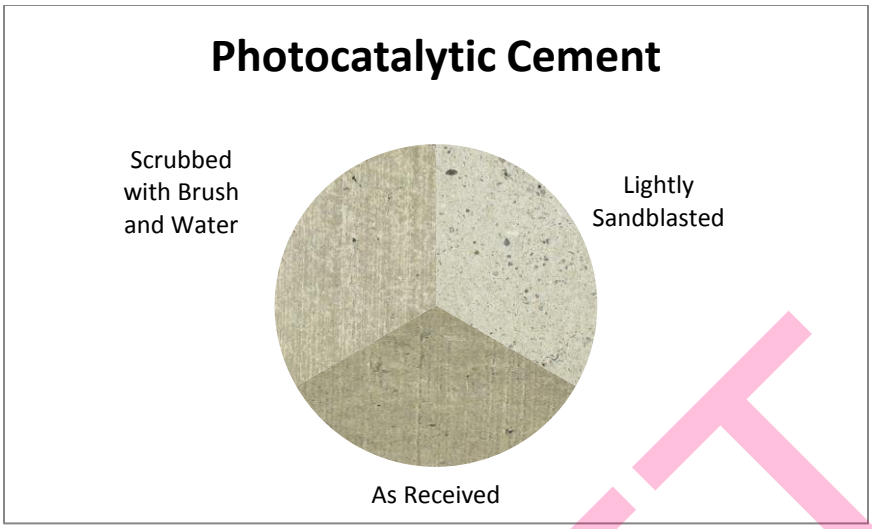

Figure 2: Photocatalytic cement (Core 4) composite photograph.

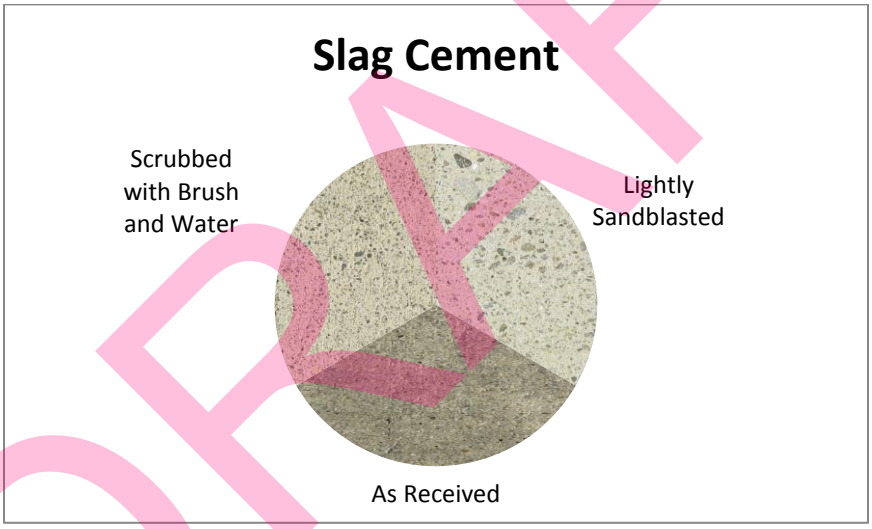

Figure 3: Slag cement (Core 8) composite photograph.

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Petrography

It is evident in the composite photographs presented in Figures 1 through 3 that the dark surface could be removed from the concrete pavement, revealing a much more reflective concrete substrate that exists just below. In order to assess the nature of this surface, a detailed petrographic analysis was conducted on the following three cores which had the mid-level reflectivity for each of the pavement sections:

- Core 2: Traditional PCC mixture.
- Core 6: Photocatalytic cement.
- Core 9: Slag cement.

Petrographic examination was performed in accordance with ASTM C856, *Standard Practice for Petrographic Examination of Hardened Concrete*. The cores were visually inspected and photographed as received. Prior to sample preparation, a low-viscosity blue epoxy was applied to portions of the core top surfaces, to stabilize any potential coatings, deposits, or softened paste. Each core was cut in half longitudinally, and one of the resulting halves from each core was ground (lapped) to produce a smooth, flat, semi-polished surface. Lapped and freshly broken surfaces of the concrete were examined using a stereo optical microscope (SOM) at magnifications up to 45X.

Thin-sections were also created by cutting a small rectangular block from the top 25 mm (1 in.) of each core and lapping one side of the block to produce a smooth, flat surface. Each block was cleaned and dried, and the prepared surface was mounted on a ground glass microscope slide with epoxy resin. After the epoxy hardened, the thickness of each mounted block was reduced to approximately 20 μm (0.0008 in.) through careful grinding. The resulting thin sections were examined using a polarized-light (petrographic) optical microscope (POM) at magnifications up to 400X to study aggregate and paste mineralogy and microstructure. The extent of paste carbonation was confirmed in thin section.

In addition, scanning electron microscopy (SEM) was performed in accordance with ASTM C1723, *Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy*. The examination was performed on the thin sections of the same concrete prepared for the petrographic examination. The petrographic report is attached as Appendix B to this report.

Figure 4 show images of the concrete core surfaces as delivered and Figure 5 shows the side of these same cores. Figure 6 shows the lapped slabs used in the SOM evaluation. It is clearly seen in Figure 6 that the color of the concrete through the depth of the core varies from core to core, and even over the depth of some of the cores. In particular, the surface of Core 6 appears lighter than the bottom of the core, which appears similar in color to the bulk concrete observed through the depth of Core 2. This makes sense as it is reported that the test site using the photocatalytic cement was constructed in two lifts, with the bottom lift being comprised of a concrete that used a Type II/V cement binder whereas the surface was made with a lift containing the a blend of Type II/V portland cement and photocatalytically-modified white cement. Another color variation is observed in Core 9, where the very bottom appears to have a greenish-blue hue. This coloration is common in concrete containing slag cement prior to oxidization which occurs naturally over time.

The petrographic evaluation confirmed that the concrete in the surface of Core 6 contained traditional Type II/V cement, as the ferrite phase of cement is commonly present in unhydrated cement grains. It is therefore believed that the use of ferrite-bearing Type II/V cement has contributed to the darker-than-expected concrete surface in the photocatalytic test site, and if a pure white cement binder would have been used, the surface would have appeared much lighter.

But the largest contributor to the relatively dark surface is that the top concrete surface in all three cores exhibits a thin, intermittent layer or coating of a dark brown-black material. This material appears to be the primary cause for the darker-than-expected concrete surface. The presence of this coating is highly atypical of concrete pavements, and is not easily explained.

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Figure 4: Top surfaces of Cores 2, 6, and 9.

Figure 5: Side view of Cores 2, 6, and 9 with top surfaces up.

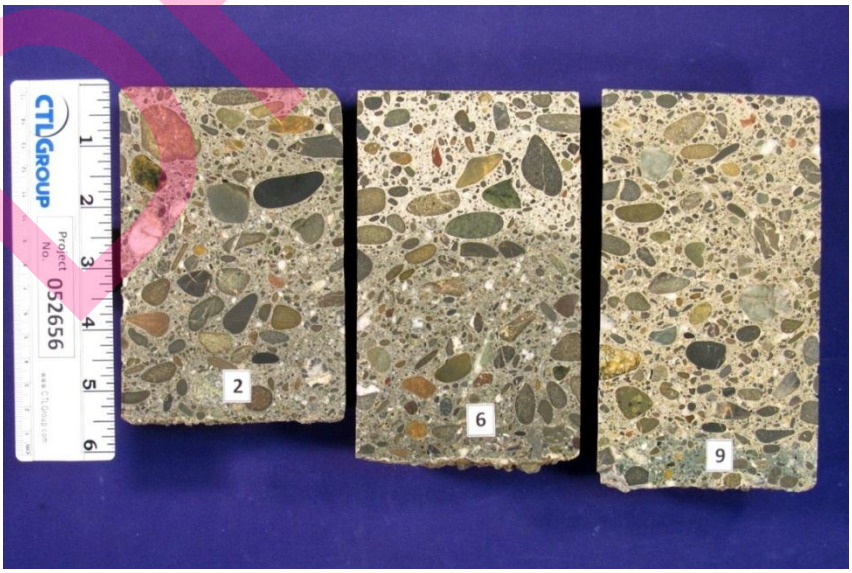

Figure 6: Lapped, cross-sectional (longitudinal) surfaces of Cores 2, 6, and 9.

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Optically and under magnification, the dark brown-black material is non-crystalline and opaque. The brown-black material layer is adhered to the concrete top surface, appearing like a coating, and locally as particulate matter. It is also incorporated into the near-surface region of the concrete surface. This can be seen in the POM micrograph taken from a thin section of Core 2 in Figure 7.

Results of scanning electron microscopy (SEM) analysis show the elemental composition of the surficial brown-black material to be silica, calcium, oxygen, magnesium, aluminum, potassium, and iron. This elemental assemblage suggests clay-like mineralogy and therefore the material is likely a soil or debris.

The origin of the brown-black material could not be completely discerned using petrographic methods. Two hypotheses, either working independently or in conjunction with each other, are described below:

- External sources. In some areas the brown-black material appears as a coating or particulate matter on the concrete top surface. This indicates the material may have originated from a source external to the concrete mixture. Several possible scenarios that may have led to this occurrence include:
  - While the freshly-placed concrete surface was still in a wet condition, fine particulate debris blew onto and adhered to the concrete top surface.
  - The debris originated during use from street traffic.
- Internal source. The brown-black material may be inherent in the concrete mixture, potentially originating from aggregate surfaces. Evidence supporting this possibility includes the following:
  - Several small areas of very fine debris-like material are present along both coarse and fine aggregate particles. The material is dark brown to black, non-crystalline, and opaque. Results of SEM analysis (Table 3) of this material reveal its elemental composition to be very similar to that of the brown-black material at the concrete top surface.
  - Very small brown-black particulates are common throughout the pastes in all three cores) reveal its elemental composition to be very similar to that of the brown-black material on the concrete top surface and the debris-like material along the aggregate particles.
  - The paste in the near-surface region of each concrete core is permeable. This near-surface region varies in depth from 0.25 mm to 1.25 mm. It is not carbonated, although the paste below it is carbonated. This indicates that this top near-surface noncarbonated paste region was altered in some way, possibly by chemical alteration, penetration of a surface coating, or leaching of the paste.
  - From this, the following hypothesis is given: It is reasonable to assume that the very small brown-black clay-like particulates (presumed coatings on or part of the natural aggregate) within the paste are easily suspended in water. Therefore, in the fresh concrete mixture, particulates in the permeable near-surface region could have moved upward with the rising bleed water. As the bleed water evaporated from the surface and near surface voids, the particulates would concentrate, forming an intermittent surficial layer and/or particulate accumulation. The high porosity of the near surface zone of the concrete suggests that there was a lack of curing and thus likely a high level of evaporation from the surface. This would create a wicking action, bringing more and more water to the surface and along with it the fine brown-black particulate.

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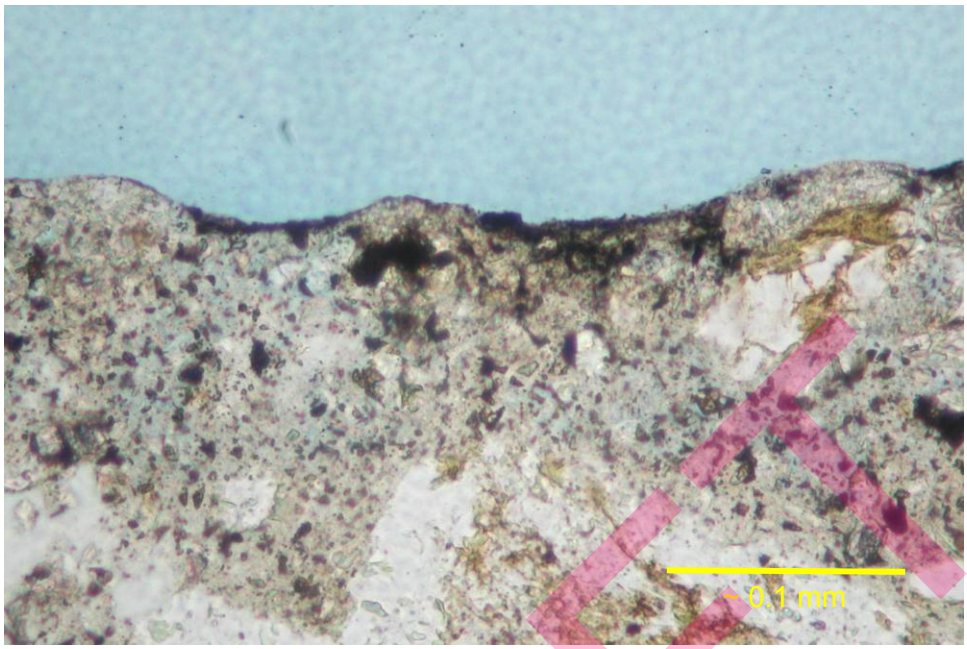
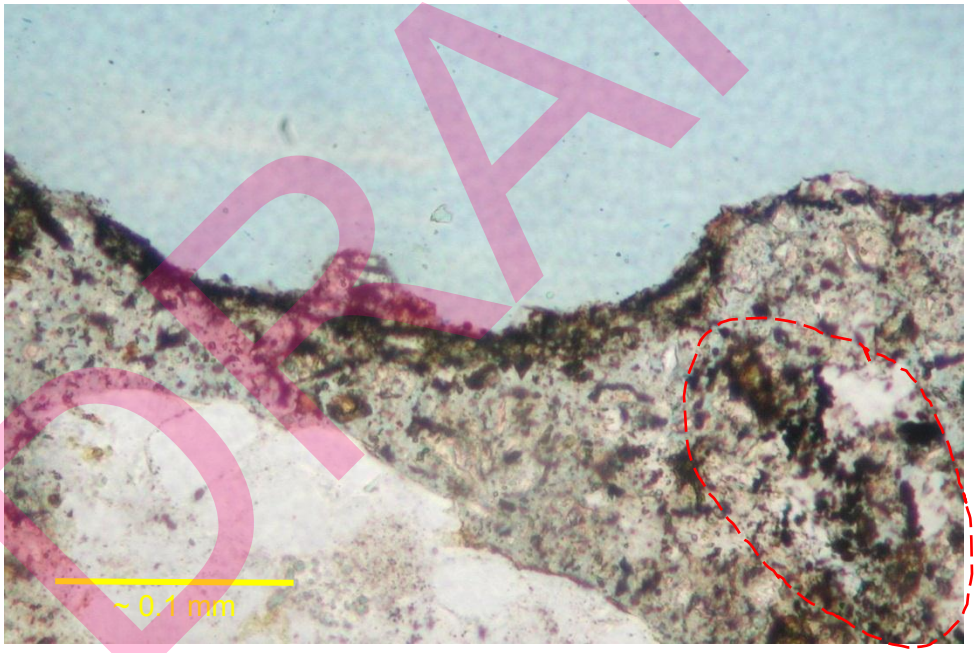


7a.



7b. The red-dashed circled area depicts an area in the near-surface region of concrete, where many small brown-black particulates have accumulated. Below this accumulation is a microcrack (not present in the image).

Figure 7: Thin section photomicrographs of Core 2, showing cross-sectional views through near-surface regions of the concrete. Brown-black material appears embedded into, and/ or accumulating at, the concrete top surface. The pale blue area within the concrete is blue epoxy, which originally was applied to the concrete top surface during sample preparation and which then penetrated into the near-surface region of the concrete. Here, little to no paste (void space) is present and small brown-black particulates are very common, easily visible, and appear inherent to the concrete mixture. Plane-polarized light.

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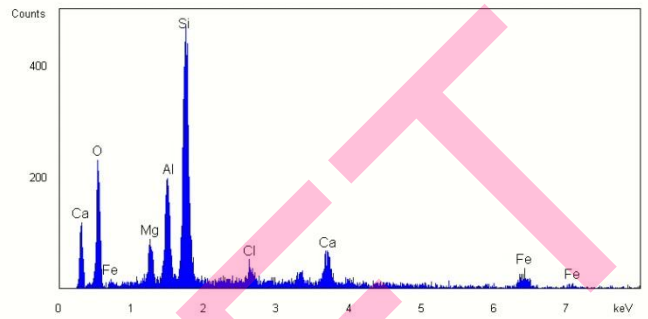
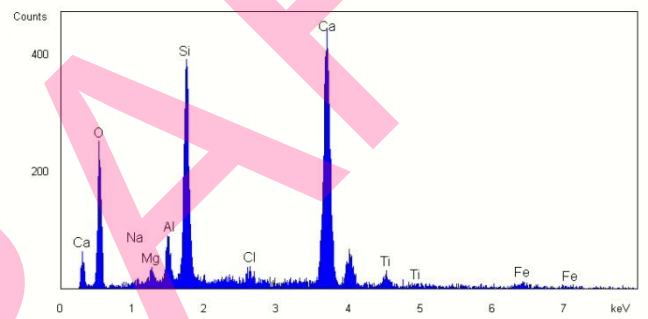
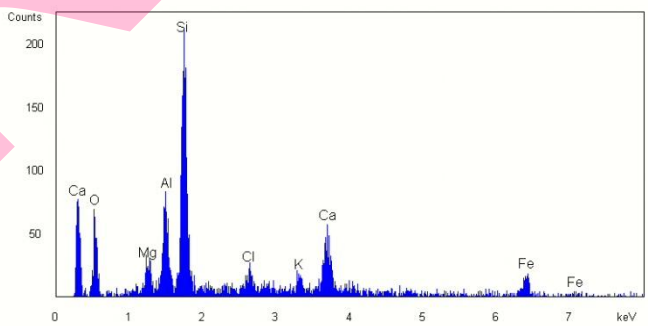
Table 3: Elemental composition results from SEM analysis performed on the brown-black materials.

Core	Location of Analysis Within Core	Elemental Composition
2	Top surface of concrete.	
6	Along aggregate particle within concrete. Note: The high calcium (Ca) and titanium (Ti) peaks are likely from the close proximity of the concrete paste.	
9	Within paste in near-surface region.	

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In addition to the brown-black material, the following two other coatings or deposits were observed on the concrete top surfaces:

- A crystalline material is present in small to very small amounts, very intermittently in a uniformly thick zone along the concrete top surfaces of all three cores. It may be a secondary carbonate deposit or crystallized surface coating.
- A clear layer or coating is present on the top surface of Core 2. It is present as several short, broken remnant pieces of a coating across the concrete top surface. It is non-crystalline and amorphous. Results of SEM analysis reveal its elemental composition to be silica and oxygen.

An absolute identification of the substances could not be resolved petrographically. Yet the optical properties suggest, as does the very thin nature of the films, that these are not polymeric coatings such as acrylic resin. If it is an applied coating, it is more likely to be a silicate sealer or hardener. Due to the scant presence of each, definitive testing by chemical analysis cannot be performed. Applications of sealers, coatings, or hardeners will also affect the appearance of the concrete surface.

Conclusions

The conclusions of this study are summarized as follows:

- The measured solar reflectance values of the concrete surfaces of the core specimens from the typical PCC, photocatalytic cement, and slag cement test sites are relatively low, on average being 0.19, 0.26, and 0.24, respectively. These laboratory measured values are consistent with the reported field measurements.
- The reduced solar reflectance is due to a thin coating on the concrete surface. Scrubbing with water and a nylon brush removes much of this coating, and almost all of the coating can be removed with light sandblasting. It is likely that a moderate pressure power washing would also be effective at removing most of the coating.
- The Type II/IV portland cement contained in all the concrete in all the test sites had sufficient ferrite-phases to impart a gray color to all of the concrete. The coloration was most pronounced in the traditional PCC test site and in the bottom concrete lift in the photocatalytic test site, as this concrete cement binder was 100% Type II/V portland cement.
- The primary reason for the relatively low solar reflectivity was the presence of a thin, intermittent layer or coating of a dark brown-black, non-crystalline and opaque material. The brown-black material layer is adhered to the concrete top surface, appearing like a coating, and locally as particulate matter. It is also incorporated into the near-surface region of the concrete surface. This coating is highly atypical.
- It is unclear whether the brown-black coating was externally applied or the result of something inherent in the concrete, or a combination of the two. It is possible that the coating is simply material that either blew onto the fresh concrete surface shortly after finishing or was ground into the surface by traffic while the pavement was is service. Alternatively, it is plausible that the material was part of the aggregate as fine particulate possibly on the surface of the aggregate. During mixing, this material was carried by bleed water and concentrated at the surface when the water evaporated. The apparent lack of curing contributed to this process. Although neither theory is completely satisfying, sufficient evidence exists to support an inherent source for the material, which is likely working in combination with particulate applied by traffic to create the coating.

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- Other coatings were also observed, but to a lesser degree. These are not polymeric coatings such as acrylic resin. If they are an applied coating, it is more likely to be a silicate sealer or hardener.

Although the precise origin of the brown-black coating could not be definitively identified, it is clear that removal of the coating will significantly increase the solar reflectivity of all three test sites. This can be accomplished by sandblasting as demonstrated in the laboratory, although it is likely that similar cleaning can be affected by moderate pressure power washing. The high porosity of the near surface zone may be providing a mechanism for road grime to adhere to the surface. If this is the case, it may be necessary to seal the concrete surfaces.

In the future, it is imperative that the concrete mixture be tested for solar reflectance during the mixture design process to ensure the desired reflectivity properties are achieved. Further, in reviewing photographs taken during construction, it is clear that the construction practices were not consistent with normal paving operations as a paver and normal finishing and curing techniques were not evident. It is highly recommended that state-of-the-practice paving methods be used in the construction of future of test site to ensure that the constructed pavement is representative of that normally constructed.

If you have any questions or comments, please call.

Sincerely,

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APPENDIX A

ASTM C1549, STANDARD TEST METHOD FOR DETERMINATION OF SOLAR REFLECTANCE NEAR AMBIENT TEMPERATURE USING A PORTABLE SOLAR REFLECTOMETER, DATA SHEETS

ASTM C1549, Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer [1, 2]
Sample Set - Traditional PCC

Specimen	Location	Location reflectance	Specimen reflectance
1	1	0.17	0.16
	2	0.16	
	3	0.16	
2	1	0.18	0.18
	2	0.18	
	3	0.18	
3	1	0.23	0.22
	2	0.22	
	3	0.21	
		Standard deviation	0.02
		Overall average	0.19
Solar reflectance index (SRI)[3] corresponding to convective coefficients of three wind conditions		**Low wind**	17
		Medium wind	18
		High wind	18

1. Tested in accordance with ASTM C 1549 - 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer* .

2. Air mass index is 1.5.

3. Solar reflectance index calculated according to ASTM E 1980 - 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* with an emittance for non-metallic opaque building materials of 0.9. Low wind corresponds to a convection coefficient of 5 W/m²•˚C, medium wind corresponds to a convection coefficient of 12 W/m²•˚C, and high wind corresponds to a convection coefficient of 30 W/m²•˚C.

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ASTM C1549, Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer [1, 2]
Sample Set - Photocatalytic Cement

Specimen	Location	Location reflectance	Specimen reflectance
4	1	0.24	0.23
	2	0.23	
	3	0.23	
5	1	0.30	0.30
	2	0.30	
	3	0.30	
6	1	0.23	0.24
	2	0.26	
	3	0.22	
		Standard deviation	0.03
		Overall average	0.26
Solar reflectance index (SRI)[3] corresponding to convective coefficients of three wind conditions		**Low wind**	25
		Medium wind	27
		High wind	28

1. Tested in accordance with ASTM C 1549 - 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer* .

2. Air mass index is 1.5.

3. Solar reflectance index calculated according to ASTM E 1980 - 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* with an emittance for non-metallic opaque building materials of 0.9. Low wind corresponds to a convection coefficient of 5 W/m²•˚C, medium wind corresponds to a convection coefficient of 12 W/m²•˚C, and high wind corresponds to a convection coefficient of 30 W/m²•˚C.

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ASTM C1549, Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer [1, 2]
Sample Set - Slag Cement Concrete

Specimen	Location	Location reflectance	Specimen reflectance
7	1	0.27	0.27
	2	0.27	
	3	0.28	
8	1	0.20	0.20
	2	0.20	
	3	0.20	
9	1	0.25	0.24
	2	0.24	
	3	0.24	
		Standard deviation	0.03
		Overall average	0.24
Solar reflectance index (SRI)[3] corresponding to convective coefficients of three wind conditions		**Low wind**	23
		Medium wind	24
		High wind	25

1. Tested in accordance with ASTM C 1549 - 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer* .

2. Air mass index is 1.5.

3. Solar reflectance index calculated according to ASTM E 1980 - 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* with an emittance for non-metallic opaque building materials of 0.9. Low wind corresponds to a convection coefficient of 5 W/m²•˚C, medium wind corresponds to a convection coefficient of 12 W/m²•˚C, and high wind corresponds to a convection coefficient of 30 W/m²•˚C.

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ASTM C1549, Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer [1, 2]
Sample Set - Traditional PCC Core 1

Specimen	Location	Location reflectance	Specimen reflectance
1 as-is	1	0.15	0.15
	2	0.15	
	3	0.15	
1 scrubbed with water	1	0.23	0.23
	2	0.23	
	3	0.22	
1 light sandblasting	1	0.30	0.30
	2	0.30	
	3	0.30	

Solar reflectance index (SRI)[3] corresponding to convective coefficients of three wind conditions			
	1 as-is	1 scrubbed with water	1 light sandblasting
Low wind	12	21	30
Medium wind	13	23	32
High wind	13	24	33

1. Tested in accordance with ASTM C 1549 - 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer* .

2. Air mass index is 1.5.

3. Solar reflectance index calculated according to ASTM E 1980 - 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* with an emittance for non-metallic opaque building materials of 0.9. Low wind corresponds to a convection coefficient of 5 W/m²•˚C, medium wind corresponds to a convection coefficient of 12 W/m²•˚C, and high wind corresponds to a convection coefficient of 30 W/m²•˚C.

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ASTM C1549, Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer [1, 2]
Sample Set - Photocatalytic Cement Core 4

Specimen	Location	Location reflectance	Specimen reflectance
4 as-is	1	0.25	0.25
	2	0.25	
	3	0.24	
4 scrubbed with water	1	0.31	0.30
	2	0.31	
	3	0.29	
4 light sandblasting	1	0.35	0.35
	2	0.36	
	3	0.34	

Solar reflectance index (SRI)[3] corresponding to convective coefficients of three wind conditions			
	4 as-is	4 scrubbed with water	4 light sandblasting
Low wind	24	30	37
Medium wind	25	32	38
High wind	26	33	40

1. Tested in accordance with ASTM C 1549 - 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer* .

2. Air mass index is 1.5.

3. Solar reflectance index calculated according to ASTM E 1980 - 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* with an emittance for non-metallic opaque building materials of 0.9. Low wind corresponds to a convection coefficient of 5 W/m²•˚C, medium wind corresponds to a convection coefficient of 12 W/m²•˚C, and high wind corresponds to a convection coefficient of 30 W/m²•˚C.

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ASTM C1549, Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer [1, 2]
Sample Set - Slag Cement Concrete Core 8

Specimen	Location	Location reflectance	Specimen reflectance
8 as-is	1	0.21	0.21
	2	0.21	
	3	0.19	
8 scrubbed with water	1	0.32	0.32
	2	0.32	
	3	0.32	
8 light sandblasting	1	0.36	0.35
	2	0.34	
	3	0.36	

Solar reflectance index (SRI)[3] corresponding to convective coefficients of three wind conditions			
	8 as-is	8 scrubbed with water	8 light sandblasting
Low wind	19	33	37
Medium wind	20	34	38
High wind	21	36	40

1. Tested in accordance with ASTM C 1549 - 09, *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer* .

2. Air mass index is 1.5.

3. Solar reflectance index calculated according to ASTM E 1980 - 01, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* with an emittance for non-metallic opaque building materials of 0.9. Low wind corresponds to a convection coefficient of 5 W/m²•˚C, medium wind corresponds to a convection coefficient of 12 W/m²•˚C, and high wind corresponds to a convection coefficient of 30 W/m²•˚C.

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APPENDIX B

Petrographic Examination, ASTM C856, of Concrete Cores
from Solar Reflectance Index Project

Copy No. 1

Report for
California Nevada Cement Association
24657 Via Melinda, Yorba Linda, CA 92887

CTLGroup Project No. 052656

Petrographic Examination, ASTM C856, of Concrete Cores from Solar Reflectance Index Project

DRAFT

December 12, 2012

Submitted by:
Jean L. Randolph

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Skokie, Illinois 60077-1030
(847) 965-7500

Austin, TX • Chicago, IL • Washington, DC

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REPORT OF PETROGRAPHIC EXAMINATION

Date: December 12, 2012

CTLGroup Project No.: 052656

Petrographic Examination, ASTM C856, of Concrete Cores from Solar Reflectance Index Project

As part of a solar reflectance index evaluation for the California Nevada Cement Association (CNCA), three concrete cores were submitted for petrographic examination on November 6, 2012, by Dr. Thomas Van Dam, principal engineer at CTLGroup, Skokie, Illinois. The cores were identified as 2, 6, and 9.

The following information was reported to CTLGroup by CNCA and the Lawrence Berkeley National Laboratory (LBNL): The cores were obtained from three experimental concrete pavement sections located in Davis, California. The pavements are part of a study being conducted by LBNL. The purpose of the study is to evaluate different concrete mixture designs and the respective solar reflectivity index for the different concrete pavement surfaces. The three submitted cores represent different concrete mixtures, as follows:

- Core 2. Conventional concrete mixture.
- Core 6. Concrete with white cement and titanium dioxide.
- Core 9. Concrete with 50% slag cement, by weight of cementitious material.

Sometime after placement, the concrete surfaces were noted to be darker than expected and exhibited low solar reflectivity indices. Figures 2, 3, and 4 show close-up images of the concrete core surfaces.

Petrographic examination, by ASTM C856, of the three cores was requested, to evaluate the concrete properties and possible cause(s) for the reported “dark” concrete surfaces.

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FINDINGS AND CONCLUSIONS

In Core 6 the concrete was reportedly designed to contain white cement. As observed petrographically, the unhydrated cement grains are not consistent with white cement but are consistent with gray cement; the ferrite phase of cement is commonly present (Figure 5). Therefore, the use of a ferrite-bearing cement is considered a significant contributing factor to the darker-than-expected concrete surface.

The top concrete surface in all three cores exhibits a thin, intermittent layer or coating of a dark brown-black material. This material appears to be the primary cause for the darker-than-expected concrete surface. The presence of this coating is atypical of concrete pavements.

Optically, the dark brown-black material is non-crystalline and opaque. The brown-black material layer is adhered to the concrete top surface, appearing like a coating, and locally as particulate matter, as well as incorporated into the near-surface region of the concrete surface. Figures 6 through 11 illustrate the material and its relationship the concrete top surface.

Results of scanning electron microscopy (SEM) analysis show the elemental composition of the surficial brown-black material to be silica, calcium, oxygen, magnesium, aluminum, potassium, and iron. This elemental assemblage suggests clay-like mineralogy; and therefore, the material is likely soil or debris. Figures 12 and 13 show results of SEM analysis performed on the surficial brown-black material. Table 1 also presents the elemental assemblage from the SEM analysis.

The origin of the brown-black material was not completely discerned petrographically. Two potential sources, either working separately or in conjunction with each other, are described below:

1. External sources. In some areas the brown-black material appears as a coating or particulate matter on the concrete top surface. This indicates the material may have originated from an external source from the concrete mixture. Several possible scenarios are given.
    a. While the freshly-placed concrete surface was still in a wet condition, debris blew onto the surface and became adhered to, and possibly slightly incorporated into, the concrete top surface.
    b. The debris may have originated from street traffic.

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2. Internal source. The brown-black material may be inherent in the concrete mixture, potentially originating from aggregate surfaces. Evidence indicating this possibility includes the following:
    - Several small areas of very fine debris-like material are present along both coarse and fine aggregate particles (Figures 14 and 15). The material is dark brown to black, non-crystalline, and opaque. Results of SEM analysis (Table 1 and Figure 16) of this material reveal its elemental composition to be very similar to that of the brown-black material the concrete top surface.
    - Very small brown-black particulates are common throughout the pastes in all three cores (Figures 6, 7, and 8). Results of SEM analysis performed on several of these particulates (Table 1 and Figures 17 and 18) reveal its elemental composition to be very similar to that of the brown-black material on the concrete top surface and the debris-like material along the aggregate particles.
    - The paste in the near-surface region of each concrete core is permeable. This near-surface region varies in depth from 0.25 mm to 1.25 mm. It is not carbonated, although the paste below it is carbonated. This indicates that this top near-surface noncarbonated paste region was altered in some way, possibly by chemical alteration, penetration of a surface coating, or leaching of the paste.
    - From this, the following hypothesis is given: It is reasonable to assume that the very small brown-black clay-like particulates (presumed soil or debris) within the paste are lightweight and easily suspendable in water, as soil is known to behave. Therefore, in the fresh concrete mixture, particulates in the permeable near-surface region could have moved upward with pore water, forming an intermittent surficial layer and/or particulate accumulation. Figures 6, 7, and 9 show near-surface particulates and their relationship to void spaces.

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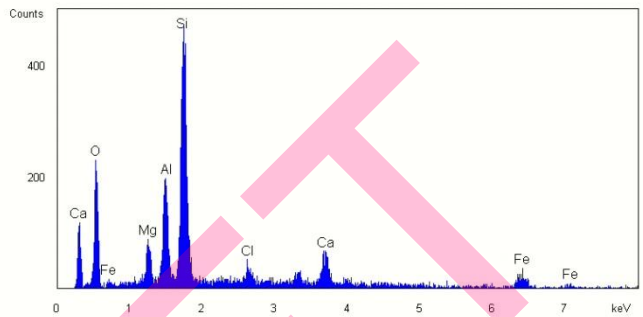
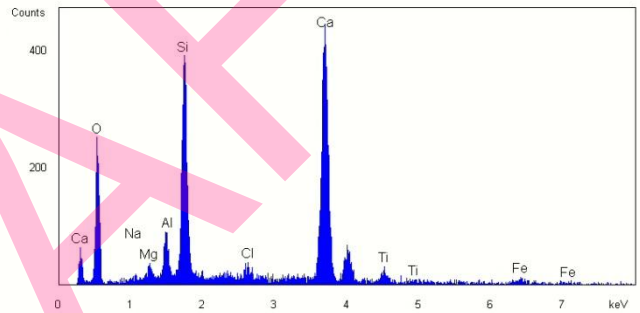
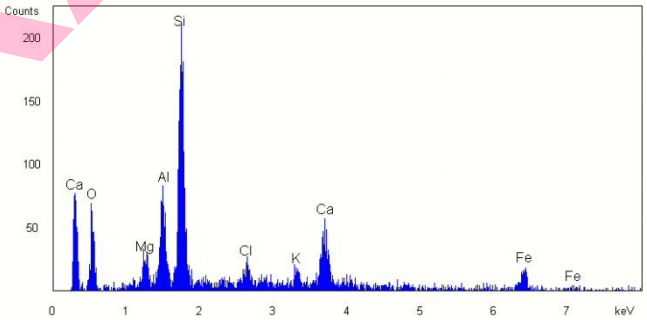
TABLE 1 ELEMENTAL COMPOSITION RESULTS FROM SEM ANALYSIS PERFORMED ON THE BROWN-BLACK MATERIAL

Core	Location of Analysis Within Core	Reference Figure	Elemental Composition
2	Top surface of concrete.	12	
6	Along aggregate particle within concrete. Note: The high calcium (Ca) and titanium (Ti) peaks are likely from the close proximity of the concrete paste.	16	
9	Within paste in near-surface region.	18	

In addition to the brown-black material, two other coatings or deposits were observed on the concrete top surfaces. An identification of the substances was not determined petrographically, however, the optical properties and that it is a very thin film, are unlike polymeric coatings such as acrylic resins. If it is an applied coating, it is more likely to be a silicate sealer or hardener. Due to the scant presence of each, definitive testing by chemical analysis cannot be performed.

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Applications of sealers, coatings, or hardeners will also affect the appearance of the concrete surface.

- A crystalline material is present in small to very small amounts, very intermittently in a uniformly thick zone along the concrete top surfaces of all three cores. It may be a secondary carbonate deposit or crystallized surface coating. Figure 19 illustrates the deposit.
- A clear layer or coating is present on the top surface of Core 2. It is present as several short, broken remnant pieces of a coating across the concrete top surface. It is non-crystalline and amorphous. Figure 20 illustrates the coating. Results of SEM analysis reveal its elemental composition to be silica and oxygen (Figure 21).

Additional information about the concretes is presented in the Petrographic Data Forms at the end of this report.

METHODS OF TEST

Petrographic examination of Cores 2, 6, and 9 was performed in accordance with ASTM C856, "Standard Practice for Petrographic Examination of Hardened Concrete." The cores were visually inspected and photographed as received. Prior to sample preparation, a low-viscosity blue epoxy was applied to portions of the core top surfaces, to stabilize any potential coatings, deposits, or softened paste. Each core was cut in half longitudinally, and one of the resulting halves from each core was ground (lapped) to produce a smooth, flat, semi-polished surface (Figure 22). Lapped and freshly broken surfaces of the concrete were examined using a stereomicroscope at magnifications up to 45X.

For thin-section study, a small rectangular block was cut from the top 25 mm (1 in.) of each core, and one side of the block was lapped to produce a smooth, flat surface. Each block was cleaned and dried, and the prepared surface was mounted on a ground glass microscope slide with epoxy resin. After the epoxy hardened, the thickness of each mounted block was reduced to approximately 20 μm (0.0008 in.). The resulting thin sections were examined using a polarized-light (petrographic) microscope at magnifications up to 400X to study aggregate and paste mineralogy and microstructure. The extent of paste carbonation was confirmed in thin section.

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Scanning Electron Microscopical (SEM) analysis was performed in accordance with ASTM C1723, "Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy." The examination was performed on the thin sections of concrete prepared for the petrographic examination.

Jean L. Randolph
Senior Petrographer
Petrography Group

JLR/

Notes: 1. Results refer specifically to the samples submitted.
2. This report may not be reproduced except in its entirety.

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1a. Top surfaces of cores.

1b. Side view. Core top surfaces are up.

Fig. 1 Cores 2, 6, and 9, as received for testing.

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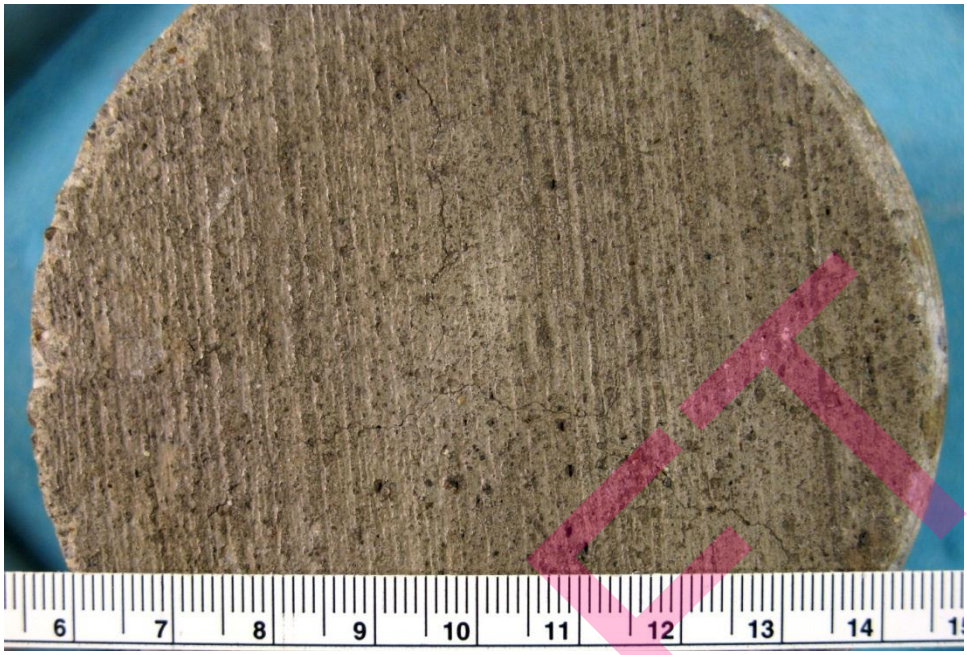

Fig. 2 Close-up of the top surface of Core 2, which is a broom-finished concrete surface. The surface has an overall shiny dark gray appearance. But close up, two colors are present on the surface: 1) a medium gray, which is generally present in the troughs of the broom-finish; and, 2) a dark gray, which is generally present along the crests of the broom-finish, where the paste is slightly worn. Some randomly-oriented microcracks are present.

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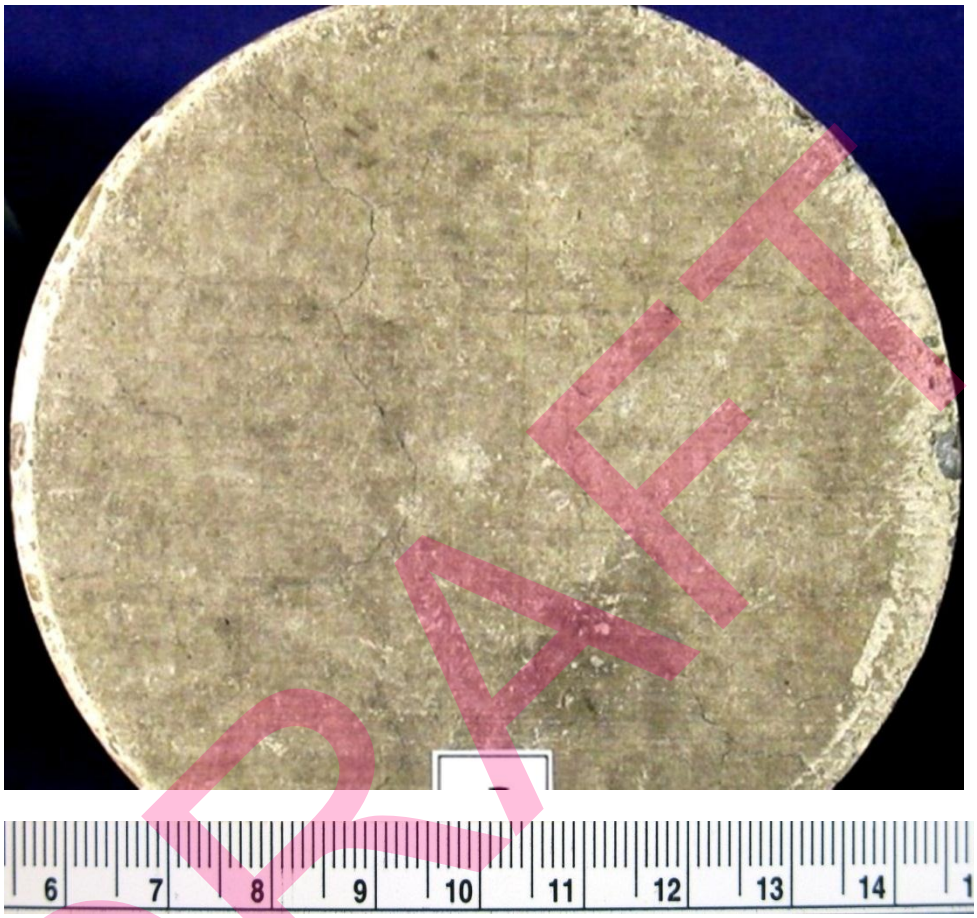

Fig. 3 Close-up of the top surface of Core 6, which is a flat, smooth surface with slight straight striations. The surface has an overall somewhat dull, light-medium gray appearance. Randomly-oriented microcracks are slightly common.

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Fig. 4 Close-up of the top surface of Core 9, which is lightly striated, possibly fine broom-finished, concrete surface. The surface has an overall moderate-luster medium gray appearance. But close up, two colors are present on the surface: 1) a light-medium gray, which is generally present in the troughs of the broom-finish; and, 2) a medium-dark gray, which is generally present along the crests of the broom-finish, where the paste is slightly worn or torn.

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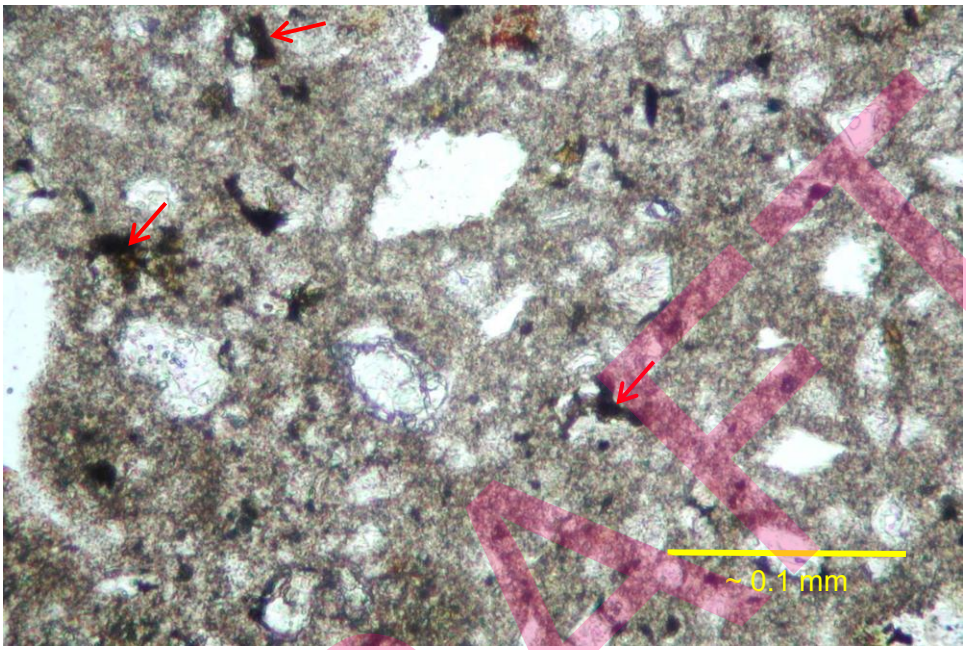

Fig. 5 Thin section photomicrograph of Core 6, illustrating the unhydrated cement grains in the paste. Arrows depict the ferrite-phase in several cement grains.

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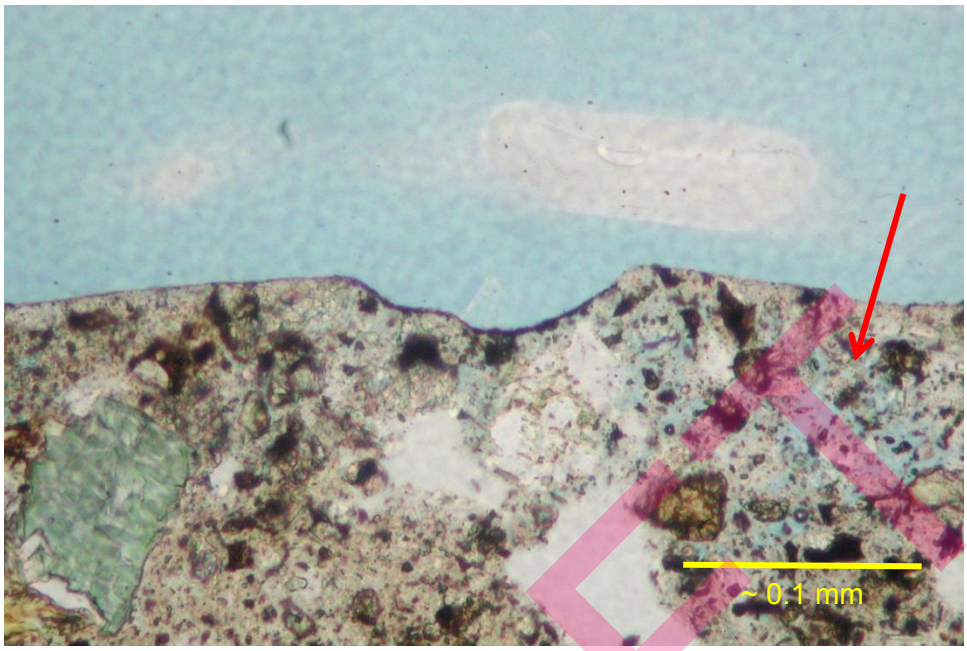
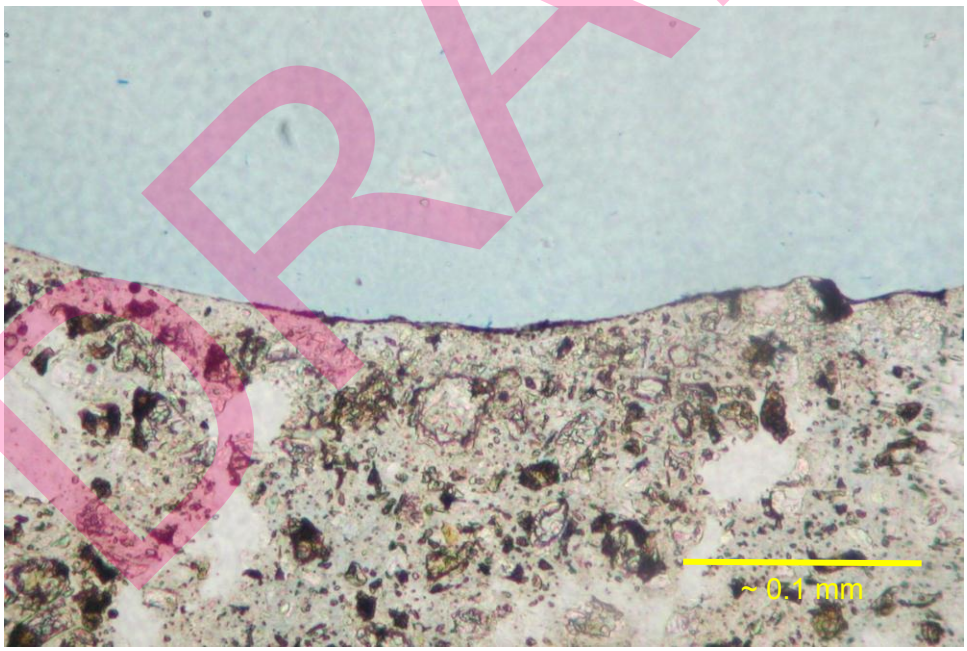


6a. Blue epoxy penetrated into the top near-surface region of the concrete in a porous region (arrow). Small brown-black particles are common in this region which appear inherent to the concrete mixture.



6b.

Fig. 6 Thin section photomicrographs of Core 2, showing cross-sectional views through near-surface regions of the concrete. Here, the brown-black material appears as a coating on the concrete surface. Plane-polarized light.

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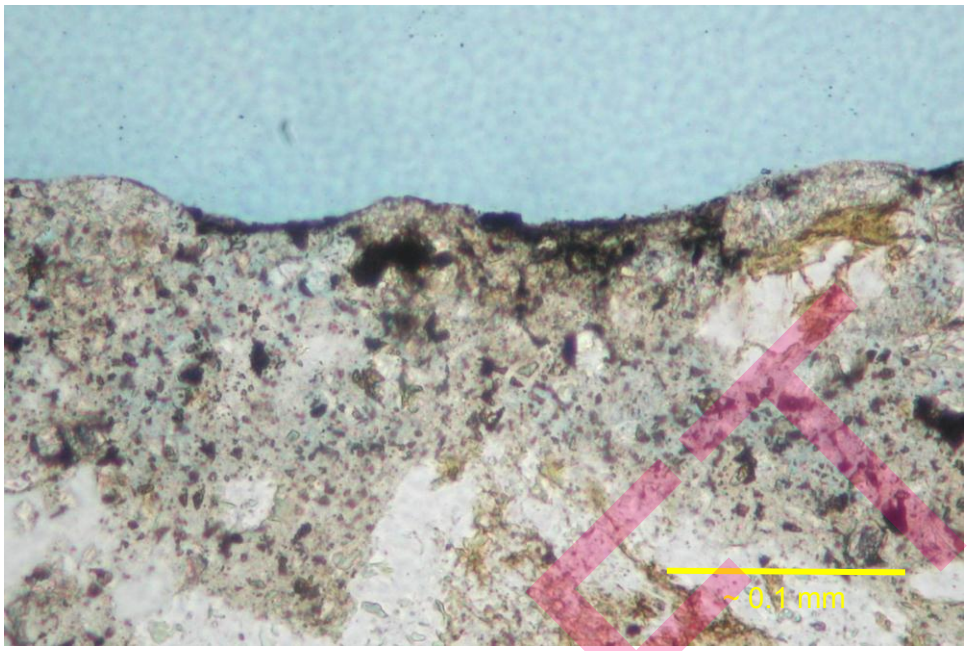
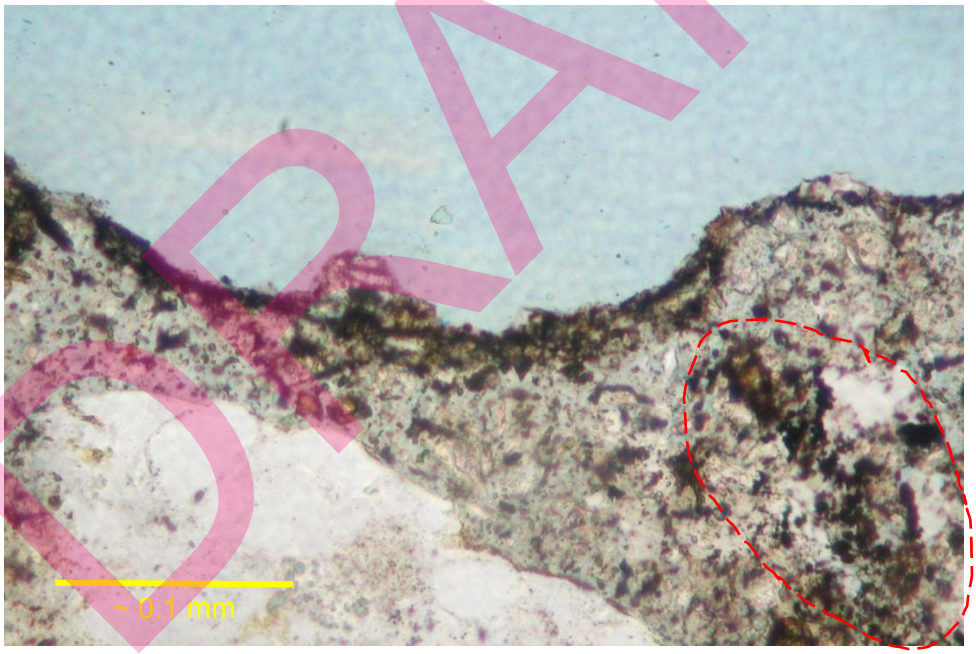


7a.



7b. The red-dashed circled area depicts an area in the near-surface region of concrete, where many small brown-black particulates have accumulated. Below this accumulation is a microcrack (not present in the image).

Fig. 7 Thin section photomicrographs of Core 2, showing cross-sectional views through near-surface regions of the concrete. Brown-black material appears embedded into, and/ or accumulating at, the concrete top surface. The pale blue area within the concrete is blue epoxy, which originally was applied to the concrete top surface during sample preparation and which then penetrated into the near-surface region of the concrete. Here, little to no paste (void space) is present and small brown-black particulates are very common, easily visible, and appear inherent to the concrete mixture. Plane-polarized light.

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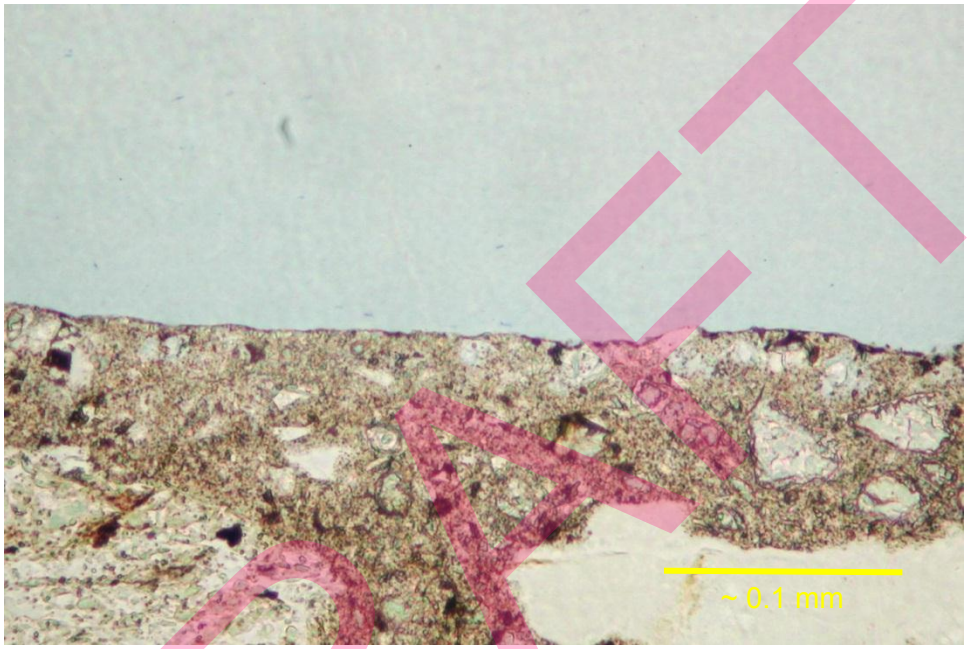

Fig. 8 Thin section photomicrographs of Core 6, showing cross-sectional views through near-surface regions of the concrete. Here, the brown-black material appears as a coating on the concrete surface. Plane-polarized light.

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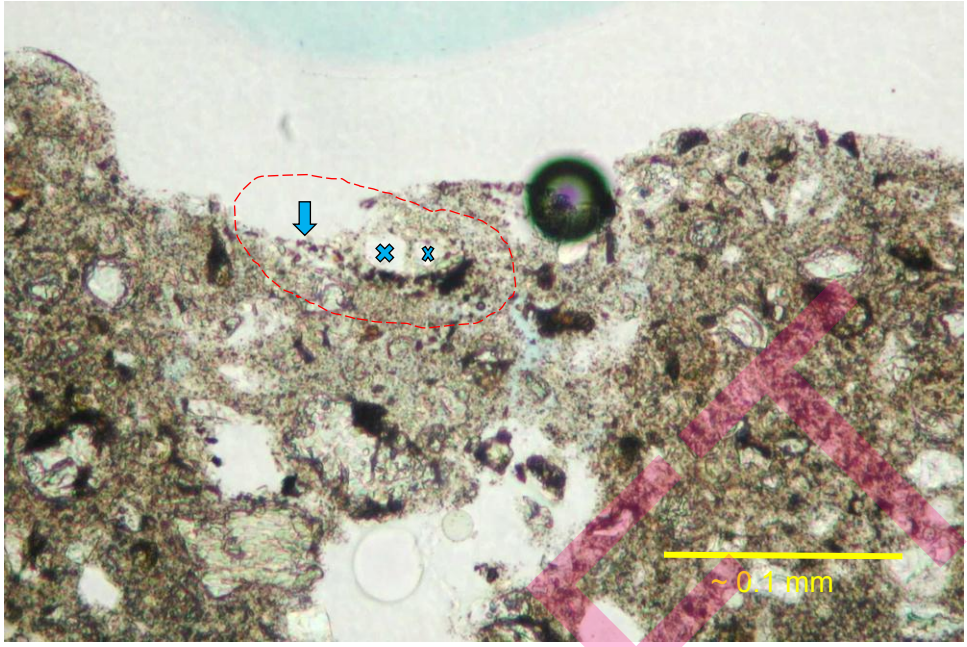
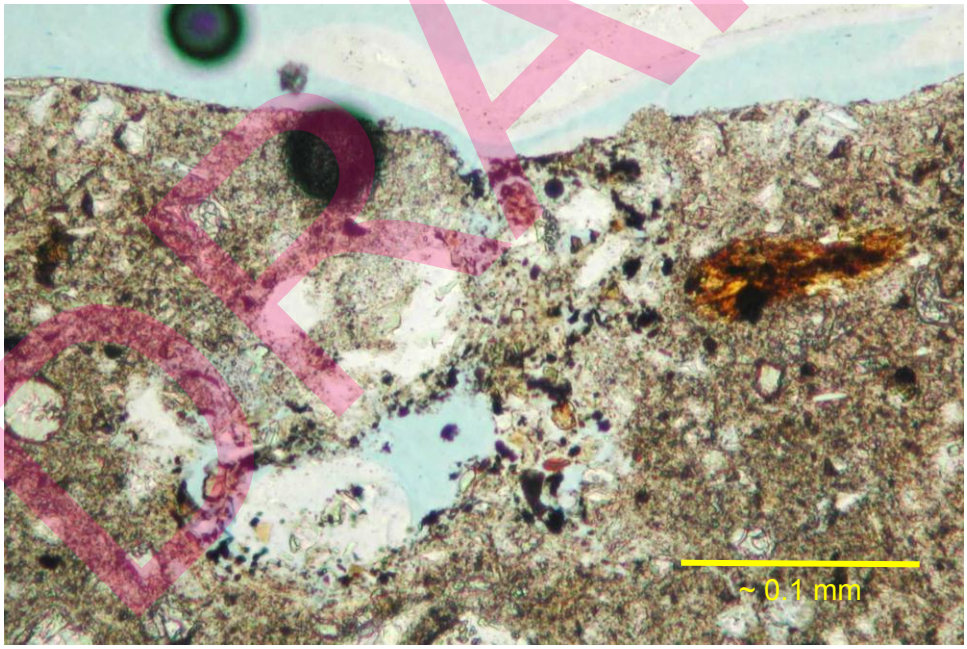


9a. The red-dashed circle shows an area of many brown-black particulates, which have accumulated beneath two small aggregate particles (blue X's), and which extend up to the concrete top surface (blue arrow).



9b. Midportion of image shows a permeable area within the near-surface region of the concrete, either porous paste or void space, which is intermittently lined (spotted) with small brown-black particulates. The particulates may be debris derived externally or may be left behind from pore water dissipation.

Fig. 9 Thin section photomicrographs of Core 6, showing cross-sectional views through near-surface regions of the concrete. Plane-polarized light.

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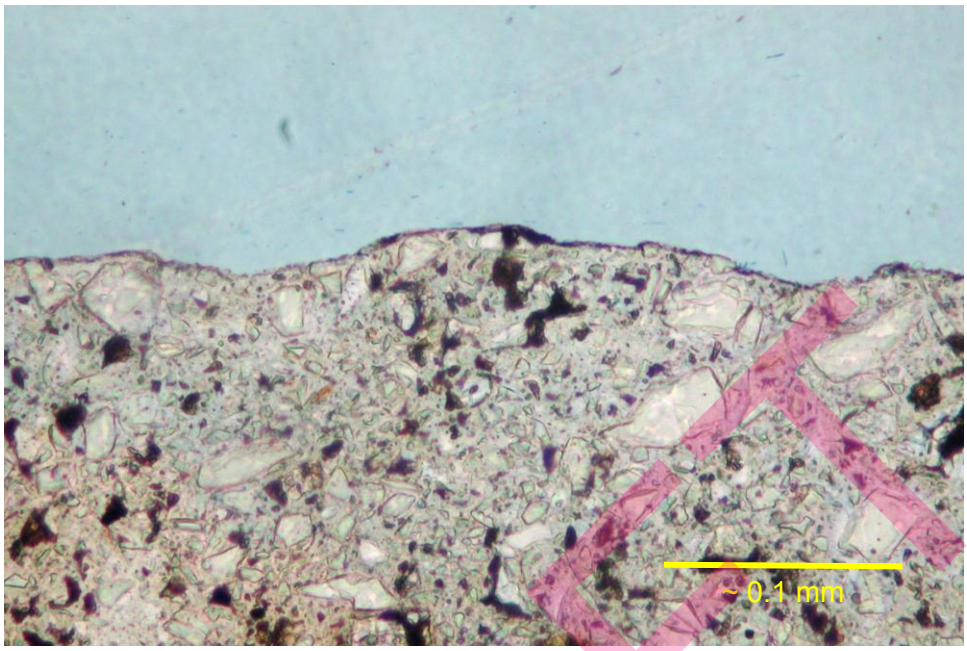
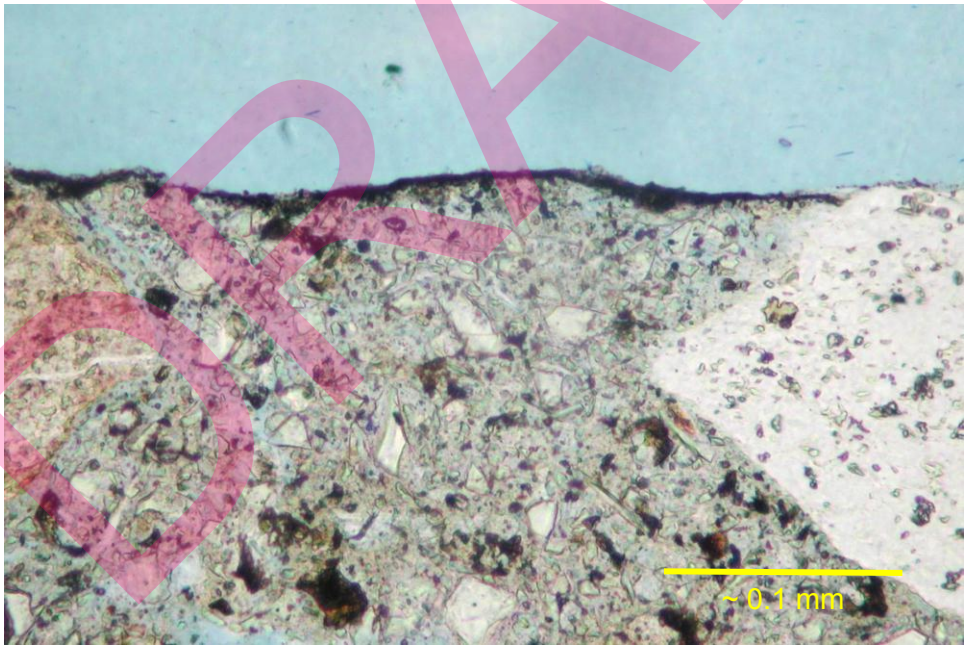


10a.



10b.

Fig. 10 Thin section photomicrographs of Core 9, showing cross-sectional views through near-surface regions of the concrete. Here, the brown-black material appears as a coating on the concrete surface. Plane-polarized light.

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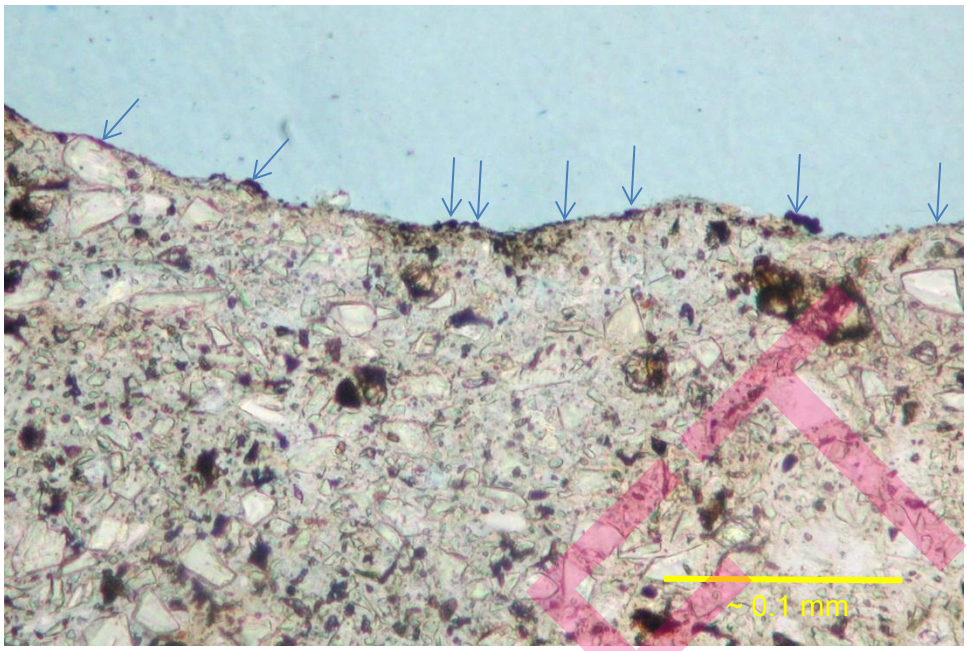
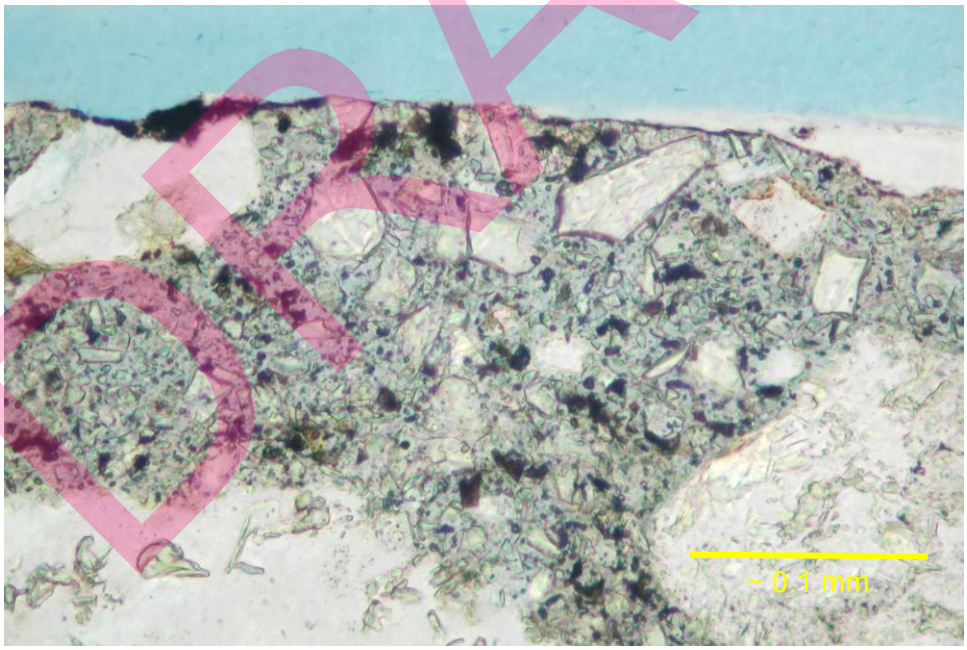


11a. Arrows show brown-black particulates that are perched on top of the concrete surface, suggesting they originated from an external source from the concrete mixture.



11b.

Fig. 11 Thin section photomicrographs of Core 9, showing cross-sectional views through near-surface regions of the concrete. Brown-black material appears embedded into, accumulating at, or perched on top of, the concrete top surface. Plane-polarized light.

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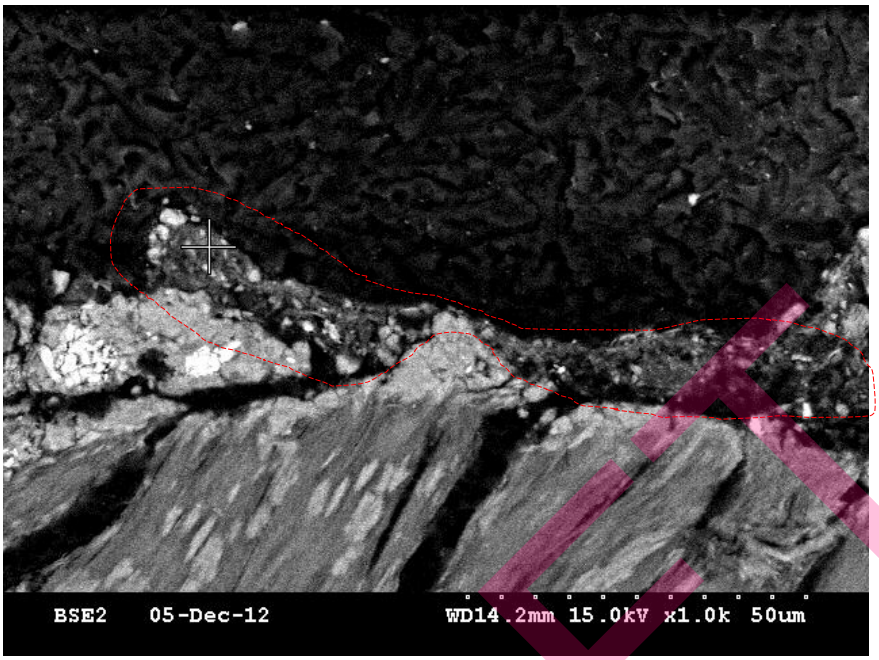
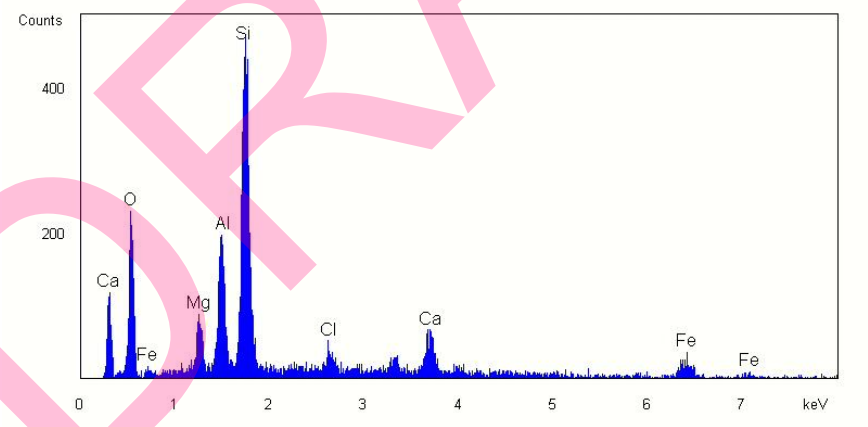


12a. Backscattered electron image, showing the area (marked by +) on which the analysis was performed. The red dashed circle roughly demarks the brown-black material on the concrete surface.



12b. Elemental composition of the area analyzed in Fig. 12a.

Fig. 12 SEM analysis results from Core 2, from the brown-black material on the concrete top surface.

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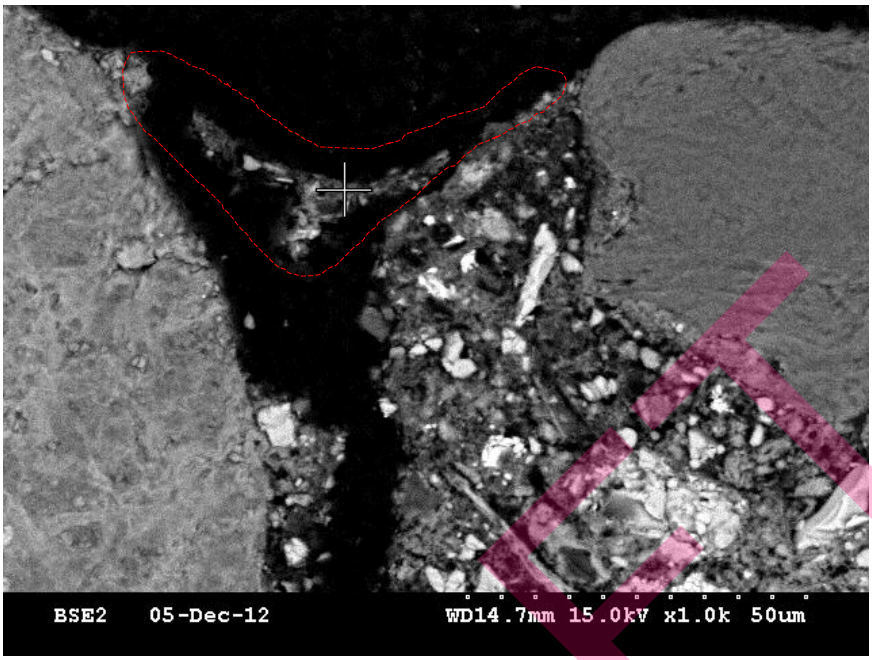
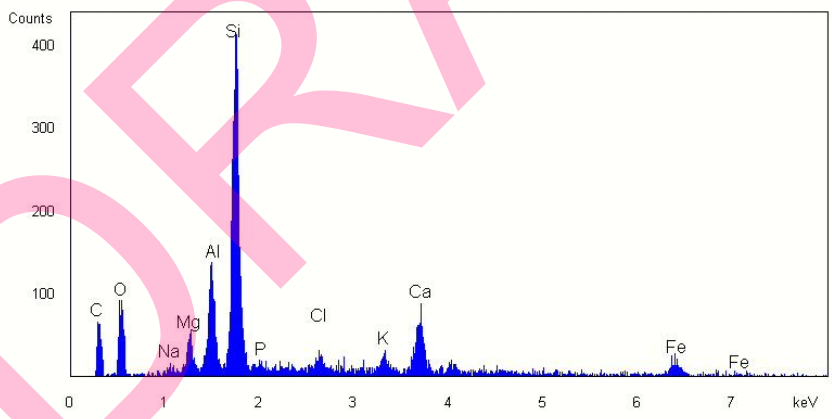


13a. Backscattered electron image, showing the area (marked by +) on which the analysis was performed. The red dashed circle roughly demarks the brown-black material on the concrete surface.



12b. Elemental composition of the area analyzed in Fig. 13a.

Fig. 13 SEM analysis results from Core 9, from the brown-black material on the concrete top surface.

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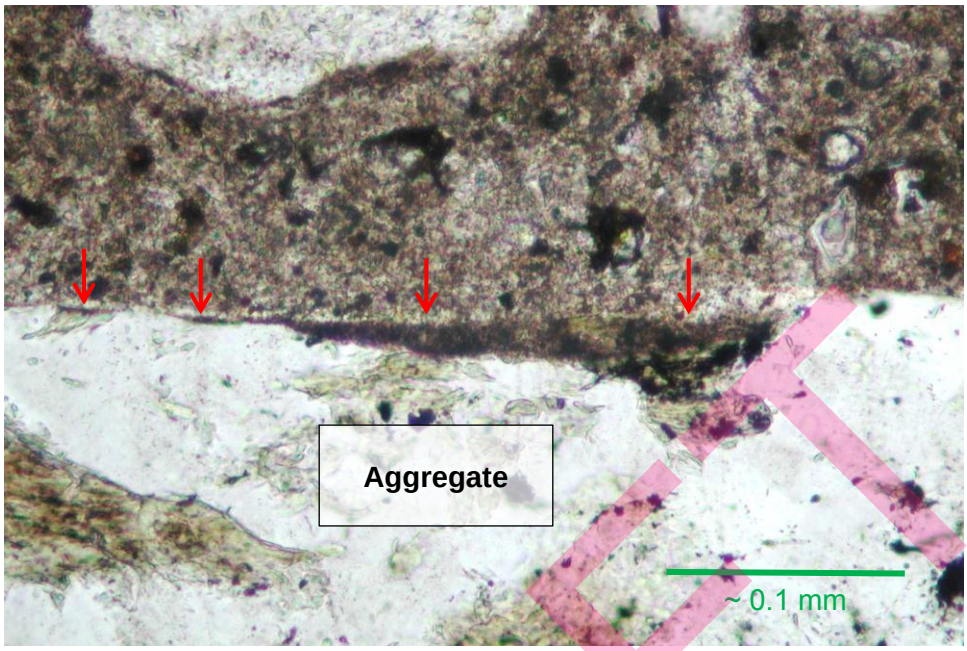
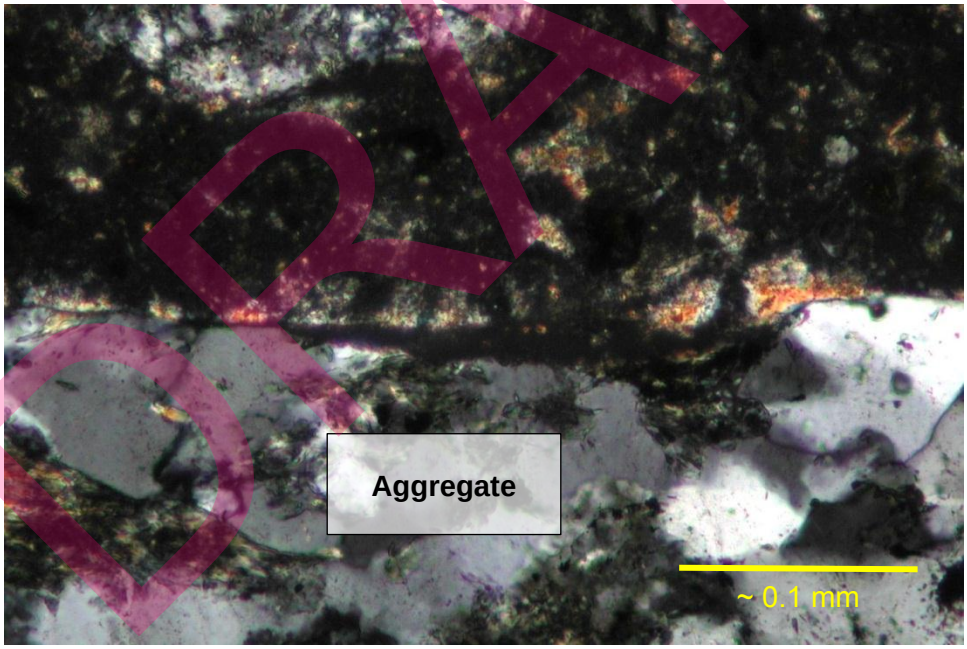


14a. Plane-polarized light.



14b. Crossed-polarized light. The bright-colored calcium hydroxide crystals (product of cement hydration) begin at the brown-black material, indicating this zone does not contain cement but only the brown-black material.

Fig. 14 Thin section photomicrographs of Core 6, illustrating a dark brown to black material (arrows), partially coating an aggregate particle. Both images show the same field of view but under different lighting.

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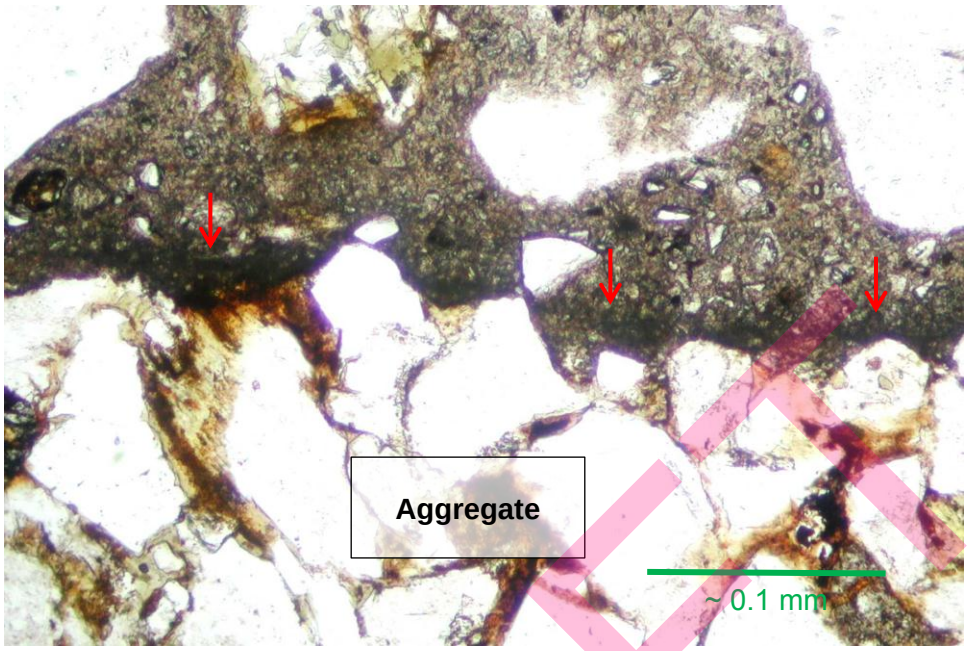
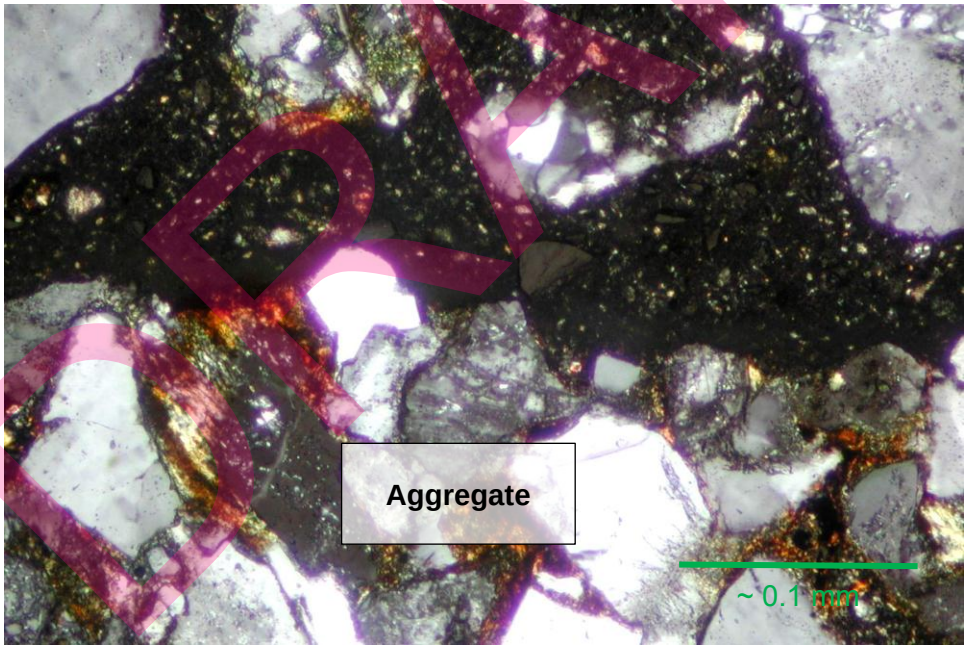


15a. Plane-polarized light.



15b. Crossed-polarized light. The dark brown-black material is noncrystalline and opaque.

Fig. 15 Thin section photomicrographs of Core 9, illustrating a dark brown to black material (arrows), partially coating an aggregate particle. Both images show the same field of view but under different lighting.

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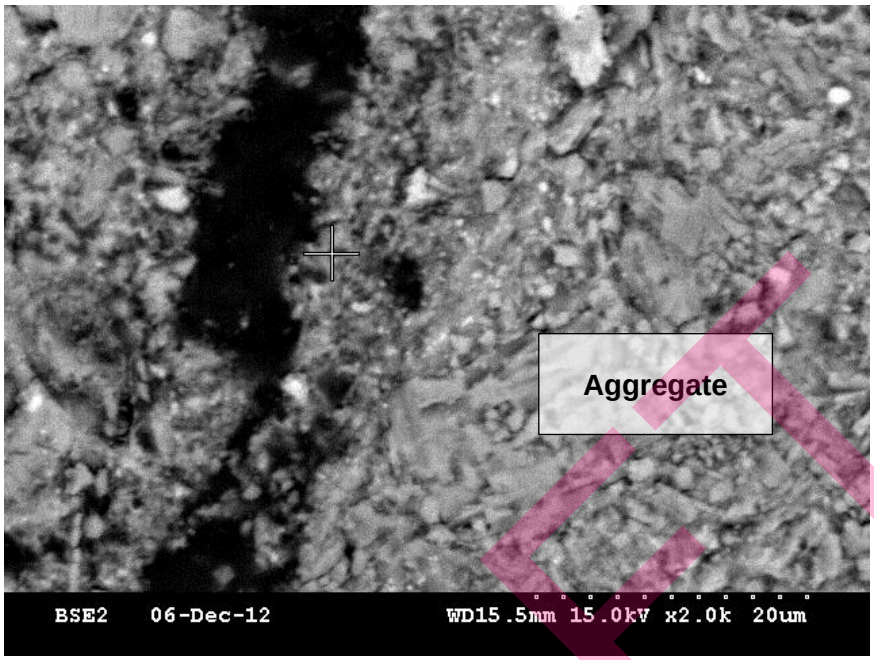
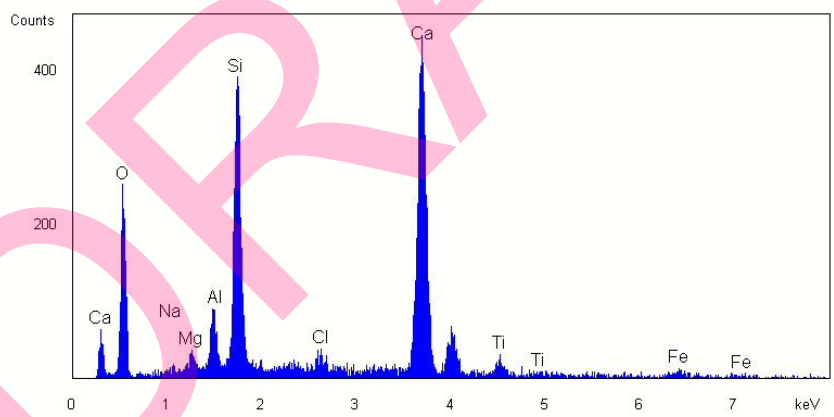


16a. Backscattered electron image, showing the area (marked by +) on which the analysis was performed.



16b. Elemental composition of the area analyzed in Fig. 16a.

Fig. 16 SEM analysis results from Core 6, from the brown-black material along an aggregate particle within the concrete.

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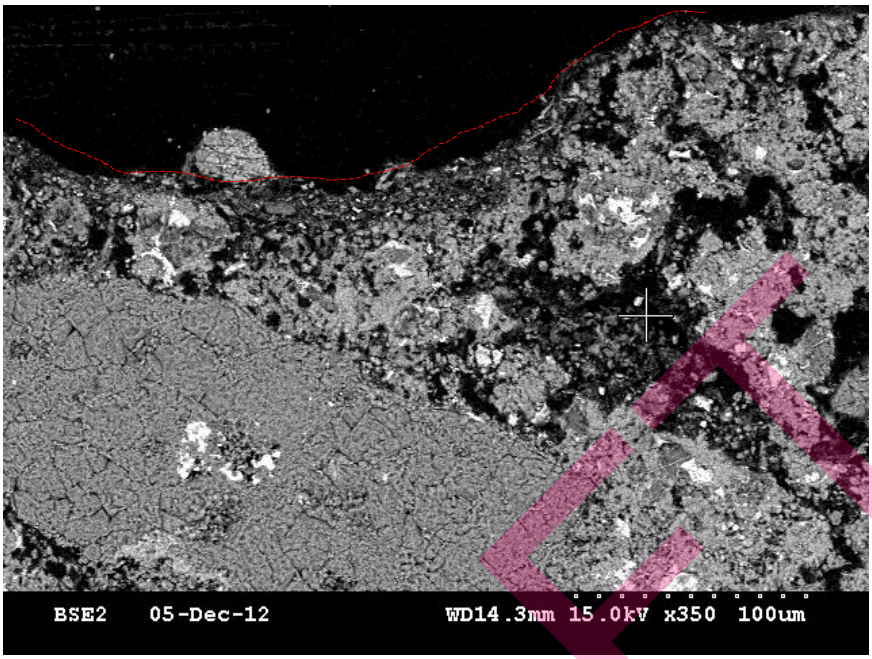
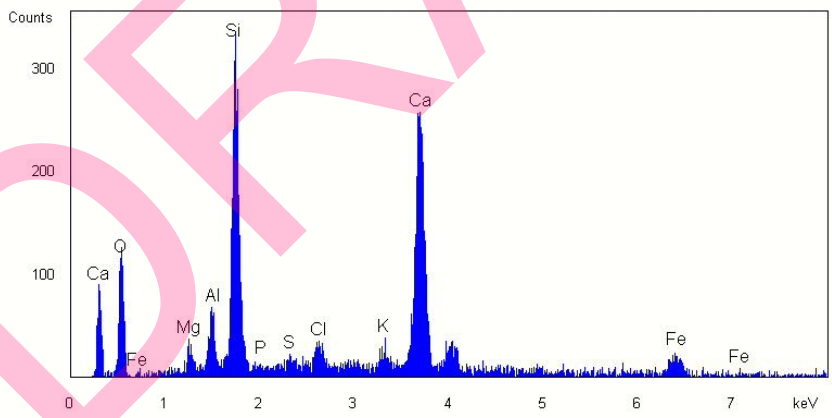


17a. Backscattered electron image, showing the area (marked by +) on which the analysis was performed. The red dashed line roughly demarks the concrete top surface.



17b. Elemental composition of the area analyzed in Fig. 17a.

Fig. 17 SEM analysis results from Core 2, from the brown-black material within the near-surface paste region of the concrete.

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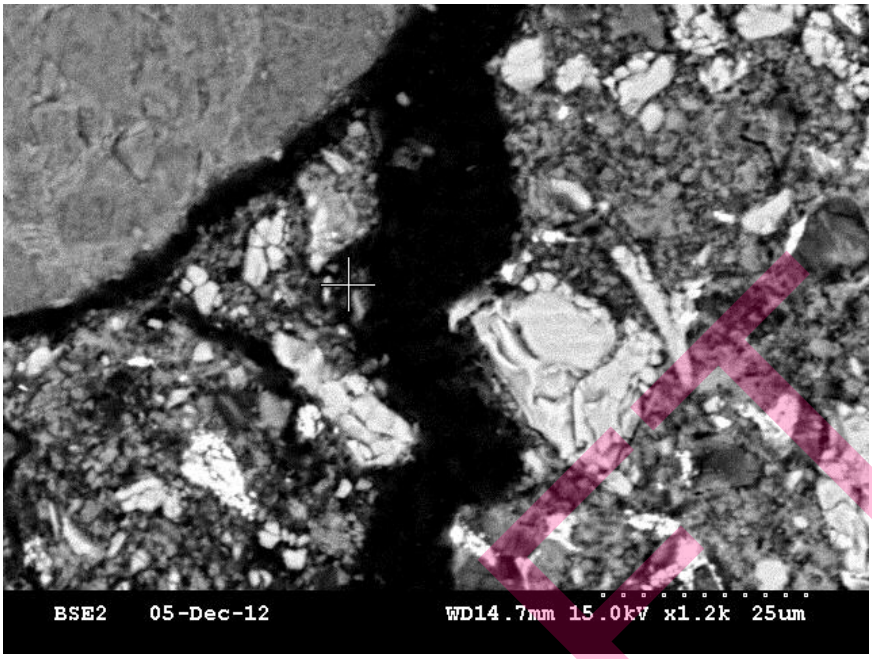
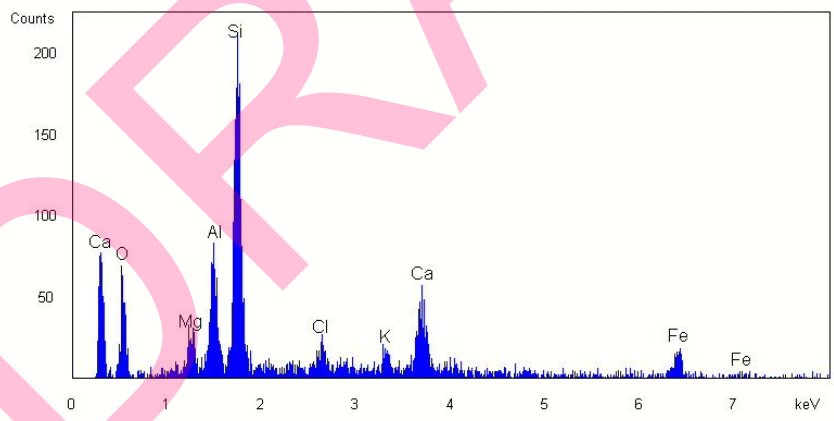


18a. Backscattered electron image, showing the area (marked by +) on which the analysis was performed. The black vertical gap is a microcrack.



18b. Elemental composition of the area analyzed in Fig. 18a.

Fig. 18 SEM analysis results from Core 9, from the brown-black material within the near-surface paste region of the concrete.

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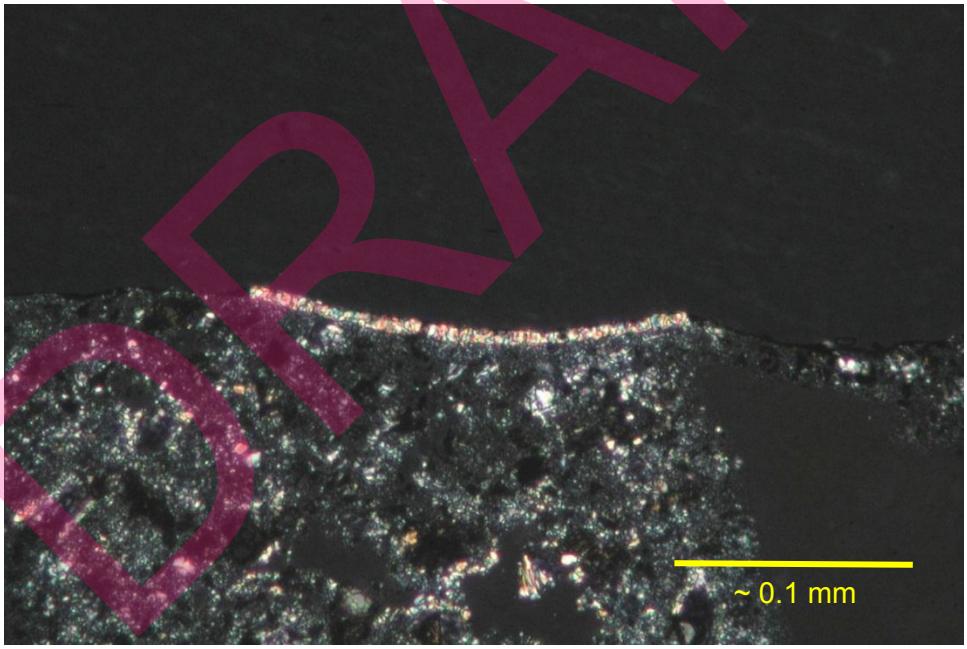
19a. Plane-polarized light.



19b. Crossed-polarized light.

Fig. 19 Thin section photomicrographs of Core 2, showing a cross-sectional view of the top portion of concrete. A small amount of a thin crystalline coating (arrows) is present very intermittently across the top surface of Core 2. Both images show the same field of view but under different lighting.

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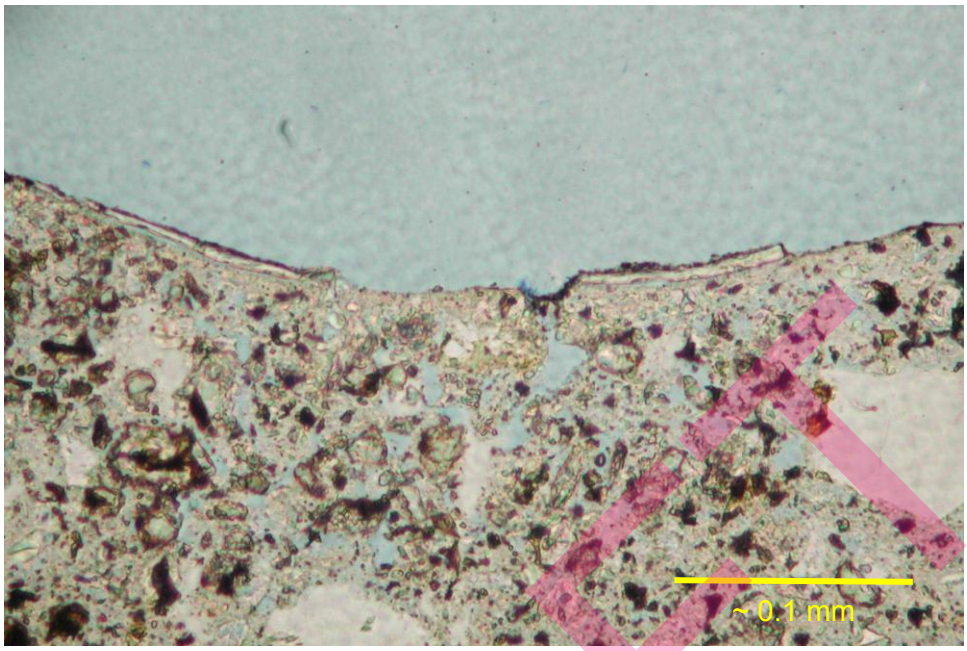
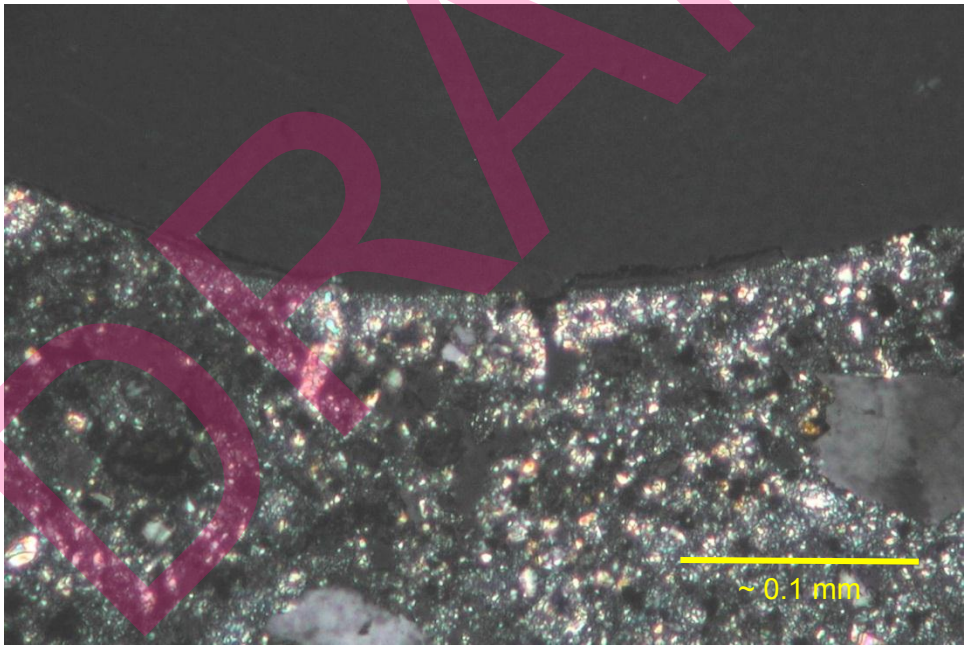


20a. Plane-polarized light.



20b. Crossed-polarized light. The coating is noncrystalline and amorphous.

Fig. 20 Thin section photomicrographs of Core 2, showing a cross-sectional view of the top portion of concrete. Fractured remnant pieces of a clear coating are intermittently present across the concrete top surface, two pieces of which are present in the images. Brown-black layer covers the coating. Both images show the same field of view but under different lighting.

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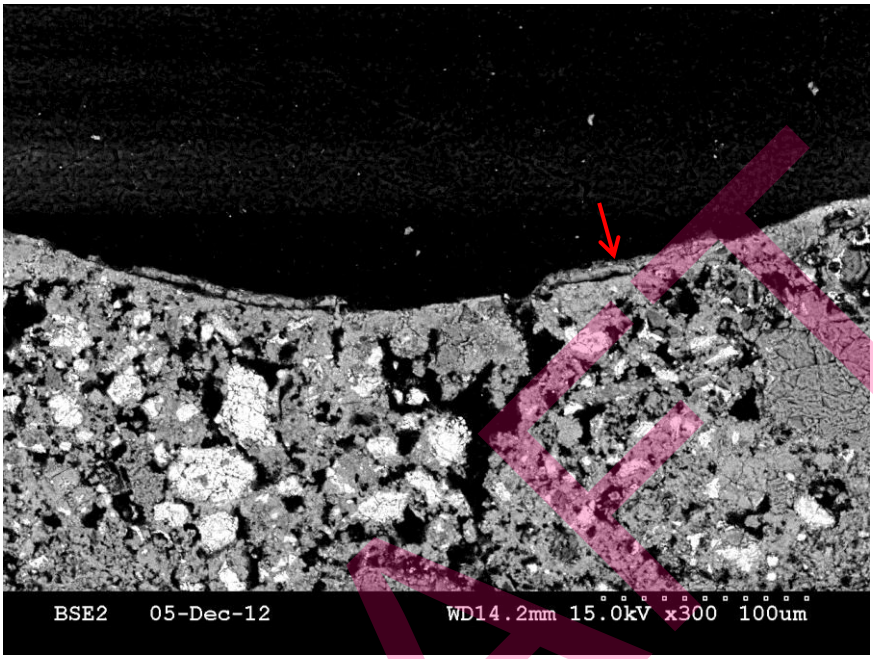
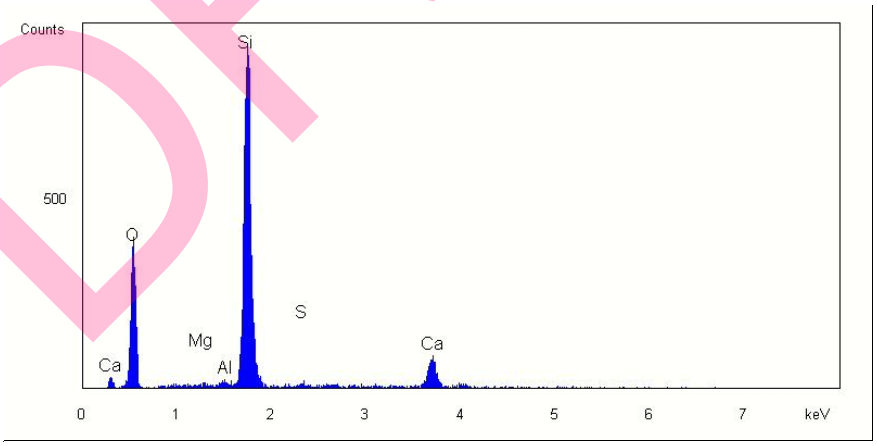


21a. Backscattered electron image, showing the area on which the analysis was performed. It is the same area shown in Fig. 20. The red arrow depicts the region of clear coating on which the SEM analysis was performed.



21b. Elemental composition of the area analyzed in Fig. 21a.

Fig. 21 SEM analysis results from Core 2, from the clear coating on the concrete top surface.

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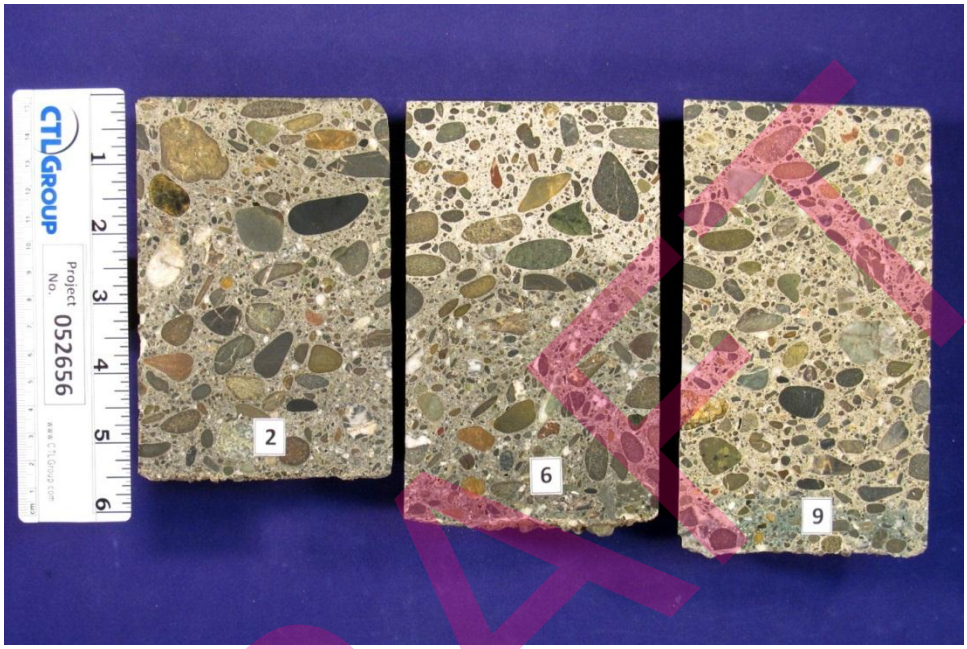

Fig. 22 Lapped, cross-sectional (longitudinal) surfaces of Cores 2, 6, and 9.

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PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C856

STRUCTURE: Concrete Pavement Slab *DATE RECEIVED*: 11/02/12

LOCATION: Davis, California *EXAMINED BY*:

SAMPLE

Client Identification: 2.

CTLGroup Identification: 3260302.

Dimensions: Core diameter = 94 mm (3.7 in.). Core length = 140 mm (5.5 in.); full slab thickness.

Top End:

Macroscopical Appearance: Broom-finished concrete surface. Satin-like luster. Overall color of surface is medium gray.

Microscopical Appearance through Stereomicroscope (Magnification Up to 40X): Paste is bicolored medium gray and dark gray. Colors follow the length of the broom striations: 1) medium gray color is present in the troughs of the broom finish; 2) dark gray is present on crests of the broom finish. Appears to be one or two very thin coatings.

Microscopical Appearance in Thin Section (Magnification Up to 400X): Three layers and/or coatings of material are present on the concrete top surface. In the thin section prepared from the concrete the three materials do not ever definitively occur together. In a few locations the dark brown or black material appears to possibly very thinly coat the other two layers in a few locations; however, the coating is so thin, it is not distinct or definitive.

1. Dark brown to black material. It is present as a somewhat intermittent layer or coating of material across the concrete top surface, as well as embedded into the concrete paste. It is very thin (generally about 5-µm thick [0.005-mm thick, 0.0002-in. thick]), noncrystalline, opaque, and appears as small specks grouped together (pigment-like).
2. Crystalline material. It is present in only a few small areas of the concrete top surface. It may be a secondary deposit. It is very thin (generally about 5- to 7-µm thick [0.005- to 0.007-mm thick, 0.0002- to 0.003-in. thick]), crystalline, and a well-defined layer.
3. Clear layer or coating. It is present as several short, broken remnant pieces of a coating across the top of the concrete surface. It is very thin (generally about 3- to 5-µm thick [0.003- to 0.005-mm thick, 0.0001- to 0.0002-in. thick]), noncrystalline, and amorphous.

Bottom End: Gravel and subbase material embedded into concrete bottom surface.

Cracks, Joints, Large Voids: None observed.

Reinforcement: None observed.

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AGGREGATES

Coarse: Natural gravel composed of a wide variety of rock types, mainly quartz-rich metamorphic rocks, including metaquartz, metasandstone, and schist. The quartz is commonly strained, microcrystalline to cryptocrystalline, with some glassy quartz present. Also present are volcanic particles, with phenocrysts of microcrystalline to glassy quartz; volcanic particles with feldspar laths and microcrystalline to glassy quartz; particles of metabasalt, some of which contain microcrystalline to glassy quartz; several clay-cemented siltstone or possibly claystone, which contain many grains of cryptocrystalline quartz,

Fine: Quartz-rich sand, composed of rock and mineral types as in the coarse aggregate.

Gradation & Top Size: Visually appears evenly graded to an observed top size of 23 mm (0.9 in.).

Shape, Texture, Distribution: Coarse- Rounded to subrounded, with a few particles to subangular, and generally equant to slightly elongated in shape; smooth to irregular texture; uniform distribution. Fine- Rounded to angular in shape; smooth to irregular texture; uniform distribution.

PASTE

Color: Dark gray color on concrete top surface is to a negligible depth; below this, paste in next underlying 25 mm (1 in.) is medium-light gray; below this, remainder of paste is light-medium gray.

Hardness: Paste on concrete top surface is hard to a negligible depth; below this, paste in next underlying 25 mm (1 in.) is moderate to moderately hard; below this, remainder of paste is hard to moderately hard.

Luster: Subvitreous.

Paste-Aggregate Bond: Moderately weak. When struck with a geology hammer in the laboratory, the concrete fractured around the majority of coarse aggregate particles.

Air Content: Estimated at 1.5 to 2.5%. The concrete is not air-entrained.

Depth of Carbonation: Paste in top 0.3 to 0.8 mm (0.01 to 0.03 in.) from concrete surface is not carbonated; below this, paste is carbonated to a concrete depth of 1.5 mm (0.06 in.); paste in next underlying 1.5 mm (0.06 in.) is partially carbonated.

Calcium Hydroxide*: Estimated 12 to 18%; coarsely crystalline.

Residual Portland Cement Clinker Particles*: Estimated 11 to 15%.

Supplementary Cementitious Materials: None observed.

Secondary Deposits: For all intents and purposes, none present.

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*percent by volume of paste

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MICROCRACKING: A few microcracks are present on the concrete top surface, extending vertically into the concrete to depths of 2 to 4 mm (0.08 to 0.16 in.), passing around aggregate particles.

ESTIMATED WATER-CEMENT RATIO: Not estimated, due to undifferentiated/unidentified particulates throughout paste. However, based on the physical paste and concrete properties, considered moderately low.

MISCELLANEOUS:

1. A blue-pigmented, low-viscosity epoxy was applied to the concrete surface, which absorbed into the paste to a depth of 0.3 to 0.8 mm (0.01 to 0.03 in.).

2. Several small areas of very fine debris-like material are present along both coarse and fine aggregate particles. The material is dark brown to black, noncrystalline, and opaque.

3. Very small brown-black particulates are common throughout the paste. Some appear to be ferrite from the cement. Others do not appear to be ferrite and are unidentified.

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PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C856

STRUCTURE: Concrete Pavement Slab *DATE RECEIVED*: 11/02/12

LOCATION: Davis, California *EXAMINED BY*:

SAMPLE

Client Identification: 6.

CTLGroup Identification: 3260306.

Dimensions: Core diameter = 94 mm (3.7 in.). Core length = 157 mm (6.2 in.); full slab thickness.

Top End:

Macroscopical Appearance: Flat, smooth, with slight straight striations, concrete surface. Light-medium gray; dull luster. Randomly-oriented microcracks are slightly common.

Microscopical Appearance through Stereomicroscope (Magnification Up to 40X): Same appearance as *Macroscopical Appearance*. Also, slightly common randomly-oriented microcracks are observed.

Microscopical Appearance in Thin Section (Magnification Up to 400X): Two, possibly three, layers and/or coatings of material are present on the concrete top surface. The dark brown to black material is commonly observed layered on top of the crystalline material.

1. Dark brown to black material. It is present as a somewhat intermittent layer or coating of material across the concrete top surface, as well as embedded or accumulated into the concrete paste. It is very thin (generally about 2- to 3-µm thick [0.002- to 0.003-mm thick, 0.00008- to 0.0002-in. thick]), noncrystalline, opaque, and appears as small specks grouped together (pigment-like).
2. Crystalline material. It is present intermittently across of the concrete top surface. It may or may not be a secondary deposit. It is very thin (generally about 5-µm thick [0.005-mm thick, 0.0002-in. thick]), crystalline, and not a well-defined layer.
3. Possibly a clear layer or coating. A defined, intermittent gap is present between the concrete top surface and the blue epoxy used to prepare the thin section. The gap is defined by a microscopical amount of debris on the top of the gap (at the gap-blue epoxy interface). The gap is very thin (generally about 2-µm thick [0.002-mm thick, 0.00008-in. thick]), clear, and amorphous. No areas are present in the thin section that definitively identifies the gap as a clear coating.

Bottom End: Gravel and subbase material embedded into concrete bottom surface.

Cracks, Joints, Large Voids: None observed.

Reinforcement: None observed.

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AGGREGATES

Coarse: Natural gravel composed of a wide variety of rock types, mainly quartz-rich metamorphic rocks, including metaquartz, metasandstone, and schist. The quartz is commonly strained, microcrystalline to cryptocrystalline, with some glassy quartz present. Also present are volcanic particles, with phenocrysts of microcrystalline to glassy quartz; volcanic particles with feldspar laths and microcrystalline to glassy quartz; particles of metabasalt, some of which contain microcrystalline to glassy quartz; several clay-cemented siltstone or possibly claystone, which contain many grains of cryptocrystalline quartz,

Fine: Quartz-rich sand, composed of rock and mineral types as in the coarse aggregate.

Gradation & Top Size: Visually appears evenly graded to an observed top size of 19 mm (0.75 in.).

Shape, Texture, Distribution: Coarse- Rounded to subrounded, with a few particles to subangular, and generally equant to slightly elongated in shape; smooth to irregular texture; uniform distribution. Fine- Rounded to angular in shape; smooth to irregular texture; uniform distribution.

PASTE

Color: Light-medium gray color on concrete top surface is to a negligible depth; below this, paste in next underlying 50 mm (2 in.) is very light gray; below this, remainder of paste is light-medium to medium gray.

Hardness: Paste on concrete top surface is hard to a negligible depth; below this, paste in next underlying 50 mm (2 in.) is moderate to possibly moderately hard; below this, remainder of paste is hard.

Luster: Paste in top 50 mm (2 in.) is somewhat dull; below this, remainder of paste is vitreous.

Paste-Aggregate Bond: Weak. When struck with a geology hammer in the laboratory, the concrete fractured around almost all of the coarse aggregate particles.

Air Content: Estimated at 1.5 to 2.5%. The concrete is not air-entrained.

Depth of Carbonation: Paste in top 0.25 mm (0.01 in.) from concrete surface is not carbonated; below this, paste is carbonated to a concrete depth of 2 mm (0.08 in.); paste in next underlying 1.5 to 2 mm (0.06 to 0.08 in.) is partially carbonated.

Calcium Hydroxide*: Estimated 8 to 13%; medium crystallinity.

Residual Portland Cement Clinker Particles*: Estimated 6 to 9%. Distinct hydration rims are common.

Supplementary Cementitious Materials: None observed.

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*percent by volume of paste

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Secondary Deposits: For all intents and purposes, none present.

MICROCRACKING: Some microcracks are present on the concrete top surface, extending vertically into the concrete to depths of 1 to 6 mm (0.04 to 0.24 in.), passing around aggregate particles. A shallow, horizontal microcrack is present, forming incipient scaling of a 13-mm-long (0.5-in.-long) section of the concrete top surface, to a depth of 0.2 to 0.3 mm (0.008 to 0.012 in.).

ESTIMATED WATER-CEMENTITIOUS MATERIALS RATIO: Not estimated, due to undifferentiated/unidentified particulates throughout paste.

MISCELLANEOUS:

1. A blue-pigmented, low-viscosity epoxy was applied to the concrete surface, which absorbed into the paste to a depth of 0.25 mm (0.01 in.).

2. Several small areas of very fine debris-like material are present along both coarse and fine aggregate particles. The material is dark brown to black, noncrystalline, and opaque.

3. Very small brown-black particulates are common throughout the paste. Some appear to be ferrite from the cement. Others do not appear to be ferrite and are unidentified.

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PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C856

STRUCTURE: Concrete Pavement Slab *DATE RECEIVED*: 11/02/12

LOCATION: Davis, California *EXAMINED BY*:

SAMPLE

Client Identification: 9.

CTLGroup Identification: 3260309.

Dimensions: Core diameter = 94 mm (3.7 in.). Core length = 155 mm (6.1 in.); full slab thickness.

Top End:

Macroscopical Appearance: Flat, with light straight striations, possibly a light broom-finished, concrete surface. Satin-like luster. Paste's overall color is medium gray.

Microscopical Appearance through Stereomicroscope (Magnification Up to 40X): Paste is bicolored light-medium gray and medium-dark gray. Colors follow the length of the finishing striations: 1) light-medium gray color present in the troughs of the broom finish; 2) medium-dark gray on crests of the broom finish. Appears to be a very thin coating.

Microscopical Appearance in Thin Section (Magnification Up to 400X): Two layers and/or coatings of material are present on the concrete top surface. In the thin section prepared from the concrete the two materials do not ever definitively occur together.

1. Dark brown to black material. It is present across most of the concrete top surface in the thin section, as well as partially embedded into the concrete paste in a few areas. It is very thin (generally about 3- to 7-µm thick [0.003- to 0.007-mm thick, 0.0001- to 0.003-in. thick]), noncrystalline, opaque, and appears as small specks grouped together (pigment-like).
2. Crystalline material. It is present in only a very few, very small areas of the concrete top surface. It may be a secondary deposit. It is very thin (generally about 3- to 5-µm thick [0.003- to 0.005-mm thick, 0.0001- to 0.002-in. thick]), crystalline, and a well-defined layer.

Bottom End: Gravel and subbase material embedded into concrete bottom surface.

Cracks, Joints, Large Voids: None observed.

Reinforcement: None observed.

AGGREGATES

Coarse: Natural gravel composed of a wide variety of rock types, mainly quartz-rich metamorphic rocks, including metaquartz, metasandstone, and schist. The quartz is commonly strained, microcrystalline to cryptocrystalline, with some glassy quartz present. Also present are volcanic particles, with phenocrysts of microcrystalline to glassy quartz;

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volcanic particles with feldspar laths and microcrystalline to glassy quartz; particles of metabasalt, some of which contain microcrystalline to glassy quartz; several clay-cemented siltstone or possibly claystone, which contain many grains of cryptocrystalline quartz,

Fine: Quartz-rich sand, composed of rock and mineral types as in the coarse aggregate.

Gradation & Top Size: Visually appears evenly graded to an observed top size of 19 mm (0.75 in.).

Shape, Texture, Distribution: Coarse- Rounded to subrounded, with a few particles to subangular, and generally equant to slightly elongated in shape; smooth to irregular texture; uniform distribution. Fine- Rounded to angular in shape; smooth to irregular texture; uniform distribution.

PASTE

Color: Medium gray color on concrete top surface is to a negligible depth; below this, paste in next underlying 25 mm (1 in.) is pale buff; below this, remainder of paste is mottled light beige and medium beige.

Hardness: Paste on concrete top surface is moderately hard to moderate to a negligible depth; below this, paste in next underlying 3 mm (0.12 in.) is soft; below this, paste is moderately soft, grading to moderately hard by a concrete depth of approximately 25 mm (1 in.); remainder of paste is moderately hard.

Luster: Paste in top 1 inch of core is fairly dull; below this, paste is subvitreous.

Paste-Aggregate Bond: Weak. When struck with a geology hammer in the laboratory, the concrete fractured around almost all of the coarse aggregate particles.

Air Content: Estimated at 1.5 to 3%. The concrete is not air-entrained.

Depth of Carbonation: Paste in top 0.5 to 1.25 mm (0.02 to 0.05 in.) of concrete is not carbonated; below this, paste is carbonated to a concrete depth of top 4 mm (0.16 in.).

Calcium Hydroxide*: Estimated 3 to 8%; finely crystalline.

Residual Portland Cement Clinker Particles*: Estimated 7 to 8%. Much ferrite is present.

Supplementary Cementitious Materials: Slag cement present; appears to be in a large amount.

Secondary Deposits: For all intents and purposes, none present.

MICROCRACKING: A few microcracks are present on the concrete top surface, extending vertically into the concrete to depths of 4 mm (0.16 in.), passing around aggregate particles.

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*percent by volume of paste

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ESTIMATED WATER-CEMENTITIOUS MATERIALS RATIO: Not estimated, due to undifferentiated/unidentified particulates throughout paste.

MISCELLANEOUS:

1. A blue-pigmented, low-viscosity epoxy was applied to the concrete surface in the CTLGroup laboratories, which absorbed into the paste to a depth of 0.1 to 1.25 mm (0.004 to 0.05 in.).

2. Several small areas of very fine debris-like material are present along both coarse and fine aggregate particles. The material is dark brown to black, noncrystalline, and opaque.

3. Very small brown-black particulates are present throughout the paste. Some appear to be ferrite from the cement. Others do not appear to be ferrite and are unidentified.

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APPENDIX C:
Local Government: Cool Pavements

Local Government: Cool Pavements

Content contributed by Heat Island Group, Lawrence Berkeley National Laboratory

If you've ever tried to cross an asphalt parking lot barefoot on a summer day, you know that paved surfaces can get hot. Traditional pavements get hot in the sunshine and warm the surrounding air in cities, especially during summers. This effect intensifies the summer urban heat island effect, which has negative impacts for health, comfort, energy use, air quality, and greenhouse gas emissions.

A "cool" pavement, however, absorbs less sunlight and stays cooler. As a result, less heat is transferred to the surrounding air, which helps communities remain cooler on hot days.

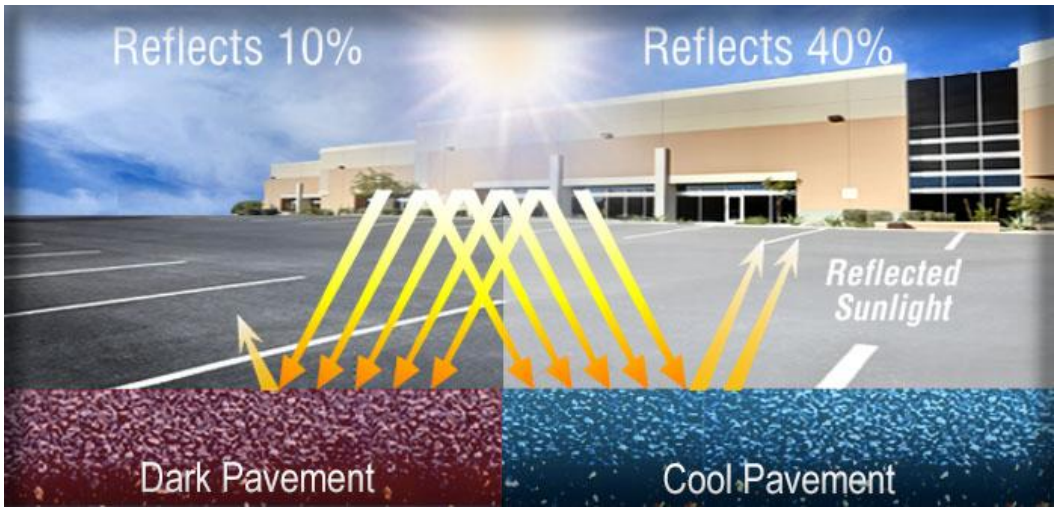

Figure 1. *Cool pavements reflect more sunlight than conventional dark pavements and are able to stay cooler in the sun (source: LBNL-Heat Island Group)*

Because pavements cover around one-third of urban surface area in most cities,[1] switching to cool pavements is particularly important for reducing summertime urban temperatures. This can help communities keep cool, reduce energy usage and greenhouse gas emissions, improve air and water quality, and maintain pavement quality.

Learn more about cool pavements:

- Explore the science of cool pavements in **Cool Pavements:** How they work
- Discover the many **Cool** Pavements: Benefits of cool pavements
- Learn what **Cool Pavements:** Codes and standards may apply to your paving project
- Find implementation tools and see what others have done in **Cool Pavements**:

[1] Akbari H, Rose LS, Taha H. 1999. Characterizing the fabric of the urban environment: A case study of Sacramento, California. Lawrence Berkeley National Laboratory report No. LBNL-44688. Berkeley, CA.

Cool Pavements: How they work

Pavements are truly more than meets the eye. While drivers and pedestrians only see the pavement surface, a typical city street can extend about a 1 ½ feet (half a meter) below the surface. The surface layer is very strong and designed to withstand the destructive effects of weather and traffic. The lower layers are weaker than the surface layer but are designed to spread the heavy traffic loads out over the base soil. The surface and base layers are often made out of the same rock and sand, but the upper layers typically use cement or asphalt to bind the rock together. Together, these layers are designed to work as a unit to support various traffic loads in all weather and on all soil types.

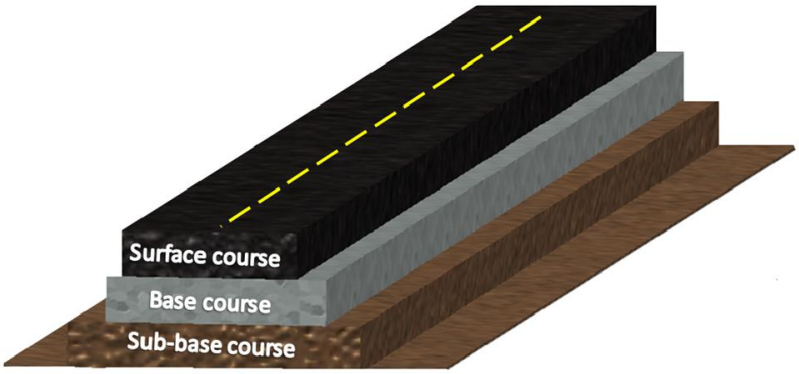

Figure 2. *A representative roadway pavement system, consisting of surface, base, and sub-base layers (source: LBNL-Heat Island Group)*

"Cooling" the pavement surface

While pavement systems can be quite thick, the top surface layer plays the largest role in determining how "cool" a pavement can be. This is because sunlight meets the surface before the subsurface layers, so the surface dictates how much sunlight is absorbed by the pavement. Like conventional dark roofs, dark pavements get hot in the sun because they absorb 80-95% of sunlight. Their surface temperatures can reach as high as 150°F (67°C), warming the air and contributing to the heat island effect.[2]

A "cool pavement" has a lower surface temperature and therefore transmits less heat to the surrounding air than traditional pavements, which keeps local temperatures lower. Pavements can keep cool by reflecting sunlight (See Figure 3). Solar reflectance, or albedo, is the percentage of sunlight that is reflected by a surface. Pavements with higher solar reflectance (measured between 0 and 1) reflect more sunlight, and thus have cooler surface temperatures. A solar reflectance of 1 (100%) means that the surface is a perfect reflector, while a solar reflectance of 0 (0%) means that the surface reflects no sunlight.

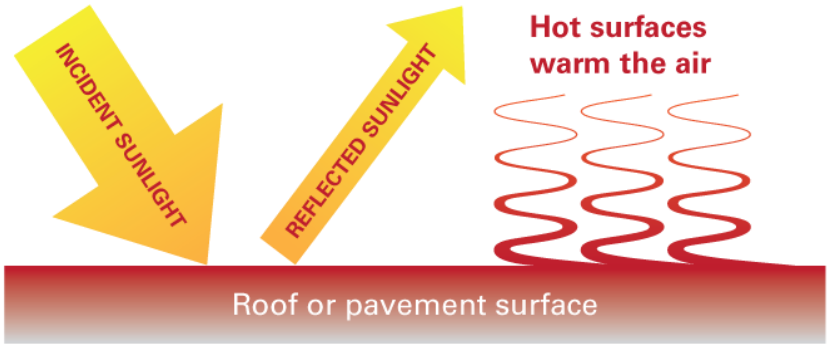

Figure 3. *Pavements radiate heat into the atmosphere when they absorb energy from the sun (source: LBNL-Heat Island Group)*

[2] US Environmental Protection Agency. 2008. "Cool Pavements." *Reducing Urban Heat Islands: Compendium of Strategies.* US EPA.

Aging of the pavement surface

Newly constructed asphalt concrete pavement has a solar reflectance of around 0.05 (5%), meaning that it absorbs 95% of the sunlight that reaches its surface, causing it to get very hot on a clear summer day. However, oxidation and wear and tear from vehicle traffic cause the dark binder of asphalt concrete pavement to dissipate over time. This leads to an increase in its solar reflectance of as much as 0.20 (20%) after seven years of use.[3] Once asphalt concrete has deteriorated to this extent, it typically requires resurfacing that has conventionally been done with dark materials that approximate the original appearance of the pavement. On the other hand, newly constructed cement concrete pavement has a solar reflectance of around 0.35 (35%), absorbing roughly 65% of the sunlight that reaches its surface. As cement concrete ages, it gets darker in color from vehicle traffic and soiling, with its solar reflectance decreasing to approximately 0.25 (25%) after five years of use.[4]

Aged asphalt concrete (left), new asphalt concrete (right)

Aged cement concrete (left), new cement concrete (right)

The role of subsurface pavement layers

While the pavement surface governs how much sunlight is absorbed by the pavement system, the subsurface layers also contribute to interactions between pavements and the natural environment. This is because hard, dense surfaces like pavements have high thermal mass, which enables them to retain heat effectively. When the pavement surface absorbs energy from the sun during the day, it transmits this energy to deeper pavement layers where it is stored as heat. Once the sun goes down, pavements release the heat they have accumulated throughout the day into the air, which can affect urban nighttime temperatures. Thus, if a pavement surface is more reflective it will transmit less heat into the subsurface pavement and will keep urban temperatures lower overnight.[5]

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[3] Tran N, Powell B, Marks H, West R, and Kvasnak A. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

[4] *Ibid.*

[5] Asaeda T and Ca VT. 1993. The subsurface transport of heat and moisture and its effect on the environment: a numerical model. *Boundary Layer Meteorology* 65: 159-179.

Cool pavements in practice

Many cities are exploring the adoption of cool pavements as a heat island reduction component of climate action and/or adaptation plans. Existing dark pavements can be made "cool" with the addition of surface treatments that reflect more sunlight. New roads can also be constructed using more reflective materials or with permeable paving materials, which keep pavements cooler by absorbing and subsequently evaporating water. In addition to pavement materials, shading from vegetation can keep pavements cooler by preventing the sunlight from being absorbed by the paved surface.

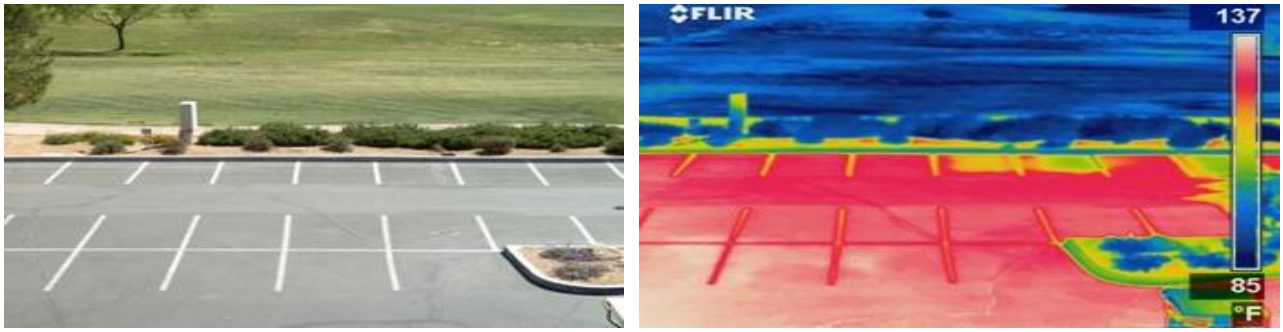

Figure 4. *Visible (left) and thermal infrared (right) images of a parking lot in Rio Verde, Arizona (source: Larry Scofield - APCA)*

Solar reflective pavements

Cities are increasingly finding that using light-colored materials for new pavements can keep their communities cooler throughout the life of the pavement.

When considering cool solutions for existing paved surfaces, cities can take advantage of routine pavement maintenance practices. Rather than applying a traditional asphalt seal coat or slurry seal to an existing pavement surface, cool surface treatments can repair the pavement surface while addressing the urban heat island effect. Cool surface treatments are available in a variety of materials (e.g., acrylic, cement, asphalt, rubber), for various paved surfaces (e.g., parking lots, residential streets, schoolyards), and a range of colors that can reflect more sunlight than dark asphalt. Another option to make existing pavement surfaces more reflective while repairing them is to use cement overlays (also called "whitetopping"), which places a thin layer of cement concrete over an existing asphalt surface.

Figure 5. *On a 72°F (23°C) June afternoon with no wind or clouds in Berkeley, CA, aged cement concrete (top right) was 21°F (11°C) cooler than new asphalt concrete (top left), and cool coatings (bottom four images) were as much as 31°F (17°C) cooler than the asphalt (source: LBNL-Heat Island Group)*

Permeable pavements

In addition to solar reflective pavements, permeable pavements are another class of cool pavements. Also called pervious or porous pavements, permeable pavements are designed to allow water to pass through pores between rocks. The pavements then channel this water either to recharge local groundwater or to appropriate stormwater infrastructure, thereby diminishing runoff that can cause sewer overflow and harm local watersheds.

As water passes through the pavement, some of it adheres to the pavement and eventually evaporates. Because water requires heat from the surrounding air to transform from its liquid phase to vapor, permeable pavements can cool the surface and surrounding air as water evaporates from pavement system.

When thinking about permeable pavements, it is important to consider that some regions have relatively dry summers. When moisture is scarce, permeable pavement systems retain less water and there is less evaporative cooling of the surrounding air. Therefore, permeable pavements may confer less of a local cooling benefit where there is little summer precipitation. It should also be noted that evaporation also occurs more slowly in humid conditions, so permeable pavements cool air less effectively on very humid days.

In addition, permeable pavements have been found to cool down faster at night because of the insulating property of the air voids in the pavement structure.[6] This could help with nighttime urban heat islands but will not be as effective at cooling during the late afternoon.

Shading

An alternate option to cooler pavement materials is to provide shading from vegetation or man-made structures over paved surfaces. Shading can reduce the temperature of paved surfaces by 20-45°F (11-25°C) relative to peak temperatures in unshaded areas.[7] A study in Davis, California found that cars parked in a shaded parking lot in the summer had interior air temperatures that were 45°F (25°C) cooler than cars parked in direct sunlight.[8]

Learn more about the other cooling benefits of urban vegetation here.

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[6] Stempihar, J., T. Pourshams-Manzouri, K. Kaloush, M.C. Rodezno. 2012. Porous Asphalt Pavement Temperature Effects for Urban Heat Island Analysis. Transportation Research Record: Journal of the Transportation Research Board,No. 2293, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 123–130.

[7] Akbari, H., D. Kurn, et al. 1997. Peak power and cooling energy savings of shade trees. *Energy and Buildings* 25:139–148. (EPA Heat Islands site: http://www.epa.gov/hiri/mitigation/trees.htm)

[8] Scott, K., J. Simpson, E. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions. Journal of Arboriculture 25(3):129-142

Cool Pavements: Benefits

Substituting cool pavements for traditional dark pavements can provide benefits locally and more broadly.

On the local level:

- During the day, solar reflective pavements absorb less solar energy, which leads to ***cooler outside air***.
- Cooler outdoor temperatures ***enhance outdoor comfort*** and ***improve public health*** by reducing heat stress and by slowing the formation of ground-level ozone, a primary component of smog.[9]
- Cooler outside conditions also allow air conditioners to cool buildings with less energy, leading to ***building energy and cost savings***.[10]
- By absorbing less energy over the course of a hot day, cool pavements trap less heat in the subsurface pavement layers and have less heat to dissipate at night, which allows cities to cool down after a hot day. During a heat wave, this can lead to ***reduced heat-related illness and mortality*** as vulnerable people return to a comfortable body temperature at night.[11]
- Light-colored pavements ***improve roadway safety*** by reflecting more light from streetlights and vehicle headlights, which enhances visibility at night; alternately, cool pavements can ***diminish the need for electric street lighting*** at night.[12]

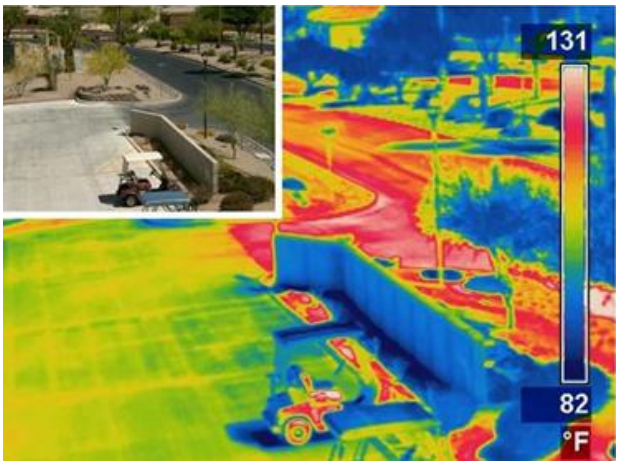

Figure 6. *Lighter-colored pavements stay cooler on hot summer days in Arizona. (source: ASU National Center of Excellence on SMART Innovations)*

Figure 7. *Flisvos Park in Athens, Greece installed 4500 m^2 of cool pavements, which decreased its peak air temperatures by 2°C (3.8°F) The white dotted lines around the park indicate the area of study. (source: Santamouris et al. 2012)*

[9] Akbari H, Pomerantz M, and Taha H. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70: 295-310.
[10] *Ibid.*
[11] Taha H, Hammer H, Akbari H. 2002. Meteorological and air quality impacts of increased urban surface albedo and vegetative cover in the greater Toronto area, Canada. Lawrence Berkeley National Laboratory report No. LBNL-49210. Berkeley, CA.
[12] Pomerantz M, Akbari H, and Harvey JT. 2000. Cooler reflective pavements give benefits beyond energy savings: durability and illumination. Lawrence Berkeley National Laboratory report No. LBNL-45370. Berkeley, CA.

- Cool pavements are ***more durable*** than conventional dark pavements; they deform less quickly and last longer owing to decreased absorption of solar energy over time.[13]
- By allowing water to pass through the pavement system, cool permeable pavements reduce water runoff, which leads to ***improved stormwater management***.[14]
- By staying cooler on hot days, whether through reflecting sunlight or permeability, cool pavements surfaces also keep stormwater cooler than dark pavements, which can ***lessen damage to local watersheds***.[15]

On a broader level:

- By saving energy on air conditioning use in nearby buildings and street lighting, cool pavements ***reduce power plant emissions*** of greenhouse gases and other air pollutants.[16]
- Reflective pavements decrease the amount of heat that is absorbed at the Earth's surface and thus lower surface temperature. This decrease in surface temperature reduces the transfer of heat into the atmosphere, which offsets a portion of the warming from greenhouse gases and thereby ***delays climate change***.[17]

Notes:

- It is important to keep in mind that these benefits vary depending on the solar reflectance value of the pavement system; typically, higher reflectance values confer greater benefits.
- While pavements that are lighter in color can confer the above benefits, there are limits to how light a paved surface should be; very bright pavements can produce glare that is unpleasant to pedestrians and dangerous to drivers.
- It is also important to consider shading from trees and buildings when making pavement decisions; a cool pavement is unlikely to generate a large benefit if it is in a well-shaded area. In cities, this applies particularly to architectural "urban canyons" and to areas near parks with tall trees.
- Pavements can be constructed using a wide range of materials—be sure to consider materials that are available locally to reduce the overall environmental impact of paving projects.
- While implementing cool pavements is a good first step, local entities that wish to capture significant cooling benefits should consider coupling cool pavements with cool roofs and vegetation. A cool community program/plan is most effective when combining these strategies to achieve maximum benefits. To learn more about cool roofs visit HERE and vegetation HERE.

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[13] *Ibid.*

[14] Booth D. and Leavit J. 1999. Field evaluation of permeable pavement systems for improved stormwater management. *Journal of the American Planning Association* 65(3): 314-325.

[15] James W and Shahin R. 1998. Pollutants leached from pavements by acid rain. In W. James (ed.), Advances in Modeling the Management of Stormwater Impacts. Vol. 6: 321-349. Guelph, Canada: Computational Hydraulics Int.

[16] *Supra* at 9.

[17] Akbari H, Menon S, and Rosenfeld A. 2009. Global cooling: increasing world-wide urban albedos to offset CO2. Climatic Change, 94 (3-4), 275-286.

Cool Pavements: Codes and standards

Cool pavements are gaining recognition as an important component of sustainable construction practices. In California and around the country, green and high-performance building codes have incorporated minimum solar reflectance requirements for the paved surfaces of new building projects or major renovations. See below for a table that summarizes these requirements.

To meet the solar reflectance requirements, the pavement materials need to be tested by an accredited and independent laboratory. Most building codes, standards and rating systems describe their respective required testing methods. The two most common testing methods for cool pavement materials are American Society for Testing and Materials (ASTM) E1918 and ASTM C1549. ASTM E1918 is performed using a pyranometer in the field while ASTM C1549 is for measurements conducted in the field or lab using a portable solar reflectometer. In addition to solar reflectance requirements, some organizations include a minimum solar reflectance index (SRI) requirement. SRI is an alternative metric for comparing the coolness of urban surfaces. It is a temperature scale calculated from solar reflectance and thermal emittance. The higher the SRI, the cooler the surface will be in the sun. It was designed for use in the roofing market where cool roof materials have variable thermal emittance values. With pavement materials, there is little variability in thermal emittance between products so often only a minimum solar reflectance value is specified.

Note: *California Assembly Bill 296, passed in 2012, requires that the California Department of Transportation and the California Environmental Protection Agency collaborate to standardize specifications for cool pavements and develop a heat island index for California cities.*

Code	Policy Type	Most Recent Edition	Climate Zones	Minimum Requirements for Compliance			Notes
				Initial SR	3-yr Aged SR	Initial SRI	
California voluntary codes and standards							
California Green Building Standards Code (CALGreen)	Green building code*	2010	N/A	0.30			Voluntary measure for cities to adopt into local codes; may be combined with shading and/or open-grid (permeable) pavement on 50% of site hardscape for compliance
National codes, standards, and rating systems that states and municipalities can adopt							
ASHRAE 189.1	Advanced model code#	2011	N/A			29	New concrete without added color is assumed to have SRI = 35
International Green	Advanced model code#	2012	US 1-6	0.30			Provides model code regulations for adoption by jurisdictions internationally and can be

Construction Code (IGCC)							adopted by reference. Excludes site hardscape covered by solar PV and solar thermal collectors
Leadership in Energy and Environmental Design (LEED)	Voluntary green building rating system*	Version 4	N/A	0.33	0.28		Must cover 50% of non-roof area and be cleaned every 2 years; applies to new and existing construction projects; aged SR value is required but if unavailable, the initial SR value is acceptable

Key: SR—solar reflectance; SRI—solar reflectance index

** A green building code is a set of standards that specifies criteria for sustainable or high-performance building practice*

[#] An advanced model code is a building code that specifies criteria for high-performance building practices, written by an independent standards organization to be adopted as mandatory by local governments or regional bodies

Cool Pavements: Taking action

Implementation resources

When considering cool pavements for your city or community, the following tools can simplify the decision-making process. The below materials serve as additional resources to demonstrate the range of cool pavement solutions that can be implemented where you live, as well as the policy guidance to lock in the maximum benefit for your area.

- U.S. Environmental Protection Agency (EPA) Reducing Urban Heat Islands: Compendium of Strategies – Cool Pavements: A detailed description of the science, technology, and application of cool pavements in the United States (developed by the U.S. EPA)
- Cool Pavement Primer: A resource that reviews key information and summarizes the topic in a way that you can share and present to others who want to learn more about cool pavements (developed by the Heat Island Group at Lawrence Berkeley National Laboratory)
- Cool Roofs and Pavements Toolkit: A comprehensive informational primer and implementation guide to help spread the adoption of reflective urban surfaces worldwide (developed by the Global Cool Cities Alliance)

Cool pavement case studies

Cool pavements are now being introduced throughout California in various contexts. Cities are looking to incorporate cool pavements as climate adaptation planning measures, and school districts are trying to cool their schoolyards by using more reflective outdoor surfaces. Learn how some California entities are approaching the adoption of cool pavements in the following case studies.

Cool pavements as a climate adaptation measure

California cities are taking measures to prepare for a changing climate by developing climate adaptation plans. A recent example of this planning comes from Chula Vista, CA, where planning efforts have explored measures to mitigate high urban air temperatures that lead to high demand for building air conditioning. Chula Vista initially identified eleven climate adaptation strategies that could mitigate heat islands, decrease energy demand, and improve air and water quality. The city then drafted an implementation plan for each of its identified adaptation strategies, including cool pavements.

The implementation plan for cool pavements spans a two-year exploratory project to learn more about the local prospects for cool pavements. The ultimate goal of the cool pavements implementation plan is to develop a new municipal policy that incorporates cool paving materials into new street and parking lot projects. The city commissioned a comprehensive cool pavements study to evaluate and test multiple technologies, taking into account the costs, benefits, drawbacks, performance, and incentive opportunities for each technology.

Chula Vista's Cool Pavements Study identifies several technologies that offer high urban heat island reduction potential, such as light-colored cement concrete products and cool pavement coatings, as well as possible funding sources for a new pavements program. The study sets forth criteria for suitable cool pavement pilot sites and for performance monitoring of the pilots to assess solar reflectance, thermal emittance, durability, stormwater effects, and noise over time. The results of this pilot program will

inform Chula Vista's guidelines for new paving as well as for pavement maintenance within five years from the study's date of publication.[18]

Cool schoolyards in California

Nowhere are the outdoor comfort and air quality benefits of cool pavements more critical than in our schools. As summers grow longer and warmer, schools are catching on and replacing the traditional asphalt "blacktop" schoolyards of yesteryear with a cooler look. By using solar reflective materials in schoolyards, California schools are attempting to lower the risk of heat-related illnesses while still allowing students to be active outside more frequently. In recognition of these benefits, the Collaborative for High-Performance Schools (CHPS) rewards schools for shading or lightening paved areas in their new construction and major modernization projects.

Figure 8. *King Elementary School in Richmond, CA adopted CHPS design criteria in 2006 and was outfitted with a cool schoolyard in 2011 (sources: Quattrocchi Kwok [architect] and Vallier Design Associates [landscape architect])*

Now Los Angeles Unified School District (LAUSD), the largest district in California and second-largest in the nation, is taking steps to incorporate cool pavements into its portfolio of sustainability improvements. They are currently piloting several cool coatings and can serve as a roadmap for large organizations that would like to experience firsthand the benefits of reflective pavements. LAUSD began its process by discussing the benefits, suitability, and availability of cool pavement technologies with technical experts from Lawrence Berkeley National Laboratory (LBNL). LAUSD next assembled a team of local champions for cool pavements who could speak to their broad array of health, educational, and aesthetic benefits. The district then engaged in peer-to-peer exchange with another district that has successfully implemented cool schoolyards to discuss ideas relating to implementation—in this case, West Contra Costa Unified School District, which has embraced cool schoolyards in recent years. Next, LAUSD reviewed a range of available cool pavement products to decide which products best suited its design objectives, including a desire for colorful coatings and the ability to be applied by in-house maintenance staff. LAUSD champions then presented their findings to the district's new product committee and arranged in-person meetings between the committee and candidate cool pavement manufacturers. Next, the new products committee selected products to be tested by the district for environmental health and safety and ease of application. Several of the products passed the tests so the district moved forward with a pilot cool schoolyard at Gardena Elementary School in the summer of 2013. The district will be evaluating the performance of the coating over time as well as the qualitative effect of the new colorful schoolyard on the students and larger school community.

[18] City of Chula Vista. 2012. Cool Pavements Study. Retrieved from: http://www.chulavistaca.gov/clean/PDF/CVCoolPavementsStudy_DRAFT9-7-12.pdf. Accessed June 2013.

CoolCalifornia.org

Local Government: Cool Roofs

Content contributed by Heat Island Group, Lawrence Berkeley National Laboratory

At noon on a clear summer day in California, one square foot of rooftop receives enough solar energy to power an incandescent traffic light (100W). Traditional dark roofs absorb most of this sunlight, heating the roof, the building, and the surrounding air. This increases energy use in air conditioned buildings, and makes buildings without air conditioning less comfortable. Hot dark roofs also intensify the urban heat island effect by warming the air above the roof, and contribute to climate change by radiating heat into the atmosphere.

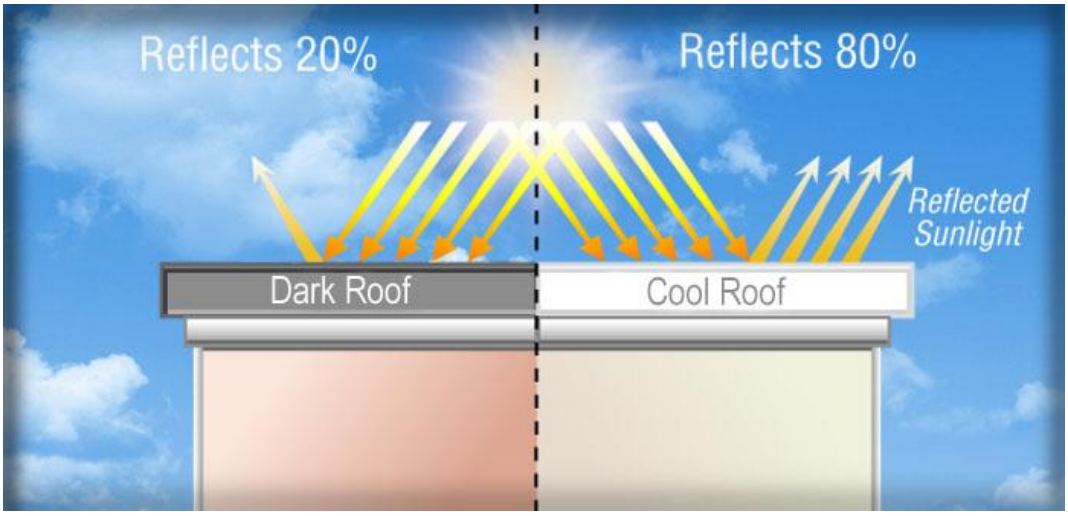


Figure 9. *Cool roofs reflect a greater share of sunlight than traditional dark roofs (source: LBNL-Heat Island Group)*

Cool roofs, which reflect a large fraction of the sunlight that dark roofs absorb, stay cooler in the sun, which saves money on energy bills and mitigates the urban heat island effect. Since roofs cover about 20% of the surface area of a typical U.S. city, adoption of cool roofs could produce substantial energy and cost savings, improve urban air quality, and even slow climate change.

Learn more about cool roofs:

- Explore the science of cool roofs in **Cool Roofs: How they work**
- Discover the many **Cool Roofs: Benefits** of cool roofs
- Learn what

- **Cool Roofs: Codes and standards** may apply to your roofing project
- Find implementation tools and see what others have done in **Cool Roofs: Taking action**

Cool Roofs: How they work

To understand how roofs can keep cool in the sun, it is helpful to first understand solar energy, which consists of ultraviolet, visible, and near-infrared energy. Almost half of the sun's energy that reaches Earth is visible; a slightly greater share arrives as invisible near-infrared radiation, and a small fraction (less than 10%) arrives as invisible but harmful ultraviolet light (see Figure 2).

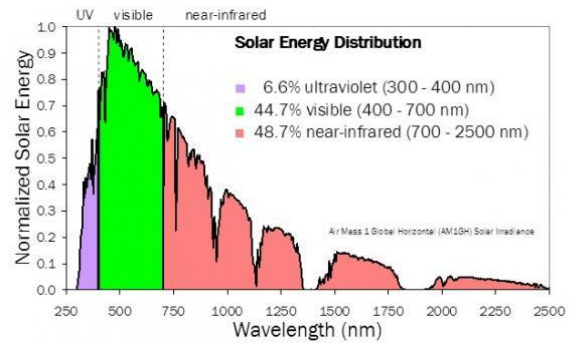


Figure 10. *The electromagnetic spectrum shows the portion of the sun's energy that arrives to Earth as ultraviolet, visible, and near-infrared radiation (source: LBNL-Heat Island Group)*

A portion of the sun's energy that strikes a rooftop reflects back into the sky, and the rest is absorbed as heat in the roof. Cool roofs reflect more sunlight and absorb less heat than traditional roofs, which keeps them cooler in the sun and transmits less heat into the building.

What makes a roof cool?

The "coolness" of a roof is determined by two properties of roofing materials and their combined effects on temperature:

- Solar reflectance : ability to reflect sunlight
- Thermal emittance : ability to cool down by emitting heat that is absorbed

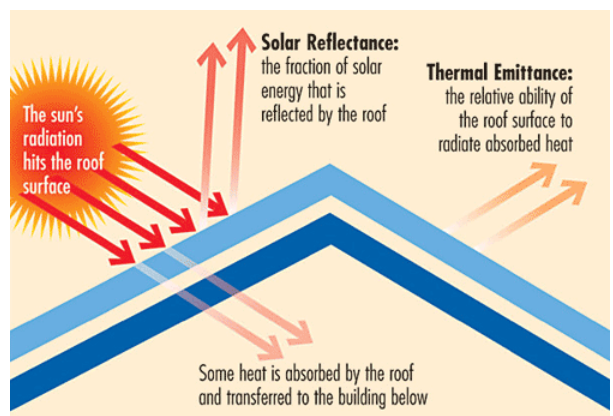
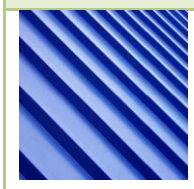
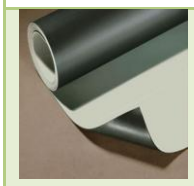


Figure 11. *Cool roofs stay cool because they have high solar reflectance and thermal emittance (source: Cool Roof Rating Council)*

These properties explain how cool roofs absorb less heat and stay up to 28-33°C (50–60°F) cooler than conventional rooftops on the hottest summer days.[19] Both of these properties are measured on a scale from 0 to 1 (0-100%), with higher values indicating a cooler roof. Another measure often cited is the solar reflectance index (SRI). Solar reflectance and thermal emittance can be combined to calculate a material's SRI, which is a measure of a roof's coolness, with higher values again indicating a cooler roof.

Cool roof options are available for a wide range of materials, but the values for solar reflectance and thermal emittance vary with the material. See the below table for the approximate ranges of these radiative properties for various cool roof options:

[19] Calculated under the standard summer afternoon weather specified in ASTM Standard E1980-11, using the medium wind speed condition.

	Product	Application	Solar Reflectance (initial)	Thermal Emittance (initial)	Solar Relectance Index (initial)
	Asphalt shingle	Pitched roofs	0.20 – 0.30	0.85 – 0.90	16 – 32
	Clay tile	Pitched roofs	0.40 – 0.50	0.80 – 0.90	41 – 58
	Concrete tile	Pitched roofs	0.20 – 0.60	0.80 – 0.90	14 – 72
	Coated metal	Pitched roofs	0.25 – 0.70	0.80 – 0.90	21 - 86
	Liquid-applied coating	Low-slope roofs	0.60 – 0.90	0.85 – 0.90	71 - 114
	Modified bitumen	Low-slope roofs	0.60 – 0.75	0.85 – 0.95	71 – 94
	Single-ply membrane	Low-slope roofs	0.70 – 0.85	0.85 – 0.95	85 – 108

Cool roofs in practice

All cool roofs reflect more sunlight than conventional roofs, but that doesn't mean all cool roofs look alike! One popular cool option for flat, low-slope, roofs are white roofs, which are available in a variety of materials. For pitched roofs (like on many residential buildings), cool-colored roofing materials can reflect more sunlight without sacrificing traditional aesthetics.

White roofs

White buildings with white roofs have been common architectural practice in Mediterranean and Middle Eastern societies for thousands of years because they keep the interiors of buildings cooler. It has taken some time, but white roofs are now spreading throughout other regions of the world as a cost-effective way to reduce indoor temperature and energy use.

White materials are a popular cool option for building surfaces that cannot be seen from the street, such as low-sloped "flat" (that is, nearly horizontal) roofs. In some parts of the world, pitched roofs may also be white. White roofing products are available as membranes, coatings, coated metal, tile, and ballast roofs, among other materials.

Cool-colored roofs

There are also cool alternatives that mimic the appearance of traditional roofing products. "Cool-colored" roofs increase reflection of sunshine while maintaining the color and aesthetic of nonwhite roofing products. They reflect more invisible infrared radiation while reflecting the same amount of visible radiation as the conventional products. Cool-colored products are a good choice for pitched roofs that are visible from the street, so that cool-colored asphalt shingles, metal, and tiles products can preserve the aesthetics of the building.

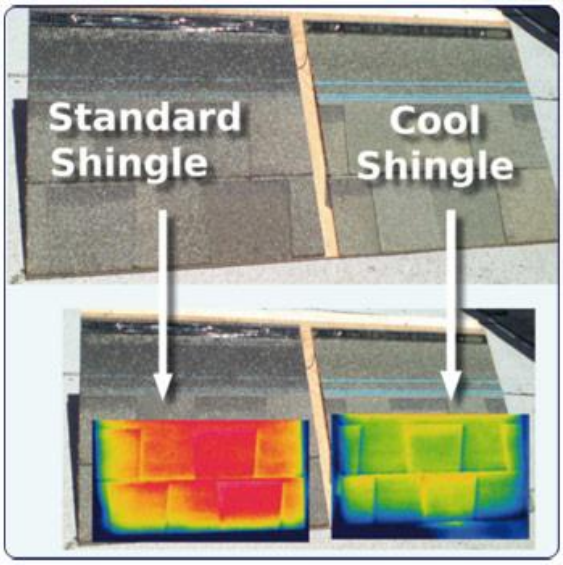


Figure 12. *Cool asphalt shingles look just like conventional shingles to the naked eye, but thermal imaging reveals a key difference - they stay much cooler in the hot sun. (source: LBNL-Heat Island Group)*

Cool Roofs: Benefits

Substituting cool roofs for traditional dark roofs can provide benefits for your comfort, your wallet, your city, and our planet.

On the building level:

- Cool roofs absorb less sunlight and therefore heat up less on a sunny day, which reduces the transfer of heat into the top floor of buildings and ***lowers indoor air temperatures***.[20]

- Lower indoor air temperatures translate to ***energy and cost savings*** by reducing the need for air conditioning.[21]

Figure 13. *On a summer afternoon, the black roof at left was measured to be 30°C (54°F) warmer than the white roof at right (source: U.S. Department of Energy)*

- In buildings without air-conditioning, lower indoor air temperatures provide ***enhanced indoor comfort***, which promotes increased productivity and wellbeing.[22]

On the city level:

- Because cool roofs absorb less sunlight and heat up less than dark roofs, they transfer less heat to the local atmosphere, which leads to ***cooler outside air***.

- Lower outside temperatures mitigate the urban heat island effect, which can lead to ***reduced heat-related illness and mortality***.[23]

- Lower outdoor temperatures lead to ***improved air quality*** by slowing the formation of smog.[24]

- Air quality will further improve because of ***lower power-plant emissions*** of greenhouse gases and other pollutants owing to reduced electricity demand, particularly during peak times (e.g., hot summer afternoons) when the most polluting plants operate.[25]

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[20] Levinson R, Akbari H. 2010. Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy Efficiency* 3:53-109.
[21] *Ibid.*
[22] Goins, J., 2007. Productivity and IEQ satisfaction. *CBE TechNote*, Prepared for Center for the Built Environment.
[23] Taha H, Hammer H, Akbari H. 2002. Meteorological and air quality impacts of increased urban surface albedo and vegetative cover in the greater Toronto area, Canada. Lawrence Berkeley National Laboratory report No. LBNL-49210. Berkeley, CA.
[24] Akbari H, Pomerantz M, and Taha H. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70: 295-310.
[25] Akbari H, Bretz SE, Kurn DM, and Hanford J. 1997. Peak power and cooling energy savings of high-albedo roofs. *Energy and Buildings* 25: 117-126.

- This reduction in peak electricity demand can also ***ease strain on the electricity grid***, which lessens the risk of power outages.

On the global level:

- Cool roofs decrease the amount of heat that is absorbed at the Earth's surface and thus lower surface temperature. This decrease in surface temperature reduces the transfer of heat into the atmosphere, which offsets a portion of the warming from greenhouse gases and thereby ***delays climate change*** (see Figure 6Figure 6).[26,27]

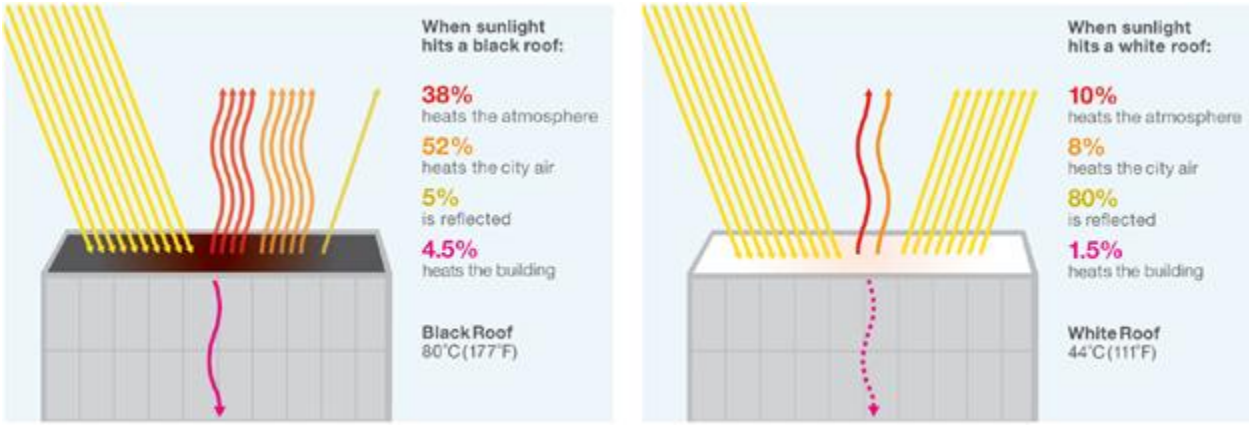


Figure 14. *White roofs absorb less sunlight, which allows them to transmit less heat to the city air and atmosphere. (source: LBNL-Heat Island Group and Global Cool Cities Alliance)*

Notes

- It is important to keep in mind that these benefits vary depending on the solar reflectance value of the roofing product. Traditionally, higher reflectance values confer greater benefits.

- During winter months, cool roofs increase the need for heating energy in cold climates because they absorb less of the sun's energy. However, in winter the sun stays low, the days are short, and the skies are often cloudy, limiting the amount of sunlight available to a roof. In addition, when snow covers roofs, the color of the roof beneath the snow becomes irrelevant. In the United States, this winter heating

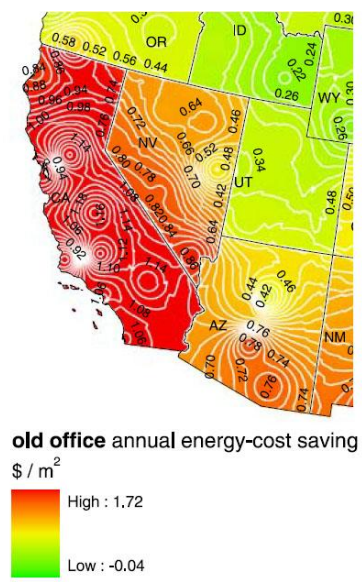


Figure 15. *The cooling energy savings from cool roofs should outweigh the winter heating penalty in all but the very Northern-most locations in the US (source: Levinson and Akbari 2010)*

[26] Akbari H, Menon S, Rosenfeld A. 2009. Global cooling: increasing world-wide u *Climatic Change* 94(3-4), 275-286.

[27] Menon S, Akbari H, Mahanama S, Sednev I, Levinson R. 2010. Radiative forcing changes in urban albedos and associated CO2 offsets. *Environmental Research Letters* 5:1-11.

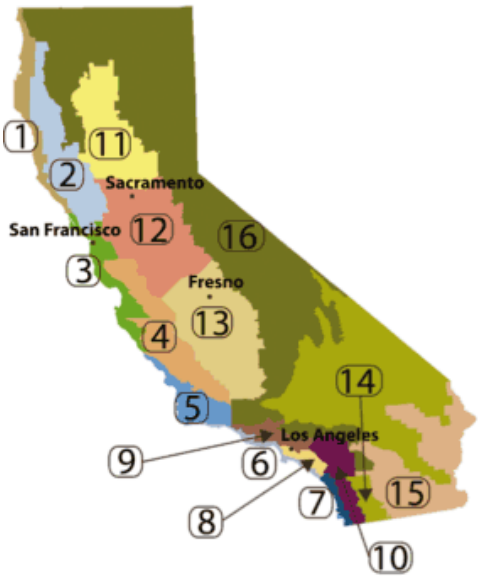
penalty is typically small compared to the summer cooling benefit.[28]

- Bright, solar-reflective roofs can produce glare, which may disturb occupants of taller neighboring buildings. In such situations, a cool-colored (nonwhite) roof may be more appropriate for the shorter building to stay cooler while avoiding visual concerns.
- While implementing cool roofs is a good first step, local entities that wish to capture significant cooling benefits should consider coupling cool roofs with cool pavements and vegetation. A cool community program/plan is most effective when combining these strategies to achieve maximum benefits. To learn more about cool pavements visit HERE and vegetation HERE.

[28] *Supra* at 20.

Cool Roofs: Codes and standards

Many federal, state and local government entities now include cool roofs in their building codes, green building standards and energy efficiency programs. However, requirements for cool roofs differ by national or state climate zone in some cases so be sure to refer to the California and U.S. climate zone maps below to understand the requirements in your area.



California has 16 climate zones for the purposes of state codes and standards (source: LBNL-Heat Island Group)

In California, all new or replacement low-slope roofs are required by the building energy efficiency standards (Title 24) to be cool roofs, as are steep-slope roofs in several California climate zones.

The Cool Roof Rating Council (CRRC) is an independent, non-profit organization that maintains a third-party rating program, which rates and publishes a roof product's radiative properties (solar reflectance and thermal emittance). Once a product is rated, the results are published on their online Rated Products Directory, which is a great resource to check to see whether roofing products comply with Title 24 or other codes and standards.

CRRC tests products when they are both new and aged. Aged products are weathered outside for three years. The weathered rating will indicate how the roof products' radiative properties change when exposed to sun, soil, wind, rain and other natural elements. Many building codes and utility rebates specify the weathered rating because some products become less reflective over time, thus become less effective at conserving energy.

See below for more on these building codes, green building standards and energy efficiency programs that currently include cool roof provisions, broken down by roof slope.

Note: *Title 24 requirements for the 2013 standard will go into effect in 2014.*

Code	Policy Type	Most Recent Edition	Target		Climate Zones	Minimum Requirements for Compliance						Notes
						SR		TE		SRI		
			Low-slope	*Steep-slope*		*Initial*	*Aged*	*Initial*	*Aged*	*Initial*	*Aged*	
California mandatory codes and standards												
California Building Energy Efficiency Standard (**Title 24**)	Building energy efficiency standard	2013	COM		CA 1-16		0.63		0.75		75	Effective 1/1/2014
			RES		CA 13,15		0.63		0.75		75	
				COM	CA 2-16		0.20		0.75		16	
				RES	CA 10-15		0.20		0.75		16	
		2008	COM		CA 2-15		0.55		0.75		64	In effect through 12/31/2013
			RES		CA 13,15		0.55		0.75		64	
				COM	CA 2-16		0.15		0.75		10	
				RES	CA 10-15		0.20		0.75		16	Roof product density<5 lbs/sf
					CA 1-16		0.15		0.75		10	Roof product density≥5 lbs/sf
California Green Building Standards Code (**CALGreen**)	Green building code*	2013	x		CA 2, 4, 6-15		0.65		0.85		78	Tier 2 voluntary compliance above 2008 Title 24 mandatory requirements
				x			0.23		0.85		20	
			x		CA 13,15		0.55		0.75		64	Tier 1 voluntary compliance is consistent with 2008 Title 24 mandatory requirements
				x	CA 1-9,16		0.15		0.75		10	
				x	CA 10-15		0.20		0.75		16	
National codes and standards that municipalities can adopt												
ASHRAE 90.1	Model code^	2010	COM		US 1-3		0.55		0.75		64	
ASHRAE 90.2	Model code^	2007	RES		US 1-3	0.65		0.70		75		
ASHRAE 189.1	Advanced model code#	2011	COM		US 1-3					78		ENERGY STAR criteria meet requirement
				COM						29		
ENERGY STAR	Voluntary program	2012	x		N/A	0.65	0.50					
				x		0.25	0.15					
International Energy Conservation Code (**IECC**)	Model code^	2012	COM		US 1-3	0.70	0.55	0.75	0.75	82	64	
International Green Construction Code (**IGCC**)	Advanced model code#	2012	x		US 1-3		0.55		0.75		60	
				x			0.30		0.75		25	
Leadership in Energy and Environmental Design (**LEED**)	Voluntary green building code*	LEED V4	x		N/A					82	64	Must cover 75% of non-vegetated roof area; new & existing construction
				x						39	32	

Key: SR—solar reflectance; TE—thermal emittance; SRI—solar reflectance index; COM—applies to commercial buildings; RES—applies to residential buildings

* *A green building code is a set of standards that specifies criteria for sustainable or high-performance building practice*

^ *A model code is a building code that is written by an independent standards organization to be adopted as mandatory by local governments or regional bodies*

An advanced model code is a model building code that specifies criteria for high-performance building practices

Keep in mind that these requirements are only the minimum criteria for compliance; many California cities have gone above and beyond to exceed these requirements in their local planning efforts – see what local initiatives some California cities are undertaking.

And to find products that meet the required minimum values for solar reflectance, thermal emittance, and solar reflectance index (listed in the table above), you can browse the Cool Roof Rating Council's Rated Products Directory.

Cool Roofs: Taking action

Cool roof funding

To aid community-wide acceptance and adoption of cool roofs, it will be helpful to inform residents and businesses about financial incentives that exist for the installation of a cool roof, where applicable. To learn more about incentives available for cool roof projects, policies or programs, be sure to visit:

CoolCalifornia.org Funding Wizard: A tool to help individuals, businesses and local governments find funding from grants, incentives, and rebates for sustainable projects. When looking for cool roof funding, be sure to check out the energy efficiency funding opportunities, which can apply broadly to measures, such as cool roofs.

Energy Upgrade California: A collaborative effort between state agencies, counties, cities, utilities, and community organizations throughout California to help meet the state's energy and climate goals. Get rebates and incentives for implementing energy efficient measures in your homes, including cool roofs. *(Available in much of California, including Pacific Gas & Electric (PG&E) and Southern California Edison (SCE) service areas.)*

Local initiatives

Many communities and local governments have taken steps to develop cool roof programs by installing cool roofs on public buildings and including cool roofs in local building requirements and/or policies.

Click the links below to explore many of the voluntary programs and local initiatives that actively promote cool roofs in California.

Berkeley Climate Action Plan: The City of Berkeley is pursuing a requirement to install cool roofs on commercial buildings for new construction or re-roofing projects as part of the city's promotion of energy efficiency in their climate action plan.

Chula Vista Climate Action Plan: The City of Chula Vista performed a cost-benefit analysis of cool roof options, in conjunction with San Diego Gas & Electric. The results of this analysis were used to inform a 2012 revision to the city building code that increased the minimum cool roof requirements – now consistent with those in the CalGreen code, voluntary Tier 2. (See Cool Roofs: Codes and standards section for review of requirements.)

Contra Costa County Municipal Climate Action Plan: Contra Costa County's Municipal Climate Action Plan creates a standard for cool roofs in new county buildings and remodels. The county is also looking to upgrade county buildings with cool roofs.

Marin County Greenhouse Gas Reduction Plan: As a part of the Cities for Climate Protection campaign, Marin County includes installation of reflective roofing as a part of their Greenhouse Gas Reduction Plan.

Martinez Climate Action Plan: The City of Martinez is mitigating their urban heat island by promoting cool community strategies – cool roofs, cool pavements and urban vegetation – in their climate action plan. The city is planning to adopt new building codes along with new parking and landscape regulations to implement the cool community strategies.

Menlo Park Climate Change Action Plan: Menlo Park's Climate Action Plan proposes the use of reflective and energy star roofing materials in some city buildings. Menlo Park is also looking to begin an energy efficiency and renewable energy financing program, which would bring low interest loans to fund projects like cool roofs.

San Diego Climate Change Protection Action Plan: The City of San Diego's Climate Change Protection Action Plan seeks to adopt a heat island mitigation policy for the city. The policy would include utilizing alternative cool materials for roofs and pavement to reduce the heat island effect.

San Jose's Green Vision: San Jose's Green Vision integrates cool roofs as a part of efforts in energy efficiency.

Sonoma County Community Climate Action Plan: The Sonoma County Community Climate Action Plan outlines a plan to integrate cool roofs onto county buildings.

Union City Climate Action Plan: In their Climate Action Plan, Union City plans to promote the use of cool roof technology.

Town of Windsor Greenhouse Gas Emissions Reduction Action Plan: Part of the Town of Windsor's Greenhouse Gas Emissions Reduction Action Plan aims to put cool roofs on several public buildings. Windsor also has green building standards, which include cool roof measures.

Implementation resources

When considering cool roofs for your city, community, or building, the following tools can simplify the decision-making process. The below resources demonstrate the possible energy-saving and economic benefits of white roofs where you live, as well as the policy guidance to lock in the maximum benefit for your area.

U.S. Environmental Protection Agency (EPA) Reducing Urban Heat Islands: Compendium of Strategies – Cool Roofs: A detailed description of the science, technology, economics, and application of cool roofs in the United States (developed by the U.S. EPA)

Cool Roofs and Pavements Toolkit: A comprehensive informational primer and implementation guide to help spread the adoption of reflective urban surfaces worldwide (developed by the Global Cool Cities Alliance)

Cool Roof Product Search Wizard: A decision-making resource on CoolCalifornia.org to help homeowners find cool roof solutions that suit their unique design requirements (developed in

collaboration with the Heat Island Group at Lawrence Berkeley National Laboratory and the Cool Roof Rating Council)

Roof Savings Calculator: An industry-consensus calculator of energy savings from various roof types, based upon whole-building energy simulations (developed jointly by Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory)

Potential for residential cool roofs in Fresno, CA

Fresno is situated in California's Central Valley, among the hottest regions in the state. Over the past few years, Berkeley Lab has been monitoring two adjacent homes that are nearly identical in construction—apart from their roofs. One home has a conventional dark asphalt roof while the other has a cool tile roof. Real-time monitoring tracks differences in roof and attic temperature, heat flow through the ceiling, and energy needed to maintain a comfortable indoor temperature.[29] The resulting analysis revealed that the home with a cool tile roof saved $120 in energy expenses over the course of a summer compared to the home with a traditional roof.

Figure 16. *Two adjacent residences in Fresno, CA - the home in the background has a conventional asphalt shingle roof and the home in the foreground has a cool tile roof (source: LBNL-Heat Island Group)*

In addition to being one of California's hottest cities, Fresno is also one of its most populous, with nearly 500,000 residents and more than 170,000 housing units.[30] A 2006 study[31] that investigated the feasibility of cool roofs on residential buildings in California found that increasing the reflectance of standard shingle, metal, or tile roofs by 0.15-0.30 could save more than 100 kilowatt-hours of cooling electricity per year, which amounts to cost savings of approximately $20 per home each year.[32] Implementing cool roofs on residences throughout Fresno could thus save its homeowners more than $3 million and avoid nearly 10,000 tons of carbon dioxide emissions on an annual basis—equivalent to removing over 2,080 vehicles from the road.[33]

Cool roof savings potential for Los Angeles

Los Angeles is big and hot. As California's most populous city, there are opportunities for large savings from reducing cooling energy needs. Cool roofs have been discussed as one possibility; a 2011 report proposed the phase-in of cool roofs on new and existing buildings, estimating that Los Angeles residents

[29] You can keep track of the temperature and energy comparisons in real time at http://CoolRoofDemo.LBL.gov
[30] www.census.gov/popfinder
[31] Akbari H, Wray C, Xu T, Levinson R (2006) Inclusion of Solar Reflectance and Thermal Emittance Prescriptive Requirements for Residential Roofs in Title 24. Code Change Proposal in 2008 Title 24 Building Energy Efficiency Standards Update.
[32] Assumes average electricity rate of $0.18/kWh
[33] http://www.epa.gov/cleanenergy/energy-resources/calculator.html#results

would save $30 million each year from the associated energy savings alone. The report also notes that other benefits of cool roofs include roof longevity, reduced healthcare costs, and global cooling; increasing the solar reflectance of Los Angeles rooftops has the potential to offset 80% of the greenhouse warming from a year of the city's CO_2 emissions. The report proposes citywide adoption of cool roofs through utility incentives, consumer education and resources, and incorporating cool roof requirements into the city's building code.[34] Cool roofs also fit into L.A.'s vision for green jobs, as they are listed as one of 13 high-potential building energy efficiency retrofits that are encouraged as part of the city's Green Retrofit and Workforce Development Program.[35]

In March 2013, Los Angeles-based nonprofit Climate Resolve hosted a day-long seminar on cool roofs in L.A. called "Hot City, Cool Roofs." The event featured then-Mayor Antonio Villaraigosa speaking of the need for climate solutions, as well as presentations from the academic and nonprofit communities. Soon after the event, Mayor Villaraigosa directed the Los Angeles Department of Building and Safety to incorporate stricter cool roof requirements into its building code, and requested that the Los Angeles Department of Water and Power create incentives for cool roofs.

[34] Horowitz C (2011) Bright roofs, big city: Keeping L.A. cool through an aggressive cool-roof program. *Anthony Pritzker Environmental Law and Policy Briefs* 2: 14 pp. Online at: http://www.coolrooftoolkit.org/wp-content/uploads/2012/05/UCLA-Bright_Roofs_Big_City.pdf

[35] Delp L, Stewart E, Appelbaum LD (2009) Good, Green, Safe Jobs: The Los Angeles Green Retrofit and Workforce Development Program. UCLA Institute for Research on Labor and Employment. *Research & Policy Brief* 2: 9 pp. Online at: http://urbanhabitat.org/files/LAGreenJobs.pdf

Local Government: Cool Pavements Content

contributed by Heat Island Group, Lawrence Berkeley National Laboratory

Planting trees, shrubs, vines, and other greenery is one of the easiest and least expensive ways for a community to reduce its summer temperatures and save energy.

Vegetation can help naturally cool buildings and homes. By shading buildings and blocking out direct sunlight, trees lower indoor air temperatures. As few as 1-3 strategically planted trees can reduce a building's need for air-conditioning and significantly reduce summertime electricity bills.

Vegetation provides a wealth of other benefits as well; it can increase air circulation, improve air quality, support native plants and animals, raise property values, and reduce the localized effects of climate change.

Read more to learn about:

- How cool vegetation works
- Benefits
- Planting strategies for cool vegetation
- Guidelines for choosing the right tree
- Additional resources to make the most of your cool vegetation

Figure 17 Shading from the trees keep this pedestrian walkway cooler and more comfortable on a warm afternoon Photo credit: Alber (Flickr)

How it works

Trees and vegetation help to cool buildings and neighborhoods in a variety of ways. Here's a quick overview of how these methods work:

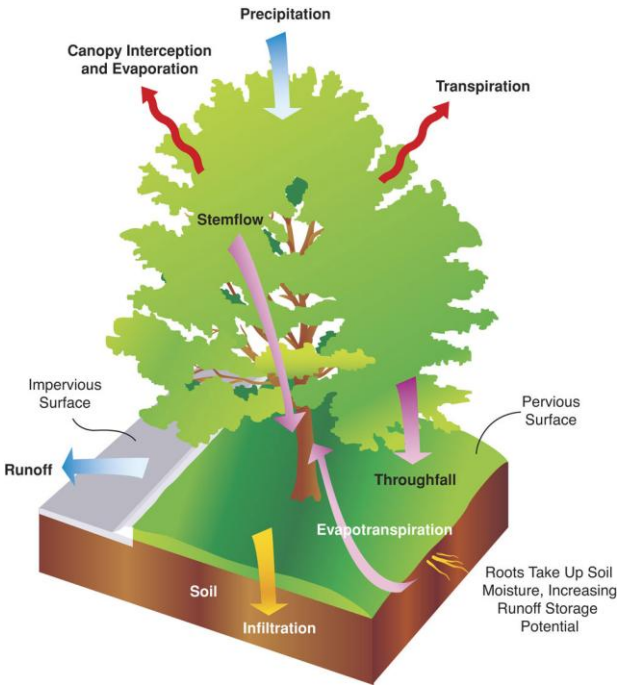


Figure 18 The water cycle helps to explain how trees generate local and regional cooling through evapotranspiration. Photo credit: Mike Thomas, International Society of Arboriculture

Evapotranspiration

Evapotranspiration includes the evaporation of water from soil and transpiration--the process by which plants absorb water through their roots and release it as vapor through their leaves. Both of these liquid-to-gas processes use heat from the surroundings and thus cool the air.

A Berkeley Lab study found that trees can transpire 100 gallons (378.5 L) of water every day, which has the same cooling effect as 5 standard air-conditioning machines running for 20 hours.[36]

Shade Effect

Shaded areas are protected from direct sunlight, which reduces temperatures by 20-45°F (11-25°C) relative to peak temperatures in unshaded areas.[37] Trees planted strategically around buildings and homes can significantly cool the indoor air. Shading windows, for example, is a very effective way to block direct sunlight from entering the building. A study in Davis, California found that cars parked in a shaded parking lot in the summer had interior air temperatures that were 45°F (25°C) cooler than cars parked in direct sunlight.[38] Something as simple as vines covering a west-facing wall can shade the wall from direct sunlight, reducing the heat transferred into the house and indoor temperatures up to 36°F (20°C) in the summer.[39]

Note Cities in cooler climates should consider that shading has the opposite effect in winter, when more sunlight and heat are desirable indoors. For most places however, the benefits from reduced cooling costs in the summer will outweigh the costs of increased heating in winter. This is because the sun is weaker in the winter, and deciduous trees shed their leaves, allowing a greater proportion of sunlight to filter through.

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[36] EPA. 1992. Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. p32.

[37] Akbari, H., D. Kurn, et al. 1997. Peak power and cooling energy savings of shade trees. *Energy and Buildings* 25:139–148. (EPA Heat Islands site: http://www.epa.gov/hiri/mitigation/trees.htm)

[38] Scott, K., J. Simpson, E. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions. Journal of Arboriculture 25(3):129-142

[39] Sandifer, S. and B. Givoni. 2002. Thermal Effects of Vines on Wall Temperatures—Comparing Laboratory and Field Collected Data. SOLAR 2002, Proceedings of the Annual Conference of the American Solar Energy Society. Reno, NV.

Wind speeds

Increased urban vegetation can have varying effects on wind speeds. While a row of trees can block cooling breezes in the summer, they can also shield the house from cold winds in the winter. However, larger expanses of trees – such as in urban parks – can help increase local air circulation, generating cooling breezes that have a community-wide cooling effect.[40]

40 Spronken-Smith RA and Oke TR. 1999. Scale modeling of nocturnal cooling in urban parks. Boundary Layer Meteorology 93: 287-312. Accessed via American Planning Association. How cities use parks for climate change management. http://www.planning.org/cityparks/briefingpapers/climatechange.htm

Benefits

Trees and vegetation benefit not only the individual properties on which they are planted, but also the community at large. What's more, they are aesthetically pleasing and help to beautify cities and towns.

The benefits of urban vegetation can be divided into two categories:

- Cooling and energy reduction
- Community-wide benefits

Figure 19 Urban vegetation can save energy in homes in a variety of ways, all of which reduce power plant emissions. Photo credit: Mike Thomas, International Society of Arboriculture

Cooling and Energy

One reason to increase trees and other vegetation in your community is their ability to cool buildings and neighborhoods, which can reduce building energy use and heating and cooling costs.

Figure 20 Students planting a tree in Maryland. Photo credit: Keith Weller, US Forest Service

Cooler communities

Here is some evidence that trees can help cool communities:

- Trees can lower outdoor air temperatures by as much as 9°F (5°C) through evapotranspiration.[41]
- In Davis and Sacramento, CA, neighborhoods with mature tree canopies enjoyed daytime temperatures that were 3 to 6°F (1.6 to 3.3°C) lower than in areas without canopies.[42]
- Trees in large urban parks help create a cool "oasis" that affects local wind patterns. Changes in the density of cooler air in parks and warmer air in the urban areas generate cooling breezes, which can extend to the surrounding neighborhoods.[43]
- A computer simulation found that a tree coverage increase of 25 percent in Phoenix, AZ, and Sacramento, CA—regions that are relatively hot and sunny—can result in temperature reductions of 6- 10°F (3.3-5.5°C) at midday in July.[44]

Cooler buildings & reduced building energy use and cost

[41] EPA. 1992. Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. p32.

[42] Ibid.

[43] Spronken-Smith RA and Oke TR. 1999. Scale modeling of nocturnal cooling in urban parks. Boundary Layer Meteorology 93: 287-312. Accessed via American Planning Association. How cities use parks for climate change management. http://www.planning.org/cityparks/briefingpapers/climatechange.htm

[44] EPA. 1992. Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. p32.

Trees and vegetation can help cool buildings by providing shade from direct sunlight. This in turn reduces the need for air-conditioning, resulting in large energy savings and cost savings in hot and sunny climates.

- Planting trees around two houses in Sacramento resulted in average energy savings of 30 percent for both houses from June through October.[45] The biggest energy savings came when trees were planted to the west and southwest of buildings.
- In a computer simulation, two trees planted west and southwest of a building, forming a canopy that shaded 20 percent of the house, could reduce cooling bills by 8 to 18 percent and reduce heating bills by 2 to 8 percent.[46]
- At the city scale, a study estimated that if the Los Angeles region increased vegetation in residential neighborhoods, near-surface air temperatures would drop by 1-2°C (1.8-3.6°F), which could save $20 million annually in air conditioning costs for the region.[47]

[45] Akbari, H., D. Kurn, S. Bretz, and J. Hanford. 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings. 25:139-148. (Accessed via *Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation*, p5)

[46] McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station. (Accessed via *Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation*, p5)

[47] Kurn DM, Bretz SE, Huang B, and Akbari H. 1994. The Potential for Reducing Urban Air Temperatures and Energy Consumption Through Vegetative Cooling. Lawrence Berkeley National Laboratory Report LBL-35320, Berkeley, CA.

Community Benefits

In addition to their energy-use and cooling benefits, trees and plants provide many other community benefits.

Figure 21 This illustration depicts the interaction between trees and carbon dioxide (CO_2). Photo credit: Mike Thomas, International Society of Arboriculture

Reduced greenhouse gas emissions:

Trees and plants are a natural carbon sink. In order to grow, plants absorb carbon dioxide from the air and turn it into oxygen and sugars through photosynthesis. This absorbed carbon is stored in the vegetation and in the soil. In recognition of trees' ability to absorb carbon, the California Air Resources Board identified urban forests as an additional strategy to achieve greenhouse gas emission reduction targets under California's Global Warming Solutions Act (AB 32), the landmark bill that commits the state to reducing its greenhouse gas emissions.

Additionally, the cooling effect of increased trees and vegetation can reduce energy consumption used for cooling. If the energy is generated by fossil fuels (such as natural gas, which is typically used in California), a decrease in energy consumption translates to a reduction in greenhouse gas emissions from power plants.

Improved air quality

Plants help to clean the air of pollutants, such as particulate matter. The pores of leaves remove dangerous compounds, such as nitrogen oxide, sulfur dioxide, carbon monoxide, and ozone from the air. A 2006 study found that urban trees remove about 711,000 metric tonnes of air pollutants in the U.S. every year, which confers an estimated $3.8 billion of economic value.[48] Tree shade can also help to reduce the evaporation of volatile organic compounds (VOCs) from parked cars by keeping the gas tanks cooler.

NOTE While plants and trees do improve air quality, they also release VOCs, also referred to as biogenic emissions. The emission of VOCs is affected by water, sunlight and humidity so there is wide variation in the emission rates. To learn more about the varying rates of emissions from trees, visit the CA Air Resources Board website for the Biogenic Working Group.

[48] Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry and Urban Greening. 4(2006):115-123. (Accessed via *Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation*, p6)

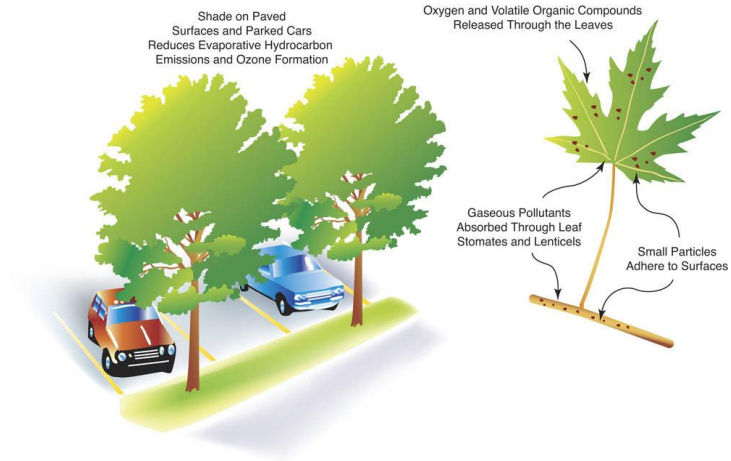

Figure 22 This illustration depicts the interaction between trees and air pollutants. Photo credit: Mike Thomas, International Society of Arboriculture

Decreased stormwater runoff

Trees and vegetation can help reduce stormwater runoff, minimize erosion, and protect water resources. Plants intercept rainfall by collecting it on their surfaces and can increase rainwater absorption by soil. During summers in Sacramento, evergreens and conifers were found to prevent 35 percent of rainfall from reaching the surface.[49]

Reduced pavement maintenance

Tree shade can help slow down pavement deterioration. One study found that shade trees reduced pavement resurfacing costs by 15 to 60 percent, depending on the type and location of the trees.[50]

Improved health and quality of life

In addition to reducing harmful air pollutants, trees and plants have many other benefits to health and quality of life. Increased shade reduces human exposure to the sun's ultraviolet rays. Their cooling effects on neighborhoods and on indoor temperatures can help decrease health impacts from summertime heat waves. Trees and vegetation help to beautify communities and create more pleasant surroundings. They can provide habitats for birds, insects and other creatures. A good row of trees can serve as an effective sound barrier between homes and urban noise pollution, such as traffic.[51] Other studies have found that urban trees are associated with reduced crime, increased property values, and other psychological and social benefits that help decrease stress and aggressive behavior.[52,53,54] These benefits cannot be easily monetized but are important for creating sustainable communities.

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[49] Xiao, Q., E.G. McPherson, J.R. Simpson, and S.L. Ustin. 1998. Rainfall Interception by Sacramento's Urban Forest. Journal of Arboriculture. 24(4):235-244. (Accessed via *Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation*, p8)

[50] McPherson, E.G. and J. Muchnick. 2005. Effects of Street Tree Shade on Asphalt Concrete Pavement Performance. Journal of Arboriculture. 31(6). (Accessed via *Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation*, p8)

[51] Nowak, D.J. and J.F. Dwyer. 2007. Understanding the Benefits and Costs of Urban Forest Ecosystems. In: Kuser, J.E. Handbook of Urban and Community Forestry in the Northeast. New York: Kluwer Academic/Plenum Publishers. 25-46. (Accessed via Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation, p9)

[52] Wolf, K. 1998. Urban Nature Benefits: Psycho-Social Dimensions of People and Plants. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #1. Seattle, WA. (Accessed via Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation, p9)

[53] Laverne, R.J. and K. Winson-Geideman. 2003. The Influence of Trees and Landscaping on Rental Rates at Office Buildings. Journal of Arboriculture. 29(5):281-290. (Accessed via Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation, p9)

[54] Kuo, Francis E. and W.C. Sullivan. 2001. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? Environment and Behavior. 33(3):343-367. (Accessed via Reducing Urban Heat Islands: Compendium of Strategies - Trees and Vegetation, p9)

Planting strategies for cool vegetation

To make the most out of your tree-planting program, it is best to be strategic about where, what, and how to plant; choosing the right setting for your tree is critical to maximizing its energy-saving and cooling benefits. These strategies can help guide your decision on the best places around a home or building to place trees or other greenery.

Air Conditioners:

According to the EPA, one of the most cost-effective ways to reduce your cooling needs is to provide shade for the building's air conditioner and its immediate surroundings. Not only do air conditioners consume a lot of electricity, they also become less efficient as outdoor temperatures rise. Shade from trees or a vine-covered trellis on the air-conditioner can increase its efficiency by roughly 10 percent during peak periods.[55]

Windows

Shading windows and other glazed areas is a good way to reduce heat entering homes and buildings, thus conserving energy.

Walls and structures

Planting shade trees by the west- and east-facing walls (instead of north- or south-facing walls) is the most effective way to cool down building interiors

- Mature tree limbs should reach within 5 ft (1.5 m) of west or east walls and 3 ft (0.9 m) of south walls for optimal cooling and microclimate effects. Planting trees too close to the building can result in damage to the building foundation or potential danger from falling tree limbs.
- Tall shrubs should be planted within 4 ft (1.2 m) of west, east, and south walls. The plants should reach within 1 ft (0.3 m) of the walls after four years of growth.
- Be careful when planting trees along south-facing walls: Choose deciduous trees – which lose their leaves in the fall – so as to not block too much winter sunlight. Do not block south-facing windows.

Pavements and parking lots

Shading pavements can reduce outdoor surface temperatures, which in turn can help reduce the local air temperature in a community. Tree shade over a parking lot can also keep parked cars cool. This is important to reduce the evaporation of gasoline, which releases volatile organic compounds into the air, a precursor to ground-level ozone. Both Davis and Sacramento require that 50 percent of parking areas be shaded within 15 years of their construction.[56]

City-wide

To maximize the benefits of city-wide cooling, trees and shrubbery should be planted in all available spaces. Consider increasing vegetation in both public and private spaces such as plazas, street medians,

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[55] EPA. 1992. *Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing.* US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. p97.

[56] City of Davis. 1998. Parking Lot Shading Guidelines and Master Parking Lot Tree List Guidelines. Davis, CA. City of Sacramento. 2003. Tree Shading Requirements for Surface Parking Lots. Sacramento, CA. Accessed via EPA Compendium, p13

parking lots, by sidewalks, residential yards, parks, commercial zones, etc. Local governments can increase urban vegetation by including a zoning requirement for vegetation or new developments in the community.

Other tips

1. Consider planting vines while trees and bushes are young and reaching maturity. Though less effective than trees and shrubs, vines grow quickly and need less space and soil.

2. Inclusion of shrubs and groundcovers can increase cooling effects, especially if replacing concrete or asphalt.

3. Planting trees in clusters helps create a broader shadow and the trees can share soil and water.

4. If you have solar panels or collectors, be sure to not shade them!

5. Consider drawing up a solar path diagram, which outlines the sun's path through the sky in different seasons relative to the building, to help plan the positions of trees.

Tree Guide

Choosing the right trees and plants for your community depends largely on the general climate of the area as well as the specific microclimate of your planting site. Thus, there is no absolute guide to what species to plant, only general guidelines.

Here are some criteria to keep in mind when selecting species and types of plants. You can find additional information on the Resources page about specific tree species.

Water consumption

Water use is a significant concern for most areas in California. Choose trees or native plants that are adapted to the local rainfall patterns. In general, it is possible to increase vegetation without increasing water usage.

Research has shown that lawns consume more water than trees, which consume more water than shrubbery and groundcover.[57] So increasing total vegetation while decreasing lawn area can actually reduce water usage. Even shading lawns with trees and plants can decrease water usage.

Tree shape

The shape of a tree's canopy is important to specific locations. Columnar trees fit well in narrow spaces. Meanwhile, vase-shaped trees like elms are good for providing a shady canopy for streets and walls.

Figure 23 An elm tree (left) is an example of a vase-shaped tree that can provide good shade for streets and pedestrian areas. The tulip tree (right) is an example of column-shaped tree. Photo credit: Smaginnis11565 & Imatrukman (Flickr)

Tree height and location

When planting at a distance from a building, tall trees are ideal as they will cast a long shadow. When planting close to a building, trees with broad canopies will provide better shade. These trees are also better for parking lots and plazas, as they will cast larger shade areas.

[57] EPA. 1992. *Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing.* US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. p55.

Maintenance

Different trees require different levels of maintenance, including pruning and protection against disease and pests. On average, maintenance makes up 40 percent of the budget of a tree program, according to the American Forestry Association.[58] Tree selection, proper planting, and good landscaping can help lower the need for maintenance. Working with local horticulturists or arborists can help reduce maintenance costs significantly.

Diversity

Growing only a single species (monoculture) can have many negative ecological impacts. A diversity of plants helps to reduce susceptibility from disease and insects and increase support for local wildlife.

Native plants

Native plants help to support the local ecology and provide food and shelter for native wildlife. They are also better adapted to local climate patterns so can reduce maintenance for watering and pest control.

[58] EPA. 1992. *Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing.* US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division. p103.

Case Study: Sacramento

Founded in 1982, the **Sacramento Tree Foundation (STF)** seeks to maximize urban tree coverage in the greater Sacramento region to create healthy, sustainable communities. Their goal is to double the region's tree canopy (from 1981) by planting five million trees. Four million of these trees will be new trees, while one million will replace those currently in decline. At least 2.5 million trees will be directly or indirectly planted by the STF; the remaining will be planted by private homes and businesses.

More than a conventional tree-planting program, the STF seeks to catalyze a social movement through public-private partnerships, extensive education, and outreach activities to develop citizen foresters and encourage community-led urban forest activities. A key component of their strategy is the Greenprint initiative, the U.S.'s first region-wide tree planting campaign that covers 22 cities and 6 counties in the region.

Figure 24 Students planting a tree in Maryland. Photo credit: Keith Weller, US Forest Service

Regional Tree Expansion Framework

The Greenprint initiative is unique in the U.S. for creating a regional master plan to expand and steward tree coverage. Participants commit to working on three areas: managing their public trees, improving tree-related policies and ordinances, and building sustainable community partnerships. There are milestones and measurable targets for each of these three areas, including a regional tree inventory and developing 5-year and 20-year planting plans.

Sacramento Municipal Utility District (SMUD) Shade Tree Program Partnership with STF

To emphasize the ability of trees to save money on energy bills, SMUD developed the Shade Tree program in partnership with the STF in 1990. As part of the program, SMUD contracts with STF to provide up to 10 free shade trees to every residential utility customer. Businesses in the SMUD service area are also eligible for free trees, as are parking lots. From 1990 to 2013, SMUD's Shade Tree program has planted over 500,000 shade trees and 30,000 community trees in schools, parks and streets.

According to SMUD estimations, in 2013 alone, the 500,000 planted trees since 1990 saved 14.9 million kWh in direct cooling load and stored 13.5 million pounds of carbon.

Community education and outreach

The STF seeks to educate community members on the benefits of trees as well as good tree planting and maintenance practices. The Tree Foundation designs interactive curricula for Sacramento schools and youth groups, runs workshops, and leads tree-planting events in parks, schools, and other public areas. Community Foresters provide free advice for residents on tree-planting sites, tree species selection, and long-term care. These programs help STF to expand its volunteer base while engaging and mobilizing a community to take the lead in urban forestry and stewardship to help STF reach its goal of 5 million new trees.

Sidebar:

Cost Benefits

Planting 5 million trees will bring Sacramento an estimated **$7 billion in net benefits**. These benefits will come about through increased energy efficiency, reduced air pollution, reduced stormwater runoff, improved water quality, sequestered carbon, and improved property values.

Environmental Benefits

Over their 40-year lifespan, Sacramento's trees will have widespread benefits throughout the region, including:

- 3°F (1.6°C) reduction in summertime temperatures in the region
- 30 percent reduction in summertime energy usage
- 50 percent reduction in air pollution
- 648,000 metric tonnes of carbon sequestered every day
- 45 million metric tonnes of air pollutants removed from the air every year

Program Budget:

The annual budget for SMUD's Shade Tree program is about $1.5 million, which funds for the contract with the STF, tree purchases, marketing, and administration.

Major Contracts, Grant Providers, and Donors:

Sacramento Municipal Utilities District
California Department of Forestry & Fire Protection
Sacramento Metropolitan Air Quality Management District

Resources

Listed below are resources that can help you find a selection of trees that fit your local climate, growing conditions, and desired attributes. The online calculators can help you calculate the energy savings potential of each tree based on the species, climate zone, and planting site. There are also resources for information on managing an urban forestry program.

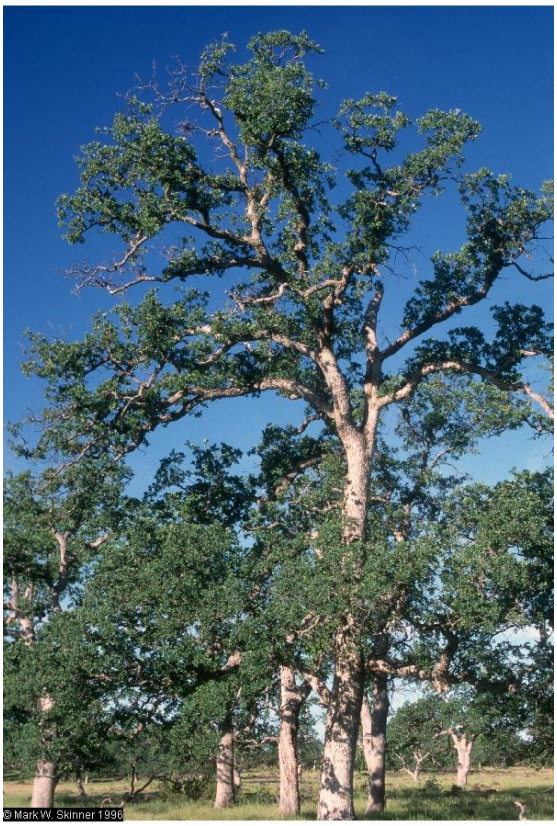

Figure 25 A blue oak tree. Photo credit: Mark Sinner, US Forest Service

Tree Guides

Urban Forest Ecosystems Institute

Run by the California Polytechnic State University, the **Urban Forest Ecosystems Institute** provides a comprehensive online tree guide. You can search for trees by name or by a detailed set of attributes, including health and environmental concerns, site conditions and constraints, leaf, flower, and fruit qualities, special uses, and more. Trees can be specified to be native to California. For each tree, the site provides a record containing growing conditions, characteristics, and notes.

The U.S. Forest Service

The U.S. Forest Service's Pacific Southwest Research Station has calculated and described the benefits and costs of planting trees for specific climate zones, including Sacramento, the San Joaquin Valley, and Coastal Southern California. These guides recommend trees for specific climate zones and can help better inform community leaders about creating and maintaining a community tree program:

Northern California
San Joaquin Valley

Coastal Southern California
Inland Empire Communities
Northern Mountain and Prairie

The California Native Plant Society
This organization is dedicated to preserving the native ecology of California. With 33 chapters around the state, the CNPS can help you find which plants are native to your specific region.

Tree Calculators

iTree
Developed by the USDA Forestry Services, iTree is a state-of-the-art, peer-reviewed software tool that analyzes and calculates the benefits of urban forests. Designed to help communities with urban forestry management, the software helps to quantify the many environmental benefits of urban forests. **iTree Streets** focuses on calculating the benefits of urban street trees. **iTree Design** uses Google Maps to analyze the energy, air quality, and stormwater-runoff benefits for a specific tree at a specific location and placement relative to a building. Communities can use **iTree Species** to choose between various tree species based upon the desired function and the geographical area. **iTree** software, including iTree Streets, is available for free as a download or CD-ROM from the website (www.itreetools.org), as are resources and manuals. **iTree Design** is available online (click here).

The National Tree Benefits Calculator
This user-friendly website uses iTree Streets data (see above) to calculate a basic approximation of the monetary benefits of trees planted in residential neighborhoods. Though it does not offer the depth and detail offered by the iTree Streets software tool, this tool provides a good basic approximation for those who want a quick estimate.

Center for Urban Forest Research Tree Carbon Calculator (CTCC)
This resource from the U.S. Forest Service calculates the amount of carbon dioxide sequestered (removed from the air and stored) by tree-planting projects. The CTCC is programmed in an Excel spreadsheet and provides information for a single tree located in one of 16 United States climate zones. The spreadsheet can tell users the quantity of carbon dioxide stored in the tree over its lifetime as well as in a single year. It can also calculate its cooling benefits and the resulting energy savings both in terms of electricity saved and tons of carbon dioxide avoided.

Program Implementation and Design

Urban Forest Management Plan
This comprehensive website, run by the California Urban Forest Council and the Inland Urban Forest Council, provides a detailed collection of resources to help communities manage their trees and forests.

Cooling our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing
Part of *Cooling our Communities*, a publication from the U.S. Environmental Protection Agency (EPA), Chapter 5, "Lessons Learned from Successful Tree Programs" (p63-92), is a good overview of best practices taken from urban forestation programs from around the country. The PDF can be found on the Lawrence Berkeley National Lab site, the EPA website, and on the University of California site.

Urban Tree Risk Management: A Community Guide to Program Design and Implementation
This publication from the U.S. Forest Service offers a guide on how to design and implement a program

to manage, evaluate, and reduce hazards from trees, such as disease.

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