WESTERN SYDNEY
UNIVERSITY

COOL ROADS TRIAL

2021

CITY OF PARRAMATTA
Blacktown City Council
CAMPBELLTOWN CITY COUNCIL

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This research was funded by the local governments of Blacktown City, Campbelltown City and Parramatta City.

With respect for Aboriginal cultural protocol, the Darug, Tharawal (also historically referred to as Dharawal), Gandangara and Wiradjuri people are acknowledged and thanked for permitting this work in their lands.

SUGGESTED CITATION:

Pfautsch, S., Wujeska-Klause, A. (2021) Cool roads trial. Western Sydney University, 48 p.

DOI: 10.26183/hstd-bj72
URL: https://doi.org/10.26183/hstd-bj72

www.westernsydney.edu.au

June, 2021.

Cover image: Sebastian Pfautsch; pages 5 and 8: unsplash.com;
all other images: Sebastian Pfautsch

PRÉCIS

Intensifying summer heat and associated Urban Heat Island Effects are a risk to public and environmental health. They contribute to higher energy consumption and associated greenhouse gas emissions in cities. Across Greater Western Sydney, home of the fastest growing urban population in Australia, increasing heat is recognised as the largest risk to local populations and economies. A range of interventions across the region aim at mitigating the negative impacts of heat.

The Cool Roads Trial is one of these interventions. It addresses the contribution of unshaded road and carpark surfaces to local heat island effects. In March 2020, 14,700 m² of road and carpark surfaces were coated with a highly reflective asphalt emulsion in the local government areas of Blacktown, Campbelltown and Parramatta to reduce surface temperatures of pavements.

The trial was accompanied by an environmental monitoring program. The program used measurements of surface, air and black globe temperatures to document the effectiveness of the surface coat on cooling. Data were collected between February 2020 and March 2021 using a full-factorial design with paired impact and control sites.

Results showed that surface temperatures of unshaded coated pavements were on average 6°C and at maximum 11°C cooler compared to uncoated pavements. Tree shade reduced temperatures of uncoated surfaces by 20°C and that of coated surfaces by 14°C leading to identical surface temperatures in the shade on coated and uncoated surfaces.

Surface coating did not systematically reduce air temperature during the day or night. Back globe temperatures during sunny days increased by 2.7°C on coated compared to uncoated sites as a result of increased reflectivity of the surface. The higher exposure to reflected solar incident radiation resulted in lower thermal comfort in the sun on coated surfaces.

The Cool Roads Trial established important information for the management of heat in Western Sydney and beyond. Increasing albedo of roads and carparks will help reduce surface Urban Heat Island Effects due to lower surface temperatures.

Ambient air temperatures were not lowered as a result of coating roads and carparks, which can potentially be a matter of scale. The Cool Roads Trial worked at the microscale where air cooling benefits could be masked by continuous mixing of local with surrounding air masses.

The range of thermal effects documented in this report make it clear that mitigating the impacts of urban heat will require a broad suite of solutions. A clear definition of desired thermal outcomes will be necessary on a case-by-case basis. Only once thermal outcomes are defined can resilience of urban populations, infrastructure and ecosystems against intensifying summer heat be improved effectively.

CONTENTS

1 BACKGROUND

The impacts of urban development and climate change accelerate the issue of excess heat stress in cities with negative impacts on local populations, economies, infrastructure and environments. More than 90% of Australia's population lives in urban landscapes that face continued growth, densification, expansion and associated development. Heat stress already has a severe impact on the quality of life in Australian cities and it is the foremost natural disruptor to life across the Greater Sydney Basin (Resilient Sydney 2018; WSROC 2018). Thus, identifying successful strategies and practical solutions that help mitigate urban heat is a necessity to maintain and where possible, improve the quality of life in our cities.

It is well documented that unshaded transport infrastructure, including roads and carparks, contribute significantly to local heat phenomena (Li 2015), including elevated night-time surface temperatures (Figure 1). The heating effect of these surfaces has two reasons. First, they are made from conventional asphalt, a material with high thermal mass and thus good storage capacity for heat. Second, the dark surface of asphalt has a low albedo coefficient (or simply *albedo*). This coefficient describes the ratio of incoming solar radiation to reflected radiation from the surface and is the most important characteristic of how a pavement material interacts with its surrounding environment when exposed to solar radiation (Van Dam et al. 2015). Low albedo means that incoming solar radiation is mostly absorbed and not reflected by the material in question. A material with very high albedo is pristine, fresh snow (albedo = 0.5-0.9). On the other side of the albedo spectrum is black asphalt used for the construction of road and carpark surfaces. Its albedo is just 0.03-0.04. During the aging process of asphalt, where its surface colour changes from matte black to a grey-silver appearance, its albedo increases to about 0.10-0.15. These levels of albedo are very similar to those observed for sheets of corrugated metal used for the construction of roofs – another material well known for its heat absorbing and heat radiating properties.

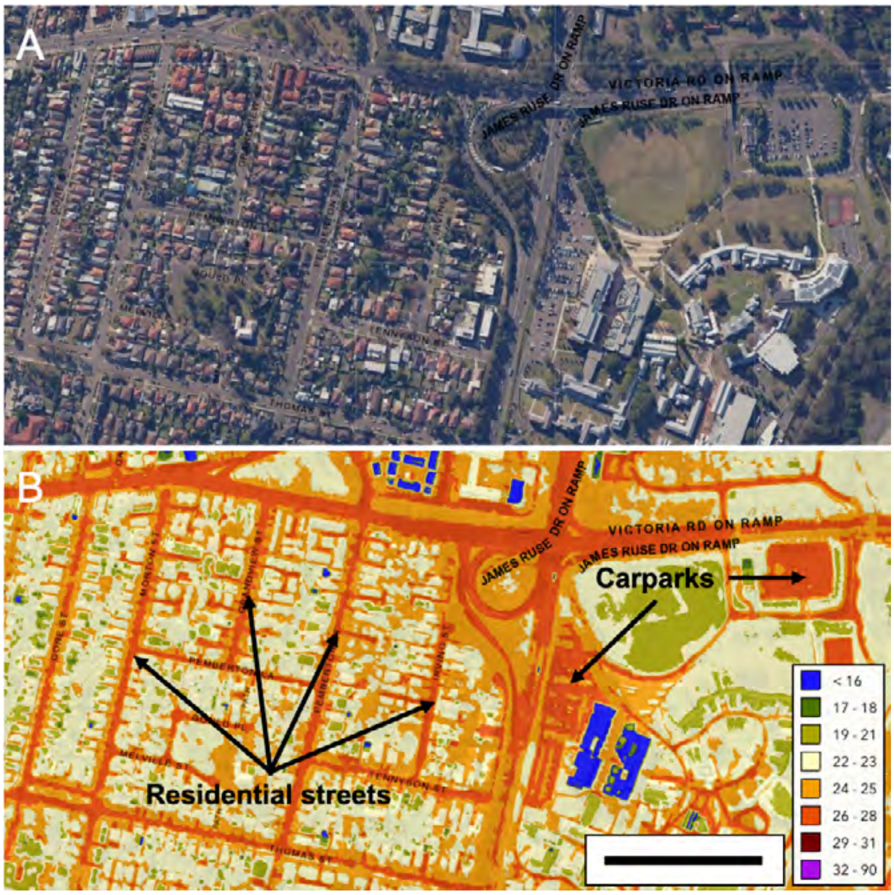


FIGURE 1: Effect of roads on night-time surface temperatures. (A) Normal view of Parramatta South with the Western Sydney University Campus on the right side. (B) Infrared view of the same area depicting surface temperatures in °C. Average ambient air temperature during the night when the image was captured was 22.6 °C. The high surface temperatures of residential streets and carparks are indicated. Scale bar = 200m. Image ©Department of Customer Service 2020.

A range of interventions to reduce the thermal impact of roads and carparks are available. While the most effective intervention is to avoid construction of roads and carparks in our cities in the first place, it is also the most difficult to implement. However, with the rise of alternative modes of transport (i.e., shared vehicles, airborne vehicles), improved public transport and car-free road and city projects (e.g., Ultra Low Emission Zones in London), road and carparking space will become available for transformation into uses that provide cooling instead of heating to the urban environment. Such projects have already been implemented successfully in the United States (e.g., West End Square, Dallas) and Australia (e.g., Prahran Square, Melbourne).

A practical intervention can be to cast shade on sun-exposed asphalt surfaces using tree canopy or man-made shade structures. Trees provide thermal benefits by transpiring water whereby air temperatures are cooled. Trees also shade surfaces around them, which reduces the exposure, storage and re-radiation of solar energy. Both processes, evaporative cooling and shade cooling make tree canopies an effective tool to increase resilience against urban heat and support liveability of our cities (Oke et al. 1989). Planting trees that develop dense and wide crowns at maturity will deliver best thermal benefits in carparks and along wide streets (Akbari, Pomerantz & Taha 2001; Onishi et al. 2010; Takebayashi & Moriyama 2009). However, expanding tree canopy cover in cities can be challenging, because space is generally limited, expensive and often has pre-assigned uses that prevent addition of trees. Man-made shade structures can include fabric sails, fixed conventional, green or solar roofs and pergola-type structures. Also, climbers, vines and other plants grown on trellises can be used to shade roads and carparks (currently tested in Darwin and soon in Holroyd).

Other interventions replace asphalt with materials that have a higher albedo. These materials are collectively referred to as *cool pavement technologies*. The capacity of high albedo materials to reduce urban heat and lower costs of electricity for air conditioning have been known for more than two decades (Bretz et al. 1998), but recent extreme heat events have resulted in wider interest in adopting these technologies.

Replacing black asphalt with light-coloured concrete (e.g., Ascrete® - a rubberised cement) will increase albedo and should theoretically reduce surface temperatures (Fig. 2). A trial in Marrickville, Sydney, demonstrated that albedo of Ascrete was nearly three times (0.23) that of asphalt (0.08) (Coutts et al. 2016). However, the same study also found that surface temperature during the day on conventional asphalt and Ascrete was very similar, and that thermal benefits of the cooler road surface only came into effect during the night. During that time a lower flux of sensible heat from Ascrete meant that radiated energy was contributing less to warming of near-surface air. While the reduction of night-time air temperature documented by Coutts and colleagues was relatively small over Ascrete (-0.2 °C compared to that over asphalt), they concluded, similar to Li et al. (2013), that "cool pavements are an effective approach for mitigating the urban heat island".

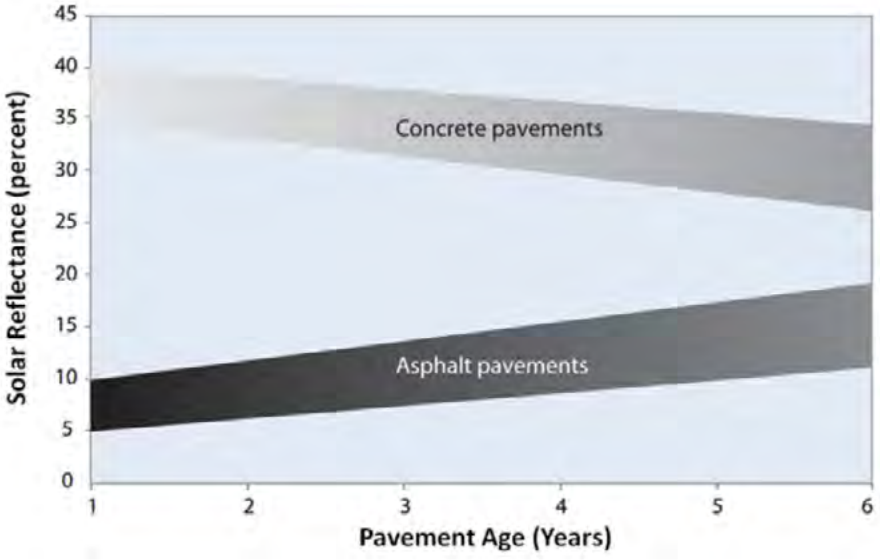


FIGURE 2: Temporal changes in solar reflectance (surrogate for the albedo coefficient) of conventional asphalt and concrete pavements. Clear and opposite aging effects can be expected for the two materials. Image © EPA 2008.

Conventional asphalt is not permeable to water. This leads to costly construction and maintenance of infrastructure to collect and direct stormwater runoff from these surfaces. However, use of permeable black asphalt not only reduces costs related to construction and maintenance of stormwater infrastructure, but it is also likely to result in lower surface temperatures. This cooling effect is generated by conversion of surface heat to latent heat when water evaporates at the surface-to-air interface. In carparks, impermeable asphalt can be replaced by reinforced turf (e.g., grass diamond pavers, grass reinforcement mesh, TurfProtecta®) or other permeable, light-coloured materials (e.g., FlowStone®, permeable pavers, TruckCell®, crushed and compacted sandstone) to reduce local heat island effects and allow absorption of stormwater. Using permeable surface materials will generally increase plant available soil water, which in turn helps maximise cooling benefits generated by green infrastructure. Most of these solutions can be applied to carparks but are not suitable for roads with high traffic frequency.

Another option is to increase the reflectivity of the surface. This option is viable for any conventional asphalt surface and can be achieved by applying an engineered surface coat that has high reflectance properties in the near infrared spectrum. In 2017 and 2018, the City of Los Angeles made headlines around the world when its workers began to paint residential streets with such engineered surface coats to combat summer heat. Since then, the city has announced its *Cool Streets LA program*, which combines a range of cooling applications, including painting more roads and carpark surfaces to further reduce heat stress of its population (https://www.lamayor.org/mayor-garcetti-kicks-cool-streets-la). A comprehensive study for the region in coastal California has modelled the effect of widespread application of reflective paint on road surfaces (increasing albedo to 0.4) and found that near surface air temperatures in urban areas could be reduced by 0.2 to 0.9°C (Mohegh et al. 2017).

At the time this report was written, a small number of cool surface coat products were commercially available in Australia (e.g., CoolSeal, Jet Cool, Jet Block, Cool Pave) and their efficiency to mitigate urban heat had been field tested. The City of Adelaide in collaboration with a number of other government agencies and private consultants assessed the effective surface and air cooling of the three aforementioned products (Edge Environment 2020). Field measurements of the study showed that CoolSeal produced the highest reduction in surface temperatures compared to black asphalt during the day (-8.65°C) and also during the night (-4.2°C). However, measurements of air temperatures at different heights above the coated and uncoated surfaces provided inconclusive results without systematic trends.

To date, only a single study (Coutts et al. 2016) is available for the Greater Sydney Basin that has field-tested the effect of cool pavement technology. This study took place in Eastern Sydney where the summer climate can be less harsh compared to that of Western Sydney. Would the observed reductions in surface and air temperature be similar or different between the two regions? Further, this study did not test a cool surface coat, but replaced conventional asphalt with Ascrete. The study from Marrickville also noted that higher reflectance of a surface can increase glare and exposure of pedestrians to higher levels of reflected solar radiation. It is unknown if these effects are intensified during hot, clear days in Western Sydney. Lastly, the potential of cool surface coats to reduce night-time air temperature remains understudied. Urban heat island effects are especially pronounced during the night where radiated energy from hard surfaces and buildings warms the air.

2 THE COOL ROADS TRIAL

The summer climate of Western Sydney is steadily warming since the middle of the 1990s. While climate modelling for the region predicts an increase of 5-10 hot summer days (i.e., days where air temperature exceeds 35 °C) in the coming two decades (NSW Office of Environment and Heritage 2014), empirical research has demonstrated that the region is already experiencing much more frequent and intense heat locally compared to official weather data from the Bureau of Meteorology (e.g., Pfautsch and Rouillard 2019 a, b, c; Pfautsch et al. 2020). For example, according to data recorded by an official weather station at Sydney Olympic Park the communities of Parramatta City endured daytime maximum temperatures above 35 °C during 10 days in the summer of 2018/19. Using a network of more than 100 data loggers, Pfautsch and Rouillard (2019a) documented daytime maximum temperatures above 35 °C during 47 days in the same summer. The work of Pfautsch and colleagues has highlighted the importance of scale when attempting to mitigate urban heat, as effective interventions will most likely take place locally, addressing microclimate phenomena.

Cooling residential roads and carparks represents such a local approach and the Cool Roads Trial was a coordinated action of three local governments in Western Sydney as response to increasing summer heat. The trial sought to increase the albedo of roads and carparks by applying a surface coat to determine the efficacy of this intervention to reduce heat loads at a local scale. Under the leadership of Parramatta City Council, the project commenced in September 2019. A complete project timeline is shown in Figure 3.

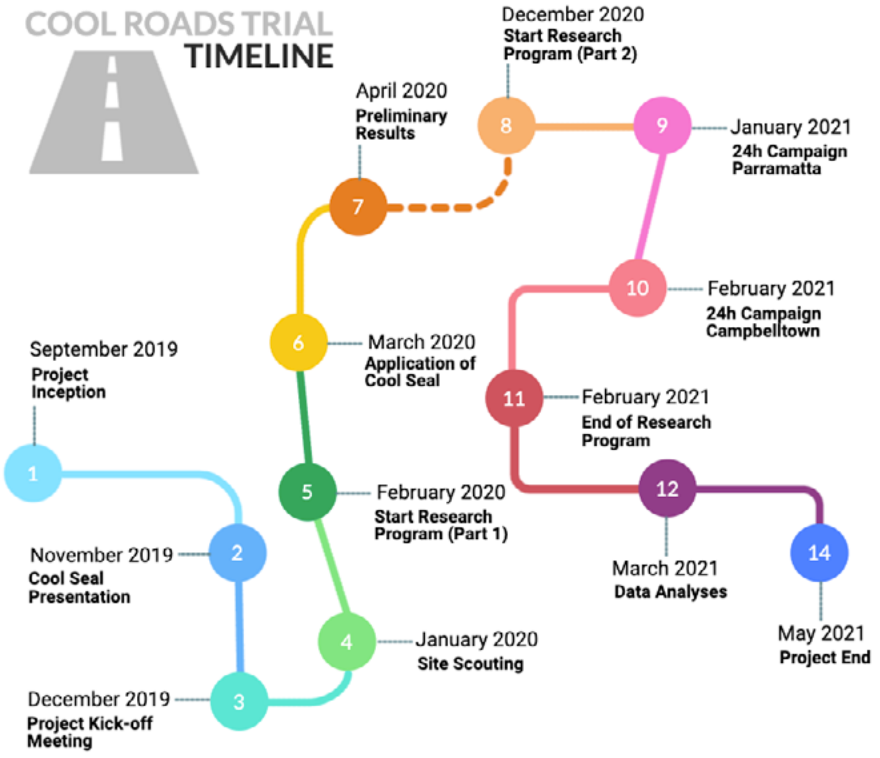


FIGURE 3: Cool Roads Trial project timeline.

Local governments in South Australia have implemented similar trials, though smaller in scale. For the Cool Roads Trial, these organisations were contacted to learn first-hand about available products, their quality and cost. Also, avenues for community engagement, practical considerations (e.g., coordinating road work with rubbish collections), barriers and lessons learned were discussed. Based on the information gathered and initial discussions with suppliers, representatives of Supersealing, the distributors of CoolSeal in Australia, were invited to introduce their product to the Cool Roads Trial consortium. CoolSeal is a surface coat manufactured by Guard Seal in the United States. It is a water-based asphalt emulsion with high reflectivity (33%).

Following these initial discussions, local governments of Parramatta, Blacktown and Campbelltown agreed to proceed with the trial. In consultation with their road engineers, site scouting across the suburbs of the participating councils commenced in October 2019. In January 2020, this work had resulted in the identification of suitable sites in three major locations in central, far western and southern Western Sydney (Fig. 4). The geographical distribution and variation in local climate zones (after Stewart and Oke 2012) of trial sites ensured that the cooling potential of CoolSeal could be assessed in a range of settings. The local climate zones included (1) open low-rise with scattered trees, (2) compact low-rise and (3) sparsely build with low plants.

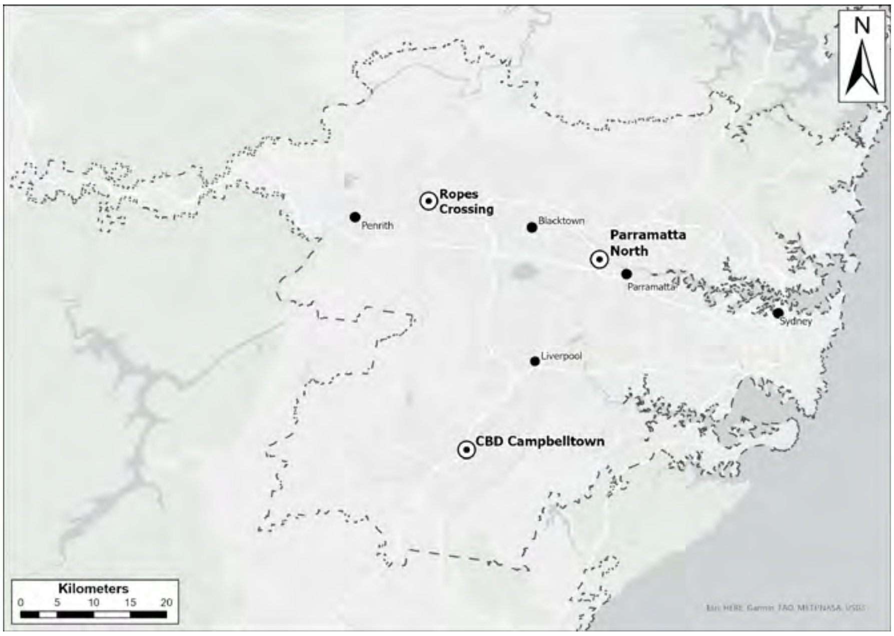


FIGURE 4: Location of the trial sites in central (Parramatta), far western (Ropes Crossing) and southern Western Sydney (CBD Campbelltown). The dashed grey line encircles Greater Metropolitan Sydney. More detailed aerial maps for all sites where CoolSeal was applied are provided at the end of this report.

A total of 12 sites were identified as suitable for coating (Supplementary Table 1). Sites were in North Parramatta, Northmead, Old Toongabbie, Ropes Crossing and the CBD of Campbelltown and included eight residential streets and four carparks. A consultation process was put in place where staff from each council personally contacted each household in effected residential streets to provide information about the trial. This process involved development of informative handouts, distribution of questionnaires and feedback forms and a door-knocking event. In addition, semi-permanent signs were designed for deployment at trial sites (Fig. 5).

FIGURE 5: Example of one of the project signs. Key elements included a brief explanation of the trial, an infrared image that documented high surface temperature of the street prior to application of the reflective seal coat, project partners and contact details.

WHAT'S HAPPENING HERE?

Cool Roads Trial

This street has been selected to take part in the Western Sydney Cool Roads Trial.

Asphalt roads absorb heat from the sun, making streets and surrounding homes hot.

This road has been coated with a light grey coloured coating which on a hot day can be 5 – 14° C cooler than regular dark asphalt.

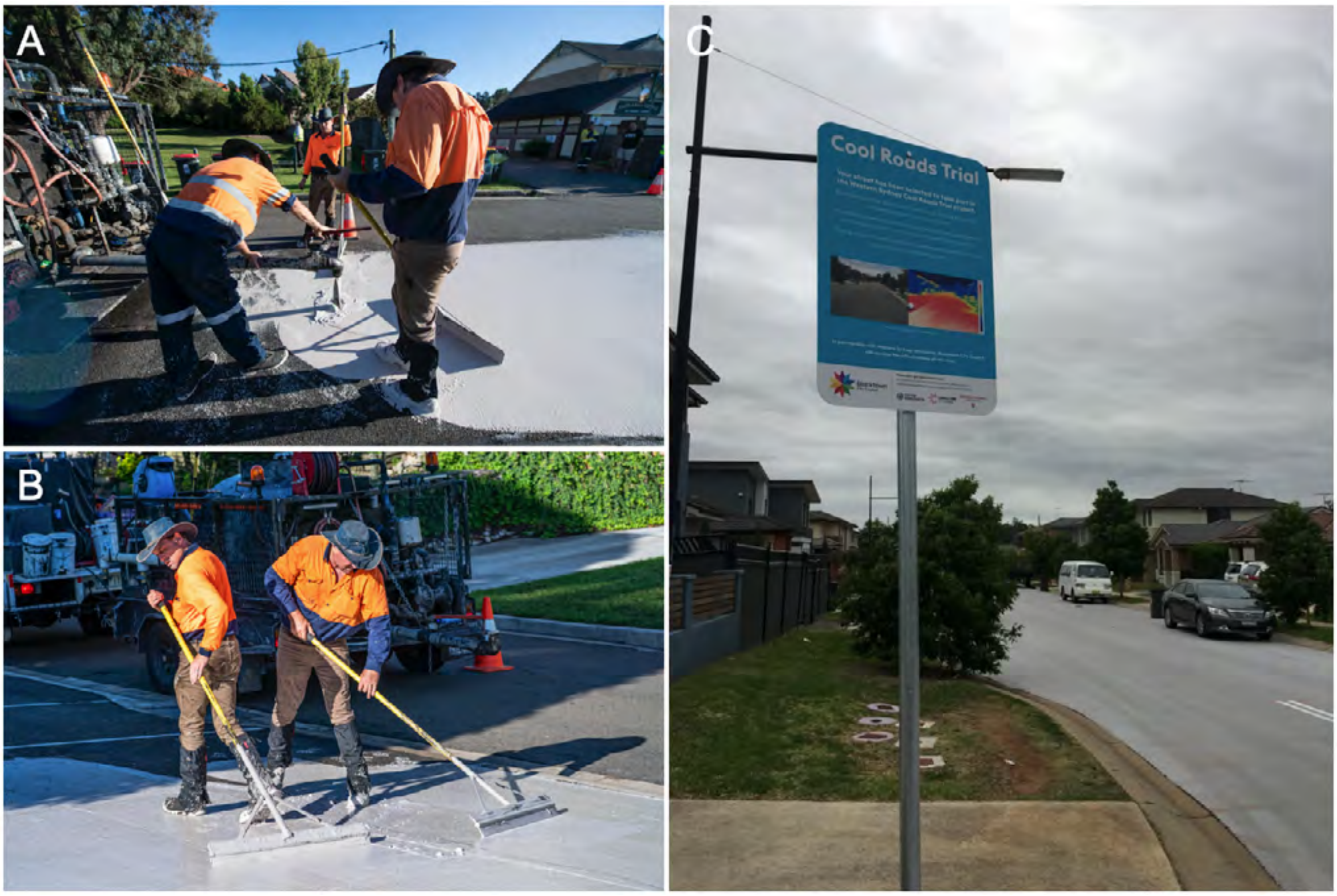
In conjunction with planting more trees for shade, cooling roads will make streets more comfortable places to live and play, and help reduce household energy costs.

Thermal image showing hot road surface compared to other areas

The City of Parramatta is working in partnership with Blacktown and Campbelltown councils, and Western Sydney University, who will monitor the effectiveness of this trial.

Where can I get more information?

For more information about this project, please visit Councils website or email environmentallysustainable@cityofparramatta.nsw.gov.au



Road and carpark surfaces of all sites were in good condition with minimal crack sealing and patches of repaired asphalt. In late March 2020, any minor damages as well as oil spills were eliminated on all surfaces. Following this preparation, a double coat of CoolSeal was applied. Road barriers blocked streets and carparks from traffic for a few hours to allow curing of the fresh coat. A total of 14.700 m^2 conventional asphalt was transformed from a highly heat absorbing to a highly heat reflecting surface (Figure 6; Supplementary Table 1). Project signs were installed at each site.

An environmental monitoring program, following the principle of a Before-After-Control-Impact design (Smith 2002) was implemented to evaluate the capacity of CoolSeal to reduce surface and air temperatures. Parameters documented during the monitoring program, measurement intervals and the instruments used for this work are explained in the next section.

FIGURE 6: Application of CoolSeal. (A) Pouring of first coat of CoolSeal. (B) Application of the seal coat using floor squeegees. (C) Cool Roads Trial sign and coated road surface at Kobe Street, Ropes Crossing.

3 MEASUREMENTS

Over the course of the trial, three techniques were used to document surface and air temperatures as well as human thermal comfort. These techniques were

- Infrared thermography (ground-based and airborne; spot measurements)
- Air temperature measurements (spot measurements and continuous data recording)
- Black globe temperature measurements (spot measurements)

Data were collected between 24 February 2020 and 16 March 2021. Environmental conditions were monitored at 19 locations, of which 10 were coated while the remaining sites were used as uncoated controls. Prior to coating, pavement type at all sites was black asphalt. Environmental conditions were assessed in greater detail at three paired sites (uncoated next to coated), termed ‘core sites’. One pair of core sites was in a suburb of each participating local government (Table 1). All additional sites were in Ropes Crossing (Blacktown local government area), North Parramatta and Old Toongabbie (Parramatta local government area).

TABLE 1: Monitoring locations. Periodic measurements of air and surface temperatures as well as human thermal comfort were collected at all sites. Continuous measurements of air temperature were only collected at core sites. LGA = Local Government Area. LCZ = Local Climate Zone; (1) open low-rise with scattered trees, (2) compact low-rise and (3) sparsely build with low plants. Identical symbols next to the street names of additional sites indicate that these sites were uncoated-coated pairs.

SITE STATUS	LGA	SUBURB	STREET ADDRESS	LCZ	LATITUDE (°)	LONGITUDE (°)	SURFACE CONDITION
Core Site	Blacktown	Ropes Crossing	Kobe Street	2	-33.724795	150.784306	Coated
			Mackay Circuit	2	-33.724582	150.783604	Uncoated
	Campbelltown	Campbelltown	HJ Daley Library (public carpark)	3	-34.069765	150.807014	Coated
			HJ Daley Library (staff carpark)	3	-34.070087	150.806118	Uncoated
	Parramatta	Northmead	Roslyn Avenue	1	-33.791446	150.991975	Coated
			Raymond Avenue	1	-33.792217	150.992549	Uncoated
Additional Site	Blacktown	Ropes Crossing	Barlett Street	2	-33.731285	150.783301	Coated
			Burnette Court	2	-33.730678	150.781691	
			Mortlock Avenue	2	-33.730363	150.781994	
			O’Donoghue Street	2	-33.731220	150.781533	
			Avoca Street	2	-33.730714	150.782695	Uncoated
			Herford Street	2	-33.730675	150.778946	
			Hollows Parade	2	-33.731750	150.783316	
	Parramatta	Old Toongabbie	Binalong Park (public carpark) +	3	-33.788359	150.965430	Coated
		North Parramatta	Corry Court ‡	3	-33.801027	151.016096	
		Old Toongabbie	Renoir Street *	1	-33.785920	150.968957	
		North Parramatta	Belmore Street ‡	1	-33.800662	151.015276	Uncoated
		Old Toongabbie	Binalong Park (overflow carpark) +	3	-33.788952	150.965446	
		Old Toongabbie	Picasso Crescent *	1	-33.784971	150.969357	

3.1 INFRARED THERMOGRAPHY

The effect of CoolSeal on surface temperature was quantified using radiometric infrared cameras and radiometers. A handheld infrared camera (T540, FLIR Systems, Wilsonville, OR, United States) was used to collect ground-based imagery. Ground-based infrared images were collected at all sites before and after the application of CoolSeal, resulting in more than 700 images. A M210 RTK aircraft (DJI, Shenzhen, China) was used to carry a FLIR Zenmuse-XT2 dual band camera for aerial imaging. Both cameras simultaneously take RGB (red-blue-green) as well as infrared images. Aerial observations of surface temperatures were collected at sites in North Parramatta (Corry Court), Old Toongabbie (Binalong Park) and Campbelltown CBD. Due to restricted air space, no aerial images were collected at sites in Ropes Crossing. A total of 278 image and video files were produced using the aircraft-based camera.

FLIR Tools software was used to extract surface temperatures from individual images. In each image, five individual random spot measurements were recorded and averaged for each target surface. Across all sites, 770 measurements were extracted from infrared images taken under different ambient environmental conditions during nine measurement days. Following the BACI experimental design, we extracted surface temperatures for identical dates and closely aligned times at paired locations (control = uncoated vs. impact = coated) before and after the application of CoolSeal. This resulted in data from 18 sunlit control-impact sites and 4 shaded control-impact sites before surfaces were coated. Once the surface coat was applied, we generated data from 45 paired sites in the sun and 10 paired sites in the shade. Locations and dates for sites where the relevant infrared images were collected are listed in Table 2.

TABLE 2: Street names and collection dates for infrared images. Cells filled black indicate data collections took place before application of the surface coat, and those filled with grey indicate campaigns after the application of the seal coat.

	SAMPLING DATES FOR INFRARED IMAGES								
STREET	**24.02.20**	**25.02.20**	**02.03.20**	**19.03.20**	**20.03.20**	**15.04.20**	**17.04.20**	**02.12.20**	**03.12.20**
Kobe Street	■				▒			▒	
Mackay Circuit	■				▒			▒	
HJ Daley Library (public carpark)		■	■				▒		▒
HJ Daley Library (staff carpark)		■	■				▒		▒
Roslyn Avenue	■			▒		▒		▒	
Raymond Avenue	■			▒		▒		▒	
Barlett Street					▒				
Burnette Court					▒				
Mortlock Avenue		■			▒				
O'Donoghue Street	■	■						▒	
Avoca Street		■							
Herford Street		■							
Hollows Parade	■								
Binalong Park (public carpark) +	■		■				▒		
Corry Court ‡		■		▒		▒			
Renoir Street *								▒	
Belmore Street ‡		■				▒			
Binalong Park (overflow carpark) +	■		■				▒		
Picasso Crescent *								▒	

While all infrared images were captured during the day, three additional field campaigns were designed to document complete 24-hour cycles of surface temperature dynamics. These campaigns were used to document heating and cooling dynamics of coated and uncoated road surfaces. To capture these dynamics, two infrared radiometers (SI431, Apogee Instruments, Logan, UT, United States) were deployed. The radiometers had an ultra-narrow aperture (half-angle = 14°) to ensure that only road surface temperature was measured even from a greater distance. The radiometers measured surface temperature every second and averaged measurements were stored on a logger (CR300, Campbell Scientific, Garbutt, QLD, Australia) every 5 minutes. The instruments were enclosed in water-proof housings and powered by sealed lead-acid batteries. Images of all instruments used for the environmental monitoring work are shown in Figure 7.

The first 24-hour campaign was monitoring conditions at Roslyn and Raymond Avenues in Northmead. This campaign started at 15:20 on 15 April 2020 and ended at 10:10 on 18 April 2020. The infrared radiometers were mounted onto lower branches of street trees. Air temperatures during 17 April were warm and the sky was cloudless. Data recorded from 06:00 on 17 April to 06:00 on 18 April were analysed. A second campaign in the same two streets was initiated at 06:00 on 12 January 2021 and ended at 06:00 on 13 January 2021. Again, air temperatures were warm, and the sky was clear. For this work, infrared radiometers were mounted on tripods (1.2 m above ground) and positioned at the curb to capture road surface temperatures. The third campaign took place at the public and staff carparks of the HJ Daley Library in the CBD of Campbelltown. It commenced at 16:00 on 28 February and lasted until 10:00 on 2 March 2021. Infrared radiometers were mounted onto light poles from where their sensors were pointed at carpark surfaces. Data recorded from 06:00 on 1 March to 06:00 on 2 March were analysed. Environmental conditions were warm with a cloud-free sky.

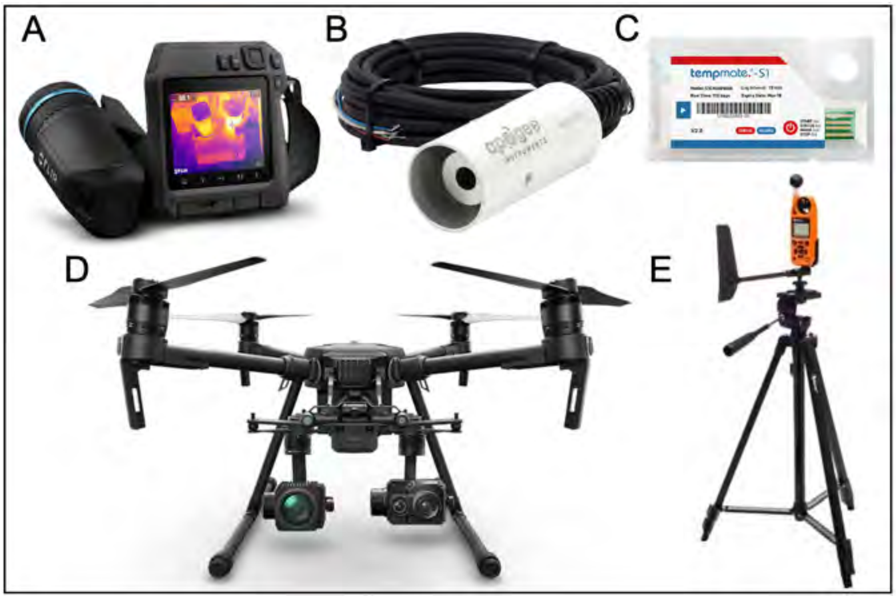


FIGURE 7: Instruments used to monitor a range of temperatures during the Cool Roads Trial. A: FLIR T540, hand-held radiometric infrared camera for on-ground spot measurements of surface temperature. B: Apogee T400 radiometer for continuous measurement of surface temperature. C: Tempmate S1 V2 temperature sensor for continuous measurement of ambient air temperature. D: DJI M210 aircraft and FLIR Zenmuse-XT2 for aerial spot measurements of surface temperature. E: tripod-mounted Kestrel 5400 Heat Stress Tracker with black globe thermometer as proxy for human thermal comfort.

3.2 AIR TEMPERATURE

Ambient air temperature was recorded at 10-minute intervals between 24 February and 24 May 2020 and from 4 December 2020 until 16 March 2021. Bespoke temperature loggers were used to record these data. Construction, technical details and calibrations of the loggers against other commercially available air temperature sensors, as well as official temperature data from the Bureau of Meteorology have been published in Pfautsch et al. (2020) and Wujeska-Klause and Pfautsch (2020). The loggers consisted of a single-use temperature sensor (Tempmate S1 V2, Imtec Messtechnik, Heilbronn, Germany; accuracy: ±0.2°C), a weather shield and mounting straps. Each temperature logger was positioned in a single street tree, approximately 2.5-3 m above ground. In each street, trees at the beginning, middle and end were equipped with loggers to capture potential inter-street variation of air temperature. We deployed a total of 18 temperature loggers (three core sites = six streets, three loggers per street) at the start of both measurement campaigns. Where possible, temperature loggers were mounted on tree branches that extended over the road.

We retrieved 15 temperature loggers at the end of the first campaign and 18 at the end of the second campaign. Two temperature loggers were lost in Mackey Circuit (Ropes Crossing, Blacktown LGA) and one at Raymond Avenue (Northmead, Parramatta LGA). Temperature loggers were returned to the laboratory for data downloads. A total of 165.600 individual measurements of air temperature were recorded during the first measurement campaign and another 311.500 measurements during the second measurement campaign. Data were pooled for each street prior to in-depth analyses. These analyses were concerned with general trends among the sites, before-after-impact-control effects and the capacity of CoolSeal to influence daytime (10:00-17:00), maximum and night-time (00:00-05:00) air temperatures.

3.3 HUMAN THERMAL COMFORT

A ‘feels like’ temperature represents a measure of heat experienced by a human in a specific location. Locations differ in their thermal and environmental characteristics that in combination create site microclimate. A feels like temperature represents the thermal sensation of a human under the simultaneous influence of several important environmental factors. A black globe thermometer can capture these combined effects and is commonly used to track heat stress in work health and safety applications. The black globe is designed to capture the temperature a seated adult human would experience in a specific location under the influence of site microclimate. It provides a composite measure of ambient air temperature, heat transfer by incident solar radiation and convection of heat between the globe and the environment, as well as wind speed (Olivera et al. 2019). We used the Kestrel Heat Stress Tracker (Model 5400, Kestrel Instruments, Melbourne, VIC, Australia) with its integrated black globe thermometer (a 25 mm diameter copper sphere with a matt black surface) to record ambient environmental conditions at the same time when ground-based measurements of surface temperatures were collected. Accuracy of the black globe thermometer was ±1.4°C.

The Heat Stress Tracker also calculates the Heat Index based on measurements of air temperature (accuracy: ±0.5°C) and relative humidity (accuracy: ±2%). The calculation is based on recommendations from the National Oceanic and Atmospheric Administration (NOAA) of the United States. More information about the Heat Index can be found here: https://kestrelinstruments.com/mwdownloads/download/link/id/11. The Heat Index was evaluated as additional variable that documents thermal comfort. This measurement does not incorporate reflected solar radiation from surrounding surfaces.

The instrument was connected to a vein mount which was screwed onto a conventional tripod. Each of two black globe thermometers were positioned 1.2 m above ground to record feels like temperature at a typical height for the centre of body mass of an adult human. Measurements were collected in the full sun and one instrument was positioned on a coated surface, the other on an uncoated surface. When shifting between measurement locations, care was taken that the instruments remained in the same conditions (i.e., on coated or uncoated surface), which shortened the time interval for equilibrating to environmental conditions (usually around 10 minutes). Once air temperature data was stable, we recorded ambient environmental conditions for 5 minutes at 30 second intervals. Data were stored on the instrument and downloaded for analyses at our laboratory. Individual measurements over each 5-minute interval were averaged and ±1 Standard Deviation (SD) was calculated to document the variability of measurements for each measurement interval.

In addition to recording black globe temperatures, we used the Heat Stress Tracker to evaluate the cooling benefits of tree shade. For this purpose, we deployed two instruments simultaneously in a shaded and a sunlit position on either uncoated or coated surfaces. This allowed us to calculate the effect of shade on feels like temperature, but also on air temperature.

4 RESULTS

4.1 SURFACE TEMPERATURE

Before the cooling capacity of CoolSeal could be assessed, it was important to establish that there were no systematic surface temperature differences between control and impact sites prior to the application of CoolSeal. Surface temperature data clearly showed that roads and carparks did not vary systematically before the application. As depicted in Fig. 8, the measurements for sunlit surfaces fell on the upper end of the 1:1 line[1]. The coefficient of determination (R^2) for the relationship between the two temperatures indicated a high probability (80%) to predict surface temperatures at impact sites based on those at control sites. Mean surface temperatures were 54.2°C (±6.3; ±1 SD) at control sites and 53.7°C (±6.2) at impact sites.

Like sunlit surface temperatures, also those measured on shaded surfaces were similar before the application of CoolSeal. Measurements fell onto the 1:1 line (Fig. 8) with a very high coefficient of determination ($R^2 = 0.93$). Mean surface temperatures on shaded surfaces were 36.8°C (±1.9) at control and 36.6°C (±1.9) at impact sites.

CoolSeal significantly ($p<0.001$) lowered surface temperatures of sunlit asphalt road and carpark surfaces. Following the application of CoolSeal, surface temperatures declined on average by 5.9°C (±2.8). Surface temperatures were slightly lower compared to measurements prior to the application as a result of seasonal variation and collection of 'before' data during predominately hot days in late February and early March 2020. Mean surface temperatures in the sun were 41.2°C (±6.9) on uncoated roads and carparks (control sites) and 35.3°C (±6.0) on those that were coated (impact sites). The relationship between these paired measurements was strong ($R^2 = 0.84$) and deviated from the 1:1 line. This deviation was an important finding and was assessed in greater detail.

Mean maximum temperatures were 54.9°C on uncoated and 48.5°C on coated sunlit

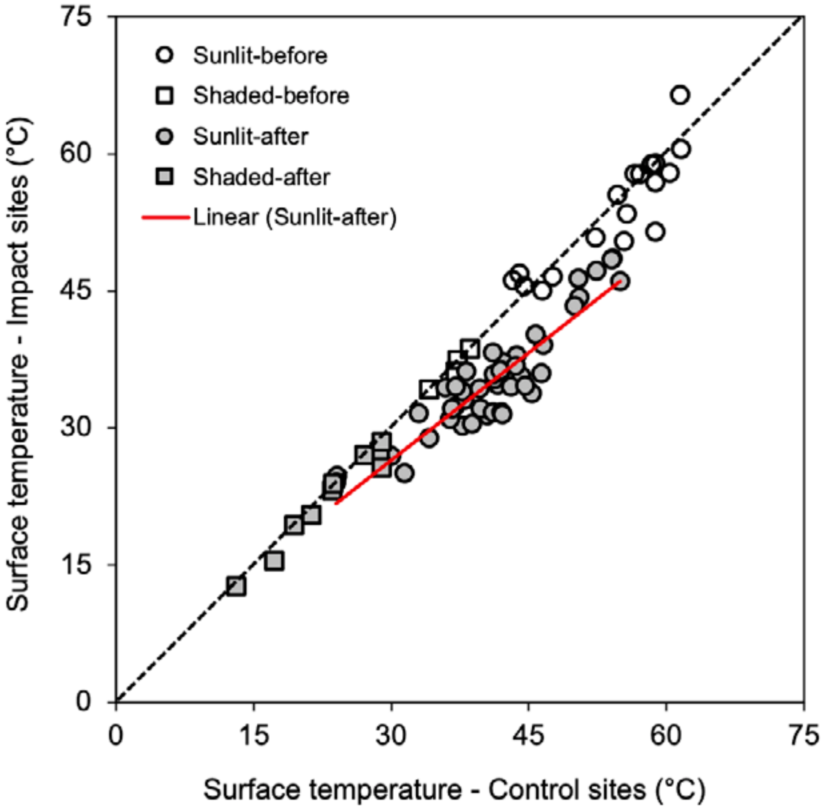


FIGURE 8: Relationship between surface temperatures on uncoated and coated as well as sunlit and shaded surfaces before and after the application of CoolSeal. The black, dashed line shows the 1:1 relationship; the solid red line depicts the linear relationship between surface temperatures measured on uncoated and coated sites in the sunshine. For reasons of clarity, lines for the linear relationships of the other measurement pairs were not included as they fell exactly onto the 1:1 line where they become invisible. The coefficients of determination (R^2) of these relationships are reported in the text.

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[1] The 1:1 line describes the perfect relationship where two variables plotted on a xy-scatter plot are identical.

surfaces. The largest cooling effect of CoolSeal measured during the Cool Roads Trial was 11.5°C. This measurement was recorded on sunlit surfaces during the afternoon of 17 April at Campbelltown. When shaded, CoolSeal did not reduce surface temperatures, as indicated in Fig. 8, where data for shaded sites fell onto the 1:1 line. The relationship between these paired measurements was very strong ($R^2 = 0.96$).

Our data analyses of 450 individual surface temperature measurements revealed that the linear relationship between sunlit surface temperatures of coated surfaces and those that are uncoated followed the equation:

$T_{coated} = 0.79 \times T_{uncoated} + 2.8$

As the formula indicates that the slope of the relationship was smaller than 1, leading to a deviation of the predicted temperature on a coated, sunlit surface from the 1:1 line (as shown in Fig. 8). In combination with the intercept that was larger than 1, the deviation from the 1:1 line increased as temperature of uncoated surfaces rose. This effect, captured by our data, suggests that the cooling benefits of CoolSeal increased proportionally when surface temperatures became increasingly hotter. When plotting this relationship, it became clear how cooling benefits progressively become larger (Fig. 9). As shown in Figure 9, the difference in surface cooling increased from 2.5°C at an uncoated surface temperature of 25°C to 13°C when the uncoated surface was 75°C hot. We note that maximum surface temperatures measured during the Cool Roads Trial were below 70°C even on very hot and clear summer days before the surface coat was applied and we did not observe a 13°C reduction. However, for reasons of applicability, Figure 9 depicts a range of surface temperatures that have been reported in the literature.

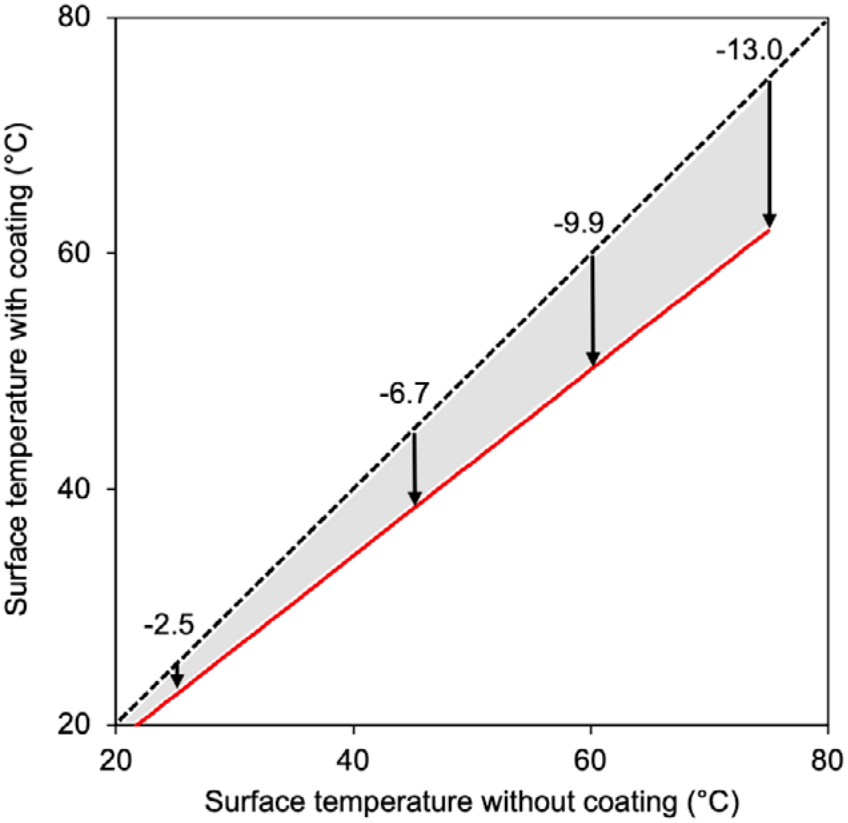


FIGURE 9: Predicted surface cooling benefits from CoolSeal at increasing surface temperatures. Temperature reductions are shown for coated surfaces when uncoated surfaces are 25, 45, 60 and 75°C hot. The dashed black line indicates the 1:1 line; the solid red line shows the linear relationship between the two parameters based on data shown in Figure 8. Here we show a truncated relationship covering a range of 55°C (20-75°C). The linear relationship was established using 450 individual measurements of surface temperatures.

Shading road surfaces resulted in maximum reductions of surface temperatures by 27 °C (Corry Court, 25 February 2020, 51°C in the sun, 24°C in the shade). Across all sites included in this study, tree shade reduced surface temperatures of roads by 16°C with overall higher reductions during days with hot and very hot air temperatures. Focussing on core sites only, shading reduced road surface temperatures by 20°C prior to application of CoolSeal (Table 3). After application of CoolSeal, tree shade reduced the surface temperature of uncoated roads by an average of 19.5°C, which is similar to the cooling effect measured prior to coating. Tree shade on coated roads reduced surface temperature on average by 18.4°C before and 13.5°C after application of CoolSeal. It is important to point out the similarity in surface temperatures of shaded sections across coated and uncoated streets (uncoated: 23°C, coated: 22°C; Table 3), which document that CoolSeal did not add cooling benefits when surfaces were shaded.

Statistical analyses showed that surface temperatures before the application of CoolSeal were not different among paired sites. However, after the application of CoolSeal, highly significant differences were observed between coated and uncoated sites ($p<0.001$). These differences were the result of lower surface temperatures in the sun at sites coated with CoolSeal.

TABLE 3: Mean surface temperatures of unshaded and shaded road surfaces before and after they were coated with CoolSeal. Uncoated core sites were Raymond Avenue, Mackey Circuit and the staff carpark at the HJ Daley Library in Campbelltown, coated core sites were Roslyn Avenue, Kobe Street and the public carpark at the HJ Daley Library in Campbelltown. A total of 180 individual surface temperature measurements were used to calculate these means. 'Before' data was collected between 24 February and 18 March 2020. 'After' data was collected between 19 March 2020 and 12 January 2021. All measurements were extracted from radiometric infrared images.

TIME INTERVAL	TREATMENT	SITE TYPE	SURFACE TEMPERATURE IN SUNLIGHT (°C)	SURFACE TEMPERATURE IN SHADE (°C)	SURFACE TEMPERATURE REDUCTION FROM SHADING (°C)
Before application of CoolSeal	uncoated	core	53.9	34.0	-19.9
	coated	core	52.5	34.1	-18.4
After application of CoolSeal	uncoated	core	42.6	23.1	-19.5
	coated	core	35.2	21.6	-13.5

The hottest surface temperature on any street was measured at the HJ Daley Library in Campbelltown. On 25 February 2020 at 15:20, unshaded asphalt in the public carpark reached 68°C. Another high surface temperature was measured at O'Donoghue Street in Ropes Crossing earlier on the same day. This was a warm clear day with ambient air temperature of 31°C during the time of measurements where the uncoated road surface had reached 64°C (Fig. 10 A, B). Similarly high surface temperatures (62°C) were measured during the same afternoon at the nearby Harford Street, where the road surface was also 62°C hot. Maximum surface temperatures around 60°C were also recorded in the staff carpark of the HJ Daley Library in the CBD of Campbelltown. These measurements were recorded on the same day and under slightly higher ambient air temperatures (34°C).

Infrared imaging consistently showed the surface cooling effect of CoolSeal during clear, sunny days (Fig. 10 C, D), but also when the sky was covered by clouds (Fig. 10 E, F). As can be expected, the overall reduction in surface temperatures under overcast condition was much less compared to reductions observed under clear sky. The infrared image shown in Figure 10 F also highlights that light-coloured concrete has a lower surface temperature than coated (+2°C) and uncoated (+5°C) asphalt.

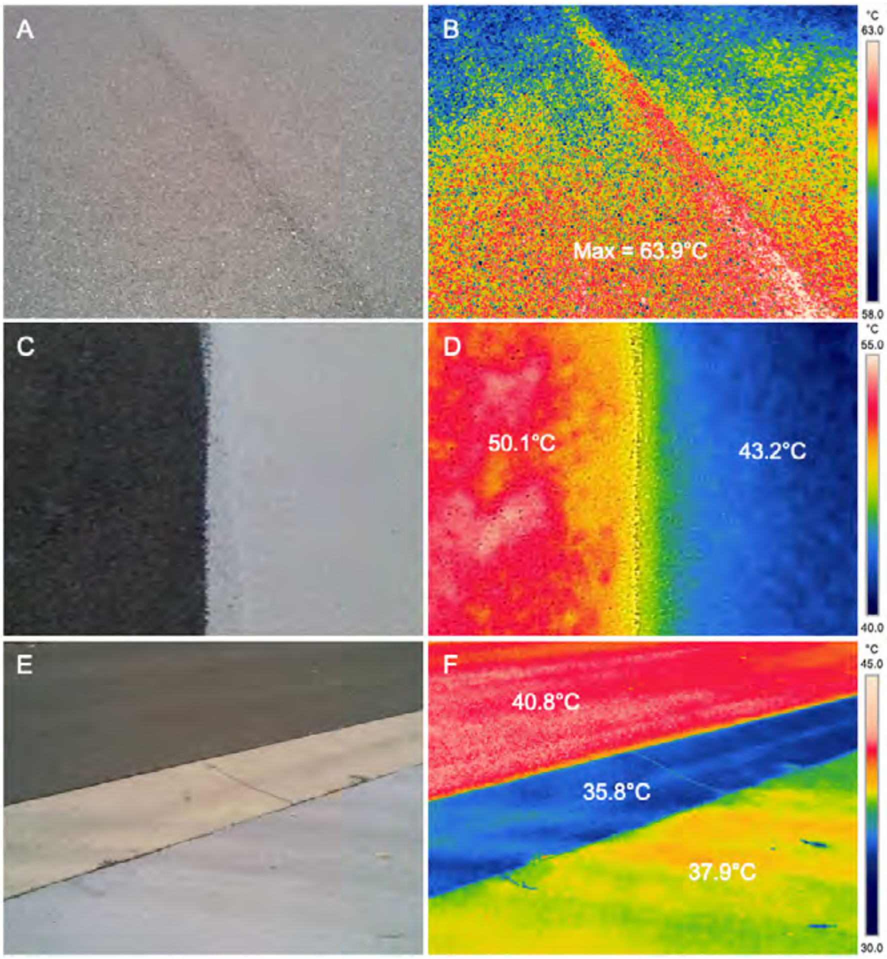


FIGURE 10: Examples of surface temperature differences. The image shown in panels A and B shows a close-up of sunlit, uncoated asphalt, taken in the early afternoon on 25 February in O'Donoghue Street, Ropes Crossing, Blacktown LGA where ambient air temperature was 31°C. Panels C and D show the freshly coated and sunlit surface of Corry Court, North Parramatta, Parramatta LGA 12:45 on 19 March 2020. Ambient air temperature at the time of imaging was 31°C. The image in panels E and F show adjacent uncoated and coated road surface separated by a light-coloured inlay of concrete at the corner of O'Donoghue and Avoca Street during an overcast day (2 December 2020) where ambient air temperature was 25°C. Panels A, C and E show normal views, panels B, D and F show infrared views where different colours represent different surface temperatures (see scale on right side).

The combined cooling effect of CoolSeal and tree shade is depicted in Figure 11. The image was taken on a warm sunny day (19 March 2020) when the small carpark and half of the street surface were freshly painted with CoolSeal. A surface temperature differential of 7.5°C existed between the uncoated and coated road surface. When tree shade was added on top of CoolSeal, the differential expanded to 21°C. Like the example shown in Figure 10 F, the lighter-coloured concrete curb visible on the right side of the street had a lower surface temperature compared to the uncoated dark asphalt. The lowest temperatures of any sunlit surface were detected on green turf at the intersection with Gladstone Street. The absolute lowest surface temperature was 12°C, recorded on the shaded, south-facing concrete curb that separates the carpark from the adjacent group of trees (Fig. 11).

As stated above, the average surface cooling achieved by CoolSeal on sunlit roads was 6°C. However, before-after comparisons captured examples of surface cooling of greater magnitude (Fig. 12). In late February 2020, the uncoated surface of a cul-de-sac in Ropes Crossing (Burnette Court) had a temperature of around 57°C. On that day, ambient air temperature was 31°C and the sky was clear. A couple of weeks later, air temperatures were even higher with 35°C. In the meantime, the road surface had been coated and although it was a hotter day, surface temperatures were below 47°C.

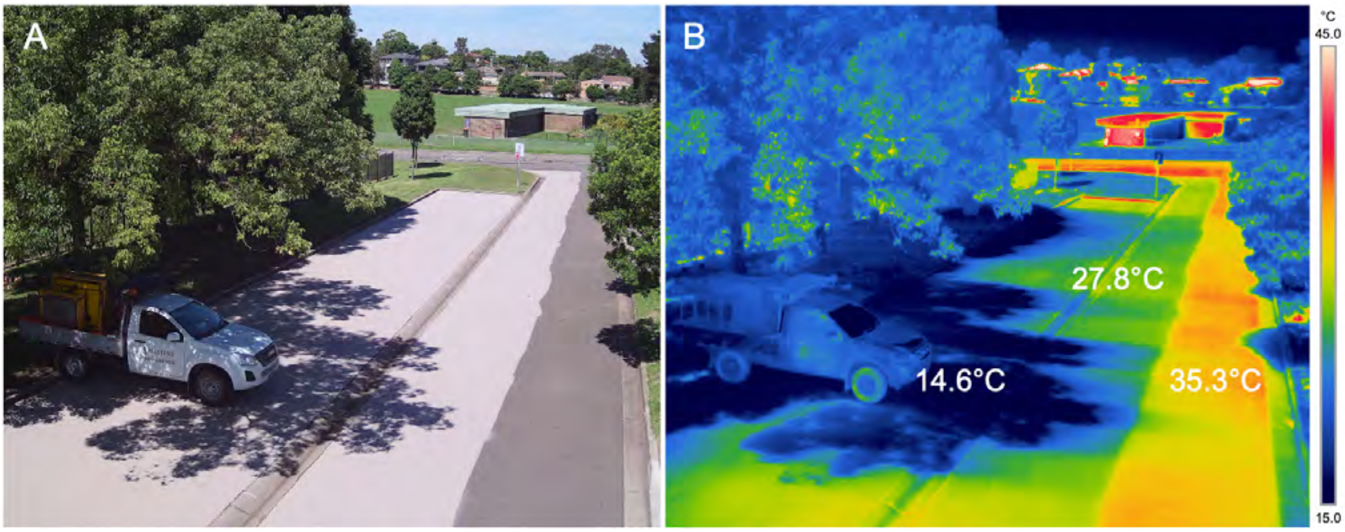


FIGURE 11: Effect of CoolSeal on surface temperature during a sunny afternoon at Corry Court, North Parramatta, Parramatta LGA. The image was taken at 12:40 on 19 March 2020 when air temperature was 31°C. At that time, only half of the road surface was coated, allowing a side-by-side comparison of resulting surface temperatures. Panel A shows the normal view, panel B shows the infrared view where different colours represent different surface temperatures (see scale on right side).

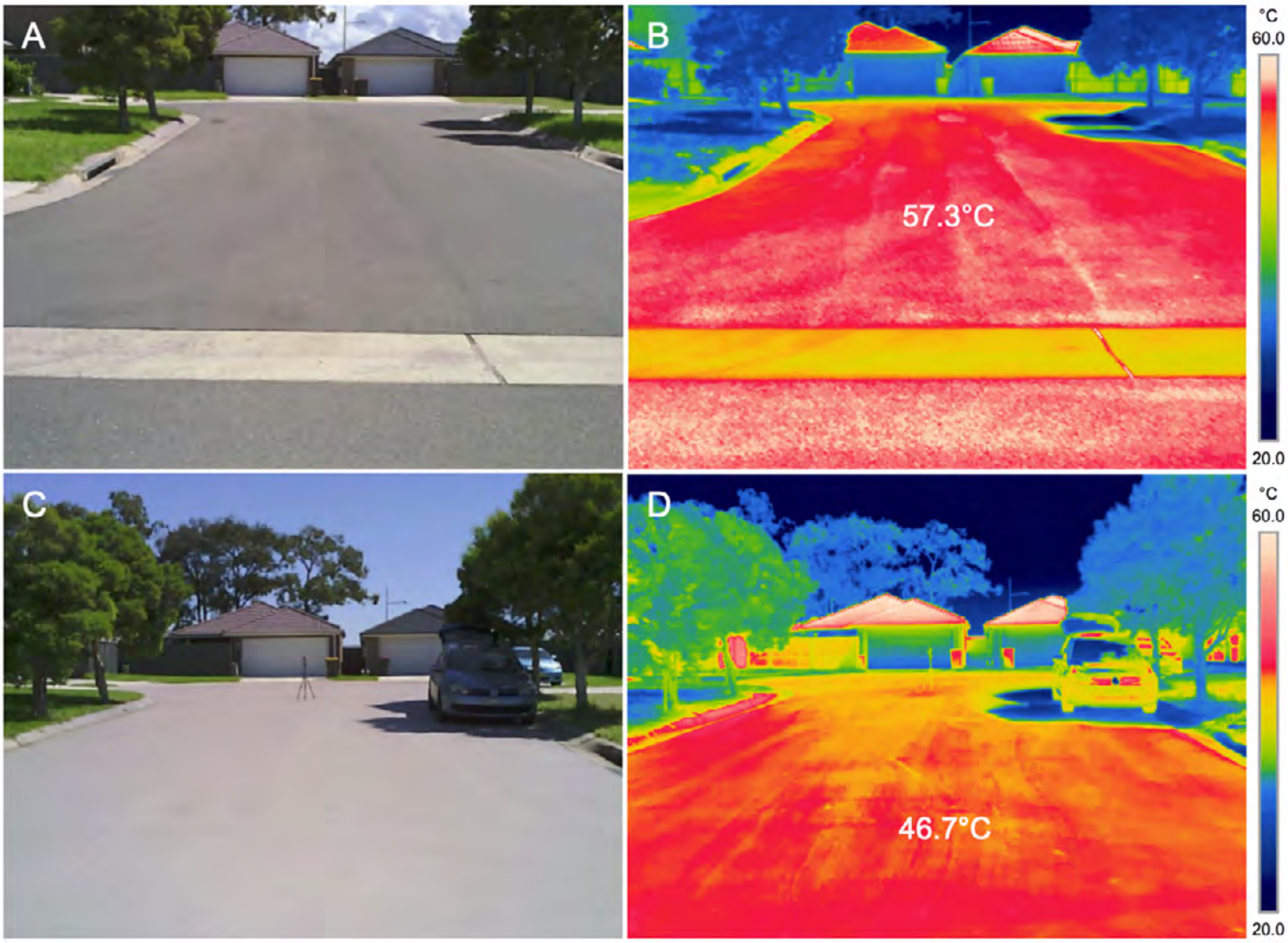
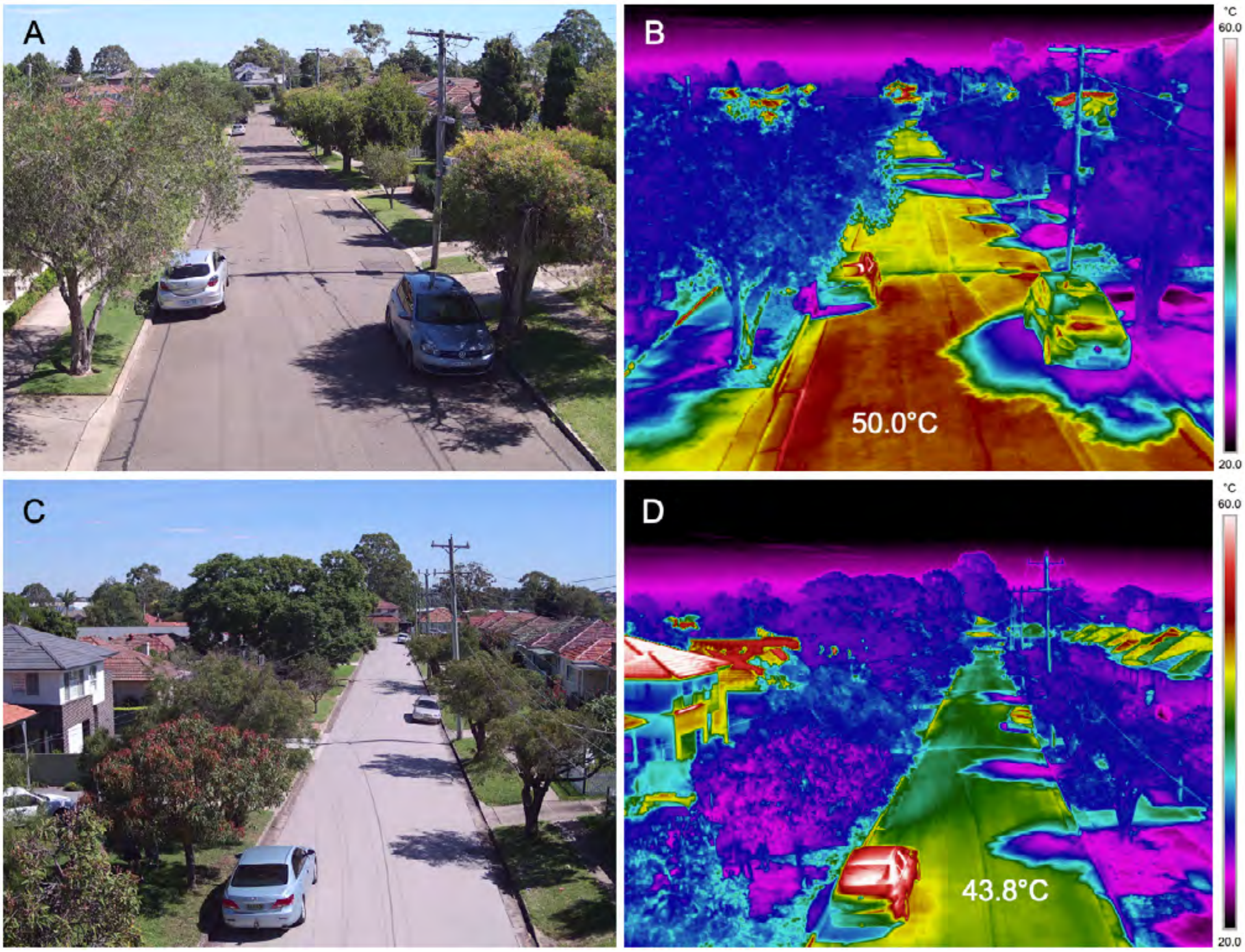


FIGURE 12: Surface temperature of Burnette Court, Ropes Crossing, Blacktown LGA. Images were taken at 13:50 on 25 February 2020 (before coating; top) and 13:45 on 20 March 2020 (after coating; bottom). Air temperature on 25 February was 31°C and 35°C on 20 March. Panels A and C show normal views, panels B and D show infrared views where different colours represent different surface temperatures (see scale on right side).

Comparisons of surface temperatures documented in the carparks of the core site in Campbelltown also revealed maximum surface cooling of 10°C. During midday (12:30) of 17 April 2020 surface temperature of the uncoated staff carpark was 47°C, while that of the coated public carpark was 37°C. Ambient air temperature during these measurements was 26°C. Another side-by-side comparison of temperatures on uncoated and coated road surfaces in Raymond and Roslyn Avenue showed a smaller surface temperature differential (6°C), even though ambient air temperatures during this sunny day (19 March 2020) were 8°C warmer (Fig. 13). Measurements at these two streets were collected at 14:30, leaving two more hours where solar energy could have further heated up the road surfaces. Also, solar inclination during midday of 19 March would have been at a higher angle compared to 17 April, resulting in a more vertical angle of solar incident radiation. Higher ambient air temperatures, longer exposure time and steeper angle of incident solar radiation should have resulted in a hotter surface temperature, at least on the uncoated surface of Raymond Avenue, compared to the uncoated carpark surface

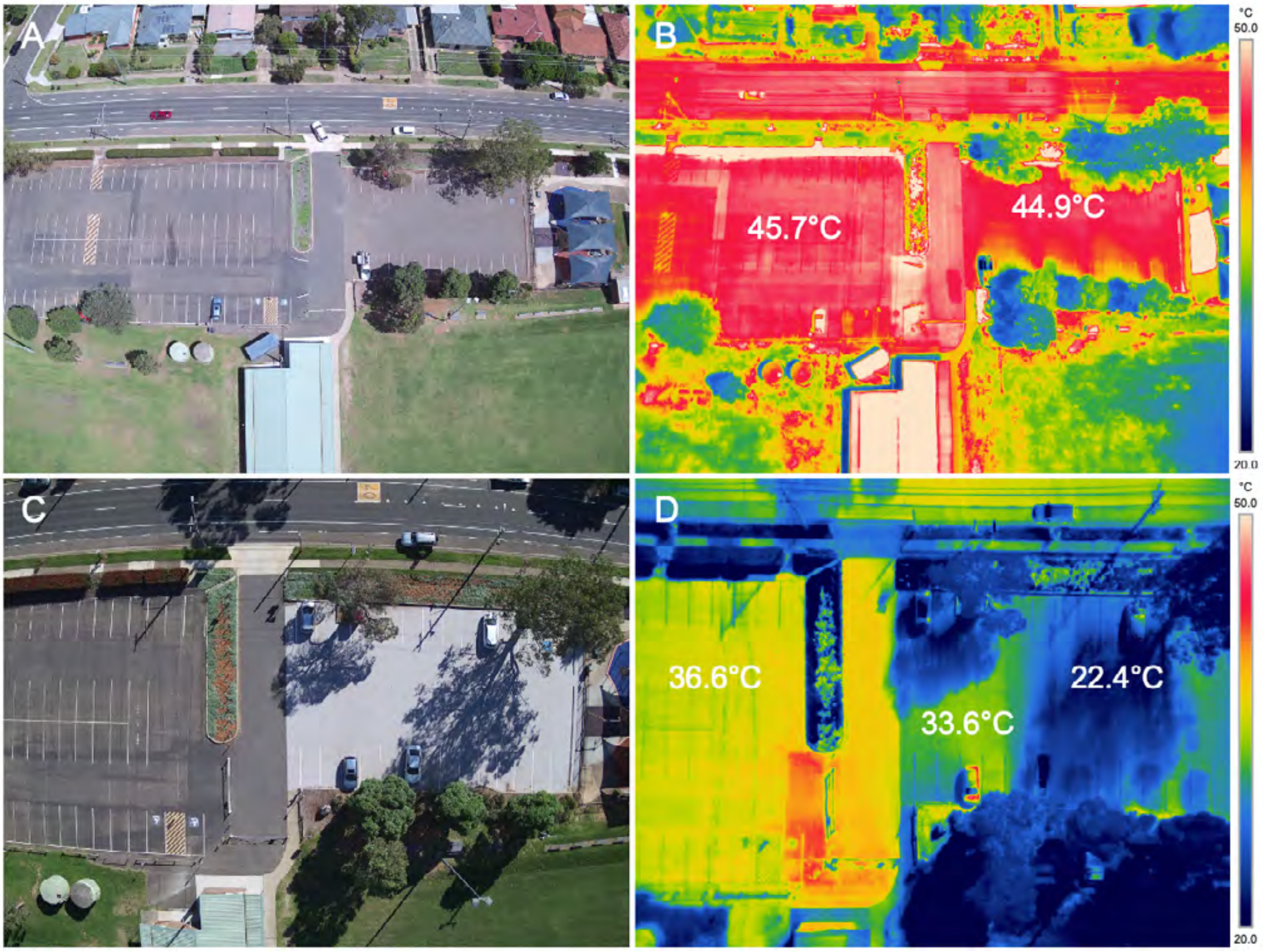


at Campbelltown. However, measurements show that this was not the case, which emphasises that a range of other factors influenced surface temperatures of roads and carparks. These factors possibly included the age and composition of the road surface and resultant albedo, surrounding shade structures and others. The high-definition infrared images reveal another phenomenon that was previously mentioned: tree shade on both surface types resulted in very similar cool temperatures indicated by the purple colour on roads in panels B and D of Fig. 13.

FIGURE 13: High-definition infrared image of Raymond Avenue (A, B; uncoated street) and Roslyn Avenue (C, D; coated street) in Northmead, Parramatta LGA. The images were taken under clear sky on 19 March 2020. Air temperature in Raymond Avenue and Roslyn Avenue was 34°C. Surface temperature of the painted road was about 6°C cooler compared to the unpainted road. Panels A and C show normal views, panels B and D show infrared views where different colours represent different surface temperatures (see scale on right side).

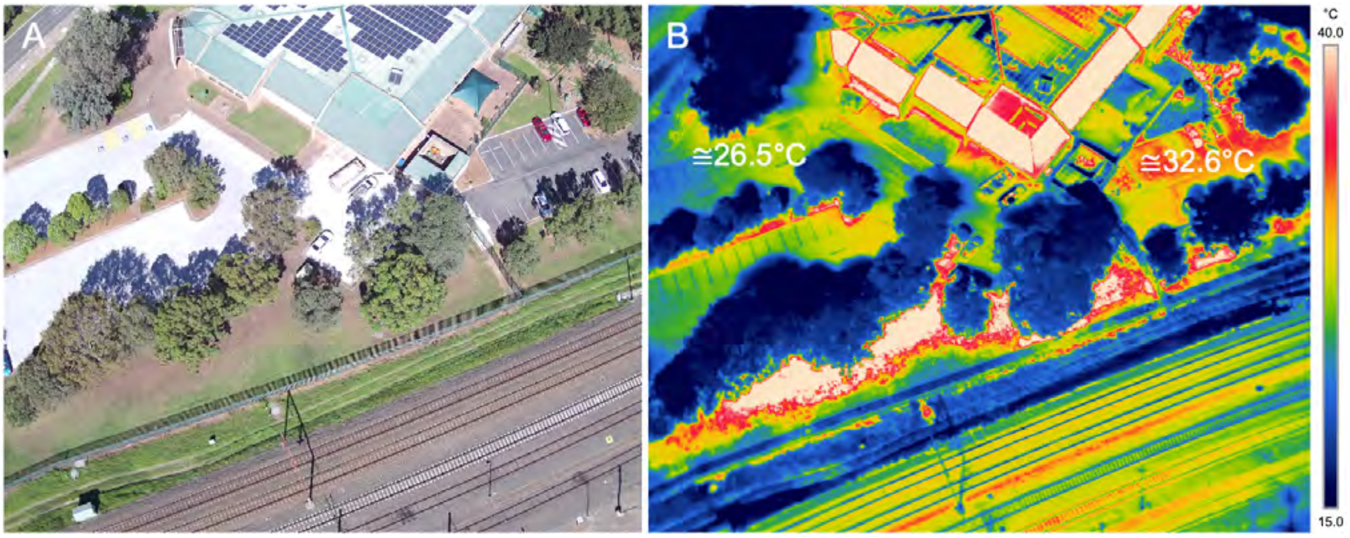
During days with cloudy skies, and particularly those that were dominated by Stratus and Stratocumulus clouds, CoolSeal continued to provide surface cooling as it reflected some of the remaining infrared radiation that penetrated the cloud cover. Although cooling benefits were much smaller under such conditions, surface temperatures on coated streets were significantly ($p<0.001$) cooler compared to those on uncoated streets (Fig. 14). The positive effect of tree or other shade on coated and uncoated surfaces was not measurable as the absence of direct solar radiation did not lead to projections of shade on surfaces.

FIGURE 14: Surface temperature during overcast conditions. The images were taken on 2 December 2020 at Mackey Circuit (A, B) and Kobe Street (C, D) in Ropes Crossing, Blacktown LGA. Panels A and C show normal views, panels B and D show infrared views where different colours represent different surface temperatures (see scale on right side).



A graphic example of the magnitude of surface cooling by CoolSeal and tree shade was documented in the carpark at Binalong Park (Fig. 15). Prior to the application of the surface coat, both sections of the carpark were displaying similar surface temperatures during clear, sunny summer days (Fig. 15 A, B). Shade provided by trees in the top right section of the carpark reduced surface temperatures from 45°C to 30°C. The magnitude of that cooling effect remained the same once the coat was applied, reducing the carpark surface temperature from 37°C (uncoated) to 22°C (coated and shaded) (Fig. 15 C, D). The example from Binalong Park reinforced two earlier findings: 1. shade limited the cooling effect of CoolSeal and 2. the cooling effect on sunlit surfaces was relatively small when surface temperatures were low. At Binalong Park, surface temperatures during the afternoon of 17 April 2020 differed by just 3°C (37°C vs 34°C) when air temperature was 27°C.

FIGURE 15: Surface temperatures at the public carpark of Binalong Park, Old Toongabbie, Parramatta LGA. Aerial images were taken on 3 March 2020 (A, B; pre-application of CoolSeal) and 17 April 2020 (C, D; post-application of CoolSeal). Images were taken under clear sky. Panels A and C show normal views, panels B and D show infrared views where different colours represent different surface temperatures (see scale on right side).



Similar to the carpark at Binalong Park, the coated and uncoated surfaces at the HJ Daley Library in Campbelltown showed little difference in their temperatures when air temperatures were lower. As shown in Figure 16, CoolSeal reduced the surface temperature in the public carpark by 6°C during midday of a clear day where air temperatures were 25°C. Trees lining the western side of both carparks provided good shade cover which helped to further reduce surface temperatures in both, the coated and uncoated carparks.

FIGURE 16: Comparison of carpark surface temperatures at the HJ Daley Library in the CBD of Campbelltown. The image was taken during noon of a clear, sunny day (17 April 2020). The painted carpark surface was 6°C cooler compared to the unpainted carpark surface. Panel A shows the normal view, panel B shows the infrared view where different colours represent different surface temperatures (see scale on right side).

24-H CAMPAIGNS

The three 24-h campaigns at streets in Northmead (2020, 2021) and carparks in Campbelltown (2021) produced high resolution and high-quality data for surface temperatures. These data were averaged over 30-minute intervals and covered the time from 06:00 of the campaign day to 06:00 the following morning.

As expected, surface temperatures of coated surfaces were lower during the late morning, midday and early afternoon when solar radiation would have been high (Fig 17). During campaigns in 2020 in Northmead and 2021 in Campbelltown, lower surface temperatures of 2°C were recorded well into the night and early morning on road and carpark surfaces that had been coated with CoolSeal (Fig. 17 A, E). However, during the 24-h campaign in January 2021 at Roslyn Avenue and Raymond Avenue in Northmead, these cooling benefits were not as obvious, and averaged around 1°C (Fig 17 C).

While surface temperatures were clearly reduced due to application of CoolSeal, air temperatures remained largely unchanged during the 24-h campaigns at all three sites (Fig 17 B, D, F). It is worth noting that surface temperatures generally rose much quicker during morning hours, compared to air temperatures that increased more gradually. On the other hand, cooling of surface and air temperatures followed a similar pattern from the late afternoon into the early morning of the following day (Fig 17). During the 24-h campaigns, no noticeable and systematic cooling of air temperature as a result of cooler surface temperatures was detected in the streets and the carpark coated with CoolSeal.

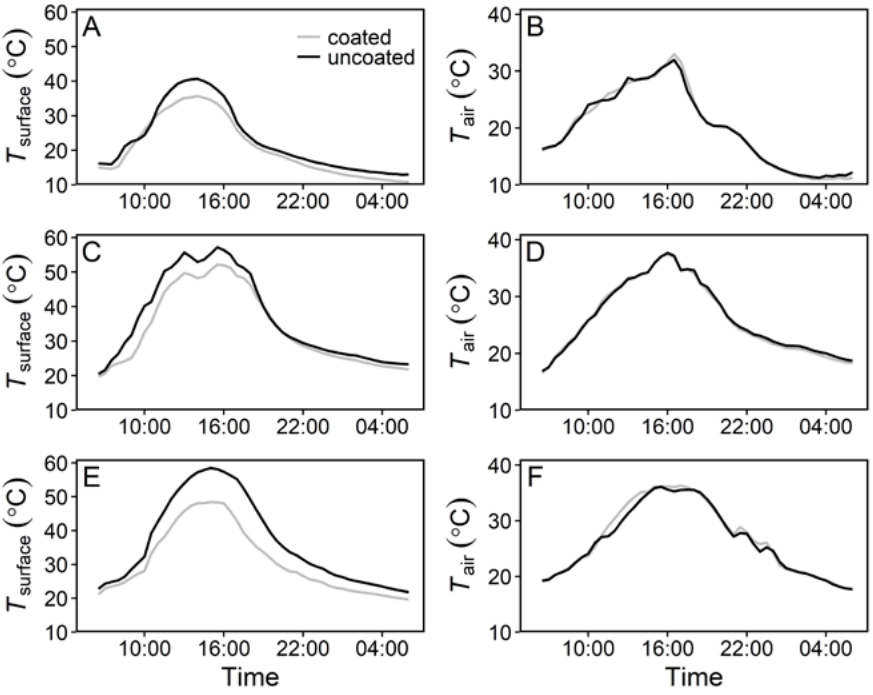


FIGURE 17: 24-hour sequences (06:00-06:00) of surface temperature ($T_{surface}$, left panels) and air temperature (T_{air}, right panels). Data were recorded at Roslyn Avenue (coated = impact) and Raymond Avenue (uncoated = control) on 17 and 18 April 2020 (A, B) and 12 and 13 January 2021 (C, D). Data at the public (coated = impact) and staff (uncoated = control) carparks of the HJ Daley Library in Campbelltown during 1 and 2 March 2021 (E, F). All campaigns recorded data during sunny, warm days.

Surface temperatures differed up to 8°C at the streets in Northmead (Roslyn Avenue and Raymond Avenue) and around 5°C during several hours in the afternoon of both campaigns (Fig. 18). At the carparks in Campbelltown, surface temperatures differences increased during the day to reach 13°C in the late afternoon. This increasing difference was the effect of increasing patchy shade from the row of eucalypt trees at the western edge of the public carpark.

Differences in air temperatures during the 24-h campaigns were much smaller compared to those observed for surface temperatures. During daytime when surface temperatures were highest (10:00-17:00), air temperatures at coated sites were slightly warmer (Roslyn Avenue, April 2020: +0.3 °C; Roslyn Avenue, January 2021: +0.1°C; Campbelltown public carpark, March 2021: +1.1°C). The reverse was observed during the night (00:00-05:00) where air temperatures were slightly cooler at coated compared to uncoated sites (Roslyn Avenue, April 2020: -0.3 °C; Roslyn Avenue, January 2021: -0.5°C; Campbelltown public carpark, March 2021: -0.1°C). The largest daytime difference was +2.2°C, measured at noon in Campbelltown. The largest night-time difference was -0.6°C, measured at 00:30 in Northmead during the campaign in January 2021.

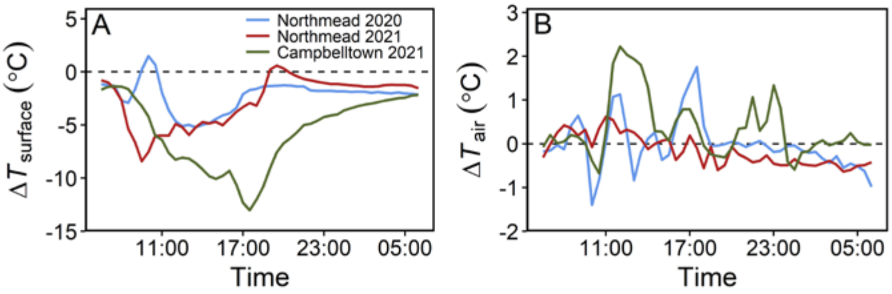


FIGURE 18: Differentials of surface temperatures ($\Delta T_{surface}$; panel A) and air temperatures (ΔT_{air}; panel B) using data shown in Fig. 16. Differentials for Northmead were calculated subtracting temperature measurements collected at Raymond Avenue (uncoated) from those collected at Roslyn Avenue (coated). Differentials for Campbelltown were calculated subtracting data from the staff carpark from those of the public carpark. Positive values indicate that temperatures at the coated site were warmer, negative values indicate that temperatures were cooler compared to those at the uncoated site. The dashed line at zero indicates equal temperatures between coated and uncoated sites.

4.3 AIR TEMPERATURE – *BEFORE VS. AFTER*

During the time interval before the application of the surface coat, air temperatures varied between 11°C and 40°C at the roads in Northmead. At the Carparks in Campbelltown and the roads in Ropes Crossing, air temperatures varied between 11°C and 42°C. Slightly cooler weather prevailed during the time interval after CoolSeal was applied and the range of air temperature was 12°C-36°C at Northmead, 7°C-31°C at Campbelltown, and 0°C-32°C at Ropes Crossing. From these data sets we calculated daily means (00:00-00:00), absolute daily maximums, daytime means (10:00-17:00) and night-time means (00:00-05:00) for each of the six sites. Before application of CoolSeal, the staff carpark at the HJ Daley Library in Campbelltown showed the warmest daily mean and maximum temperatures (Table 4). The coolest nights during the same time were recorded at Mackey Circuit in Ropes Crossing (Table 4).

TABLE 4: Mean air temperature variables before and after the application of CoolSeal in March 2020. The same number of days before and after the application were used to calculate temperature derivatives (Northmead: n = 20 days; Campbelltown: n = 23 days; Ropes Crossing: n = 22 days). All variables were calculated for each day using 10-minute measurements before being averaged for the respective time interval. Variables: mean daily air temperature (T_{mean}), daily maximum air temperature (T_{max}), daytime air temperature (T_{day}) and night-time air temperature (T_{night}). One standard deviation is shown in parenthesis.

		T_{mean} (°C)		T_{max} (°C)		T_{day} (°C)		T_{night} (°C)	
LOCATION	**TREATMENT**	before	after	before	after	before	after	before	after
Northmead	uncoated	20.6 (2.9)	19.8 (2.2)	26.8 (5.0)	25.9 (3.6)	24.4 (4.9)	23.8 (3.4)	17.7 (2.7)	16.8 (1.9)
	coated	20.7 (2.9)	20.0 (2.3)	26.8 (5.1)	26.3 (3.8)	24.5 (5.0)	24.1 (3.5)	17.7 (2.7)	16.8 (1.9)
Campbelltown	uncoated	20.8 (2.7)	18.5 (1.7)	28.7 (5.4)	26.1 (2.1)	25.8 (5.0)	23.1 (1.8)	17.1 (2.6)	14.9 (3.1)
	coated	20.4 (2.6)	18.3 (1.6)	27.4 (5.1)	25.6 (2.1)	24.7 (4.8)	22.7 (1.8)	17.1 (2.6)	15.0 (2.9)
Ropes Crossing	uncoated	20.5 (2.7)	18.7 (1.8)	26.8 (5.2)	25.3 (2.9)	24.5 (4.7)	22.8 (2.6)	16.9 (2.6)	15.4 (2.6)
	coated	20.3 (2.7)	18.7 (1.8)	27.0 (5.3)	25.2 (2.7)	24.5 (4.5)	22.8 (2.6)	17.2 (2.4)	15.5 (2.5)

We used multiple Analysis of Variance (MANOVA) with repeated measures to determine if air temperatures were impacted by the application of CoolSeal. Data from each pair of a coated and uncoated streets recorded before and after the application of CoolSeal provided us with a two-factor, full factorial design where the uncoated street was the independent and the coated street the dependent variable. This design allowed testing three specific effects (formulated here as null hypotheses):

- » Air temperature at the coated site did not differ before compared to after application of CoolSeal.
- » Air temperature did not differ between the coated and uncoated site.
- » There was no interaction between effects 1 and 2.

For these analyses the significance level was set with $p<0.05$, a widely accepted level for the probability to detect meaningful differences between variables. When statistical results showed $p>0.05$, the null hypothesis had to be accepted. Table 3 shows the resulting probability levels. The analyses showed that before-after effects were sometimes significant at coated sites, providing evidence that environmental conditions had changed as a result of a seasonal shift towards cooler air temperatures. The application of CoolSeal did not result in significant differences in air temperatures between the uncoated and coated sites at Northmead and Ropes Crossing. Also, any significant effects from interactions between effects 1 and 2 were absent at these sites. However, at the carparks in Campbelltown significant differences in mean daily air temperatures were detected for all effects, providing evidence that the application of CoolSeal had influenced site microclimate.

TABLE 5: Test results (multiple Analysis of Variance with repeated measures) for the analyses of air temperature variables. Variables: mean daily air temperature (T_{mean}), daily maximum air temperature (T_{max}), daytime air temperature (T_{day}) and night-time air temperature (T_{night}). One standard deviation is shown in parenthesis. Significant differences ($p<0.05$) are highlighted in bold.

VARIABLE	LOCATION	EFFECT 1 (BEFORE-AFTER)	EFFECT 2 (COATED-UNCOATED)	EFFECT 3 (INTERACTIONS OF 1 AND 2)
T_{mean}	Northmead	**0.200**	0.800	0.940
	Campbelltown	**<0.0001**	**<0.0001**	**<0.0001**
	Ropes Crossing	0.001	0.850	0.980
T_{max}	Northmead	0.460	0.820	0.860
	Campbelltown	0.010	0.280	0.590
	Ropes Crossing	0.060	0.930	0.880
T_{day}	Northmead	0.590	0.790	0.920
	Campbelltown	**0.003**	0.350	0.700
	Ropes Crossing	**0.047**	0.970	0.970
T_{night}	Northmead	0.081	0.950	0.990
	Campbelltown	**<0.001**	0.900	0.950
	Ropes Crossing	**0.003**	0.720	0.920

The complex statistical analyses revealed non-uniform impacts among the sites. For this reason, we used an additional procedure that reduced the intrinsic variability within each paired data set and helped identify trends. We calculated the air temperature difference between the coated and uncoated streets for the intervals before and after the application of the surface coat. The resulting differences were averaged for each time interval. In a final step, we subtracted the mean air temperature difference recorded after the application of the surface coat from the mean air temperature difference calculated for the time before the application. Such a procedure allows estimation of trends in two-factor, full-factorial experimental designs.

An example for the carparks at Campbelltown illustrates the trend estimation:

- The mean daytime (10:00-17:00) air temperature difference before application of CoolSeal was -1.0°C, indicating that air temperatures at the public carpark tended to be 1°C cooler compared to those at the staff carpark.
- Following the application of CoolSeal, the temperature differential was -0.4°C.
- Even though daytime air temperatures remained cooler at the coated compared to the uncoated carpark, the smaller difference indicated that air temperatures were 0.6°C warmer.

The trend estimations showed that application of CoolSeal likely resulted in small changes to microclimate that could not be detected in the original datasets as a result of large intrinsic variation among measurements. For most of the calculated air temperature variables we detected a warming trend between 0.1°C and 0.9°C (Fig. 19). For some air temperature variables, no trend was detected, whereas cooling trends for maximum daytime and night-time air temperatures were found for Kobe Street at Ropes Crossing. Among these trends, all four air temperature variables at the coated carpark in Campbelltown indicated potential warming. This trend was backed by the results of the relevant MANOVAs that had indicated significant and systematic differences existed in measurements of air temperature over the coated and uncoated carparks. Moreover, also the variance among measurements collected after the application of CoolSeal was smaller, yet they were still sufficiently different to remain significantly different (Table 5). Unfortunately, our data set for this site covers only 23 days before the application of the surface coat, which limits our capacity to draw stronger conclusions about the estimated warming trends. The same applies to measurements at Northmead, where warming trends were dominant, but variation of air temperatures and p-values were large.

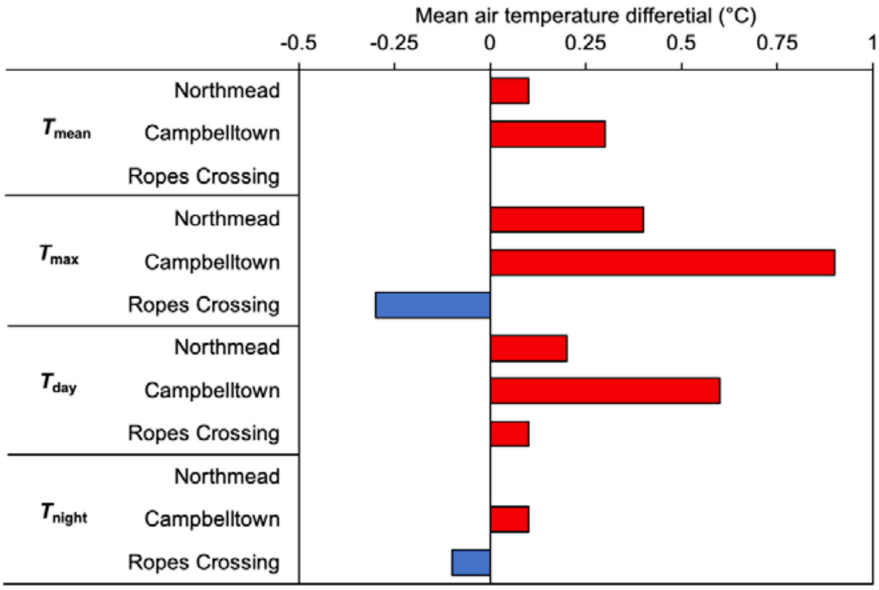


FIGURE 19: Trend estimation of air temperature differentials between coated and uncoated sites. Variables: mean daily air temperature (T_{mean}), daily maximum air temperature (T_{max}), daytime air temperature (T_{day}) and night-time air temperature (T_{night}). Positive differentials (red) indicate a warming trend, negative differentials (blue) indicate cooling. Where no bar is visible, the differential was zero, indicating that site climate was identical between coated and uncoated sites.

4.4 AIR TEMPERATURE – SUMMER 2020/21

Analyses of air temperature data recorded between December 2020 and March 2021 showed that the uncoated street in Northmead (i.e., Raymond Avenue) had the warmest microclimate and the uncoated street at Ropes Crossing (i.e., Mackey Circuit) had the coolest microclimate (Table 6). There were no statistical differences in mean air temperatures between the paired coated and uncoated sites. The mild summer of 2020/21 resulted in a relatively low number of hot (>35°C) and extremely hot days (>40°C). On uncoated/coated surfaces we recorded 14/12, 11/13 and 13/14 hot days and 5/3, 4/4, and 5/4 extremely hot days at the sites in Northmead, Campbelltown and Ropes Crossing, respectively.

TABLE 6: Ambient air temperatures during the summer of 2020/21. Mean daily, mean maximum, absolute maximum, mean minimum and absolute minimum air temperatures at the three paired monitoring sites are provided. Numbers in parenthesis show 1 SD.

LOCATION	TREATMENT	Mean daily T_{air} (°C)	Mean max. T_{air} (°C)	Absolute max. T_{air} (°C)	Mean min. T_{air} (°C)	Absolute min. T_{air} (°C)
Northmead	uncoated	22.4 (4.9)	29.8 (5.0)	42.8	17.3 (2.1)	10.5
	coated	22.3 (4.9)	29.4 (4.8)	41.7	17.1 (2.1)	10.7
Campbelltown	uncoated	22.0 (4.9)	29.1 (5.2)	41.8	16.7 (2.3)	9.8
	coated	21.9 (5.0)	29.4 (5.2)	42.9	16.7 (2.3)	10.4
Ropes Crossing	uncoated	22.0 (5.0)	29.2 (5.0)	41.4	16.6 (2.3)	10.5
	coated	22.1 (5.1)	29.4 (5.2)	41.7	16.7 (2.3)	10.7

Further analyses of temperature differences between paired sites revealed some variation in air temperature. For example, in January and February 2021 at Northmead, absolute maximum and mean daytime (10:00-17:00) air temperatures at Roslyn Avenue (coated) were 1°C cooler compared to Raymond Avenue (uncoated). Temperature differences of that magnitude were not observed during the earlier monitoring campaign (February – April 2020) before or after application of the surface coat. In agreement with earlier observations was an overall warming trend for the public carpark (coated) compared to the staff carpark (uncoated) at the HJ Daley Library in Campbelltown. Here, calculation of temperature differentials between the coated and uncoated site showed that absolute maximum air temperatures at the coated site were slightly warmer in December 2020 (1.6°C) and January 2021 (1.1°C). Average night-time temperatures (00:00-5:00) were lower (0.3°C) at the coated site in Northmead (Roslyn Avenue). During warm nights, were maximum air temperatures exceeded 22°C, air temperatures were up to 0.4°C cooler at Roslyn Avenue (coated) and up to 0.9°C cooler at the public carpark in Campbelltown (coated). Throughout the months of December 2020 to March 2021, mean and minimum night-time air temperatures were up to 0.3°C lower at coated compared to uncoated sites.

Two specific questions were of interest: (1) would CoolSeal assist in reducing absolute maximum daytime air temperatures, making this product a tool that can help reduce the impacts of heatwaves and (2) does the lower surface temperature during the day lead to lower emission of heat at night, whereby warming night-time air temperatures less? Data recorded during the monitoring campaign in the summer of 2020/21 shows that the relationships between daily maximum and night-time air temperatures at coated versus uncoated sites were highly correlated and did not deviate noticeably from an ideal relationship (1:1 line; Fig. 20). Together with the small magnitude of cooling and warming effects reported above, the uncertainty if these effects are purely attributable to the surface coat and the very high correlations shown in Figure 20 suggests that CoolSeal did not lower maximum air temperatures. Yet, the data indicated that CoolSeal may have reduced air temperatures during warm nights by 0.3°C. This effect is slightly larger than the measurement accuracy of the sensor used to record air temperatures.

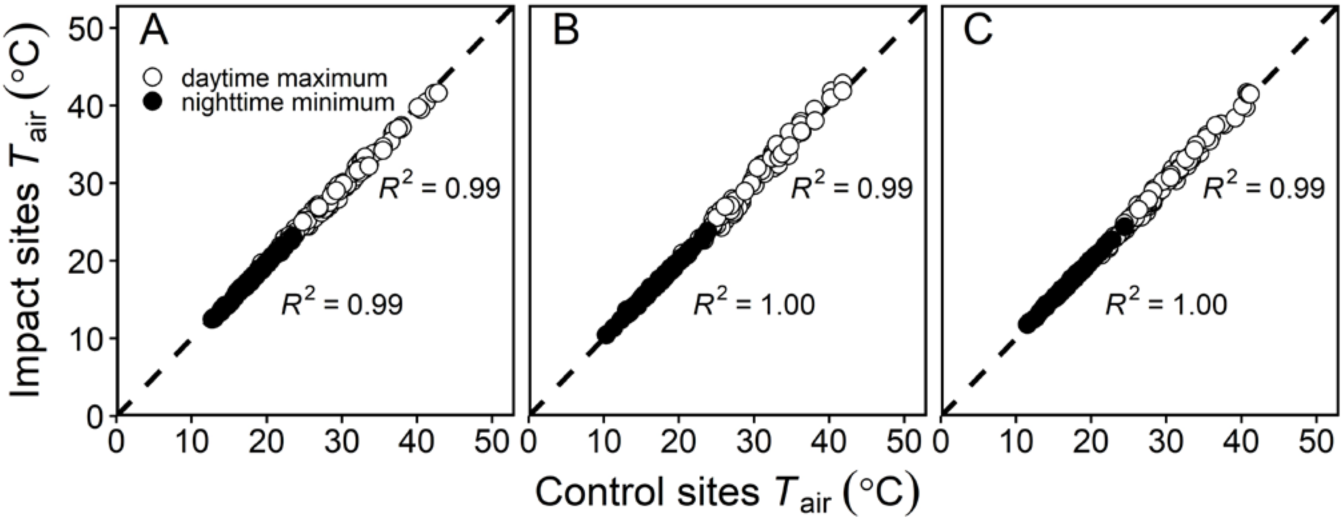


FIGURE 20: Relationship between air temperature variables at the control (uncoated) and impact (coated) sites. Data for daily absolute maximum (white dots) and minimum (black dots) are shown for sites at Northmead (panel A), Campbelltown (panel B) and Ropes Crossing (panel C). The dashed line shows the 1:1 relationship. Coefficients of determination are shown for linear regressions of each variable pair.

4.5 **HUMAN THERMAL COMFORT**

Human thermal comfort was assessed using black globe temperatures (T_{globe}) and the NOAA Heat Index (see Section 3 for details). Data collected during 25 field campaigns were analysed. During hot days, where air temperature was above 35°C, we measured feels like temperatures of more than 50°C on uncoated and coated surfaces. Over uncoated asphalt the relationship between air temperature and feels like (black globe) temperature was strong ($R^2 = 0.88$), positive and linear. While the same relationship was also linear over coated asphalt, it was slightly weaker ($R^2 = 0.79$), but more importantly, the intercept of this relationship was greater indicating that with increasing air temperature the feels like temperature over coated surfaces would be greater compared to uncoated surfaces.

During the 25 measurement campaigns, air temperatures ranged from 17°C to 37°C, covering a wider range of daytime temperatures. Mean air temperature over uncoated surfaces was 31.5°C (±0.9) compared to 31.2 (±0.9) over uncoated surfaces. This difference was not statistically significant. The relationship between air temperatures recorded over uncoated surfaces (i.e., control sites) with those recorded over coated surfaces (i.e., impact sites) was strongly linear ($R^2 = 0.95$) and followed a clear 1:1 relationship (Fig. 21). This provides strong evidence that air temperatures during the measurement campaigns did not differ between paired sites, which matches the findings reported for the 24-h campaigns and the Analyses of Variance.

Average temperatures measured by the black globe thermometer in the sun were higher over coated surfaces (43.3°C ±0.8) compared to uncoated surfaces (40.6 ±0.7). According to a two-sample t-test for means, these differences were highly significant ($p < 0.001$). As visible in Figure 21, the strong linear relationship ($R^2 = 0.96$) between black globe temperatures measured over uncoated and coated surfaces clearly falls above the 1:1 line. This offset indicates that a human body was experiencing a slightly warmer temperature sensation (2.7°C ±1.9) when standing on an unshaded surface coated with CoolSeal compared to unshaded black asphalt. This temperature difference is far greater than the measurement accuracy of the instrument.

The effect of reflected incident solar radiation on feels like temperatures was emphasised by the observation that the Heat Index was similar between coated and uncoated sites. The Heat Index represents a composite measurement of air temperature and relative humidity. It does not incorporate direct, reflected or emitted sources of heat. At uncoated sites, the Heat Index was on average 32.8°C (±1.0) and ranged between 17°C and 42°C. Where CoolSeal was applied, the Heat index ranged from 17°C to 41°C and was on average 32.5°C (±1.5).

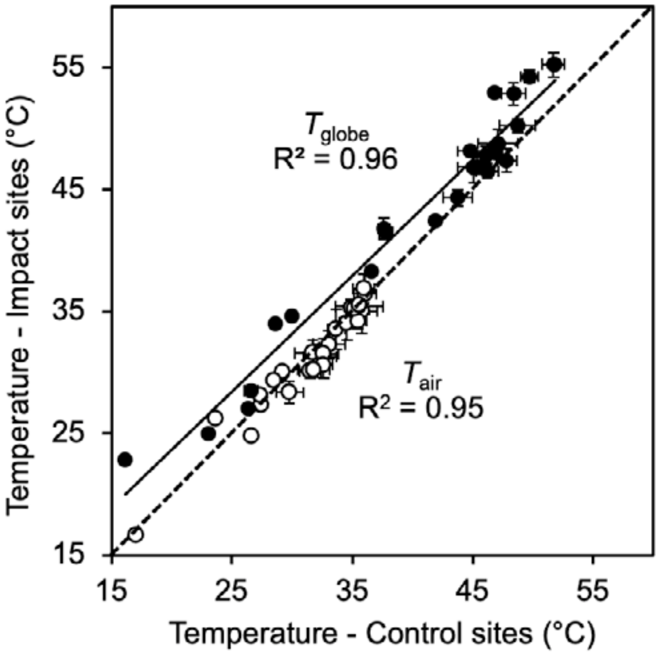


FIGURE 21: Relationships between temperature variables at paired control (unpainted) and impact (painted) sites. Circles represent air temperature measurements (T_{air}); black dots are black globe temperatures (T_{globe}). Error bars show ±1 SD. The dashed black line depicts the 1:1 line; the solid black line shows the linear relationship for T_{globe} recorded at control and impact sites. The linear relationship for T_{air} is not shown for reasons of clarity – it would fall exactly on the 1:1 line. The coefficients of determination are shown for both data sets.

5 RECOMMENDATIONS

The Cool Roads Trial is the first systematic assessment of a cool pavement paint during day and night in Greater Sydney. It is also the longest, field-based environmental monitoring program of such a product in Australia. The monitoring program was designed to document cooling benefits of a reflective surface coat beyond reduced surface temperatures. The analyses found that application of CoolSeal had different effects on different temperature variables. This result underlines the importance to clearly define the temperature variable that an intervention will address when aiming to mitigate urban heat. The following recommendations are based on data analyses described in this report.

SURFACE COOLING BENEFITS

The Cool Roads Trial collected unequivocal evidence that application of a highly reflective surface coat to roads and carparks in Western Sydney reduced surface temperatures. During warm and hot summer days, temperatures of unshaded surfaces coated with CoolSeal were on average 5.9°C cooler compared to uncoated surfaces. Maximum surface temperature reductions on unshaded roads and carparks were up to 11.5°C. It was evident that the hotter surfaces became in the sun, the greater were the surface temperature reductions provided by CoolSeal. Moreover, surface cooling benefits were not only apparent during sunny days but were also detected during overcast conditions. CoolSeal also lowered surface temperatures by 1°C-2°C during the night.

These results clearly document the effectiveness of the tested product to reduce surface temperatures of roads and carparks under a range of environmental conditions and different local climate zones. If reduction of surface temperature is the goal of the intervention, surface coating products like CoolSeal are useful.

The intervention will be most effective on surfaces that are unshaded. No additional surface cooling benefits were identified on roads and carparks shaded by trees or other structures.

AIR COOLING BENEFITS

Continuous measurements before and after the application of the surface coat in February, March and April 2020 showed no cooling effect on mean daily ambient air temperatures. Analyses of these data indicated that air temperatures had warmed at one of three sites, regardless of seasonal variability. Trend analyses enforced this result.

Air temperature data recorded between December 2020 and March 2021 showed that some temperature variables were lower at one coated site. Mean daytime air temperature at Roslyn Avenue was 1°C cooler compared to the nearby uncoated Raymond Avenue. Mean night-time air temperature at Roslyn Avenue was also 0.3°C cooler compared to Raymond Avenue. Especially during warm nights, this cooling benefit of coated residential streets seemed apparent at all monitoring sites. While valuable as trends, observations made during the second measurement interval lack independence (i.e., missing the important 'before-after' assessment) and could have been the result of other external and uncontrolled factors.

Especially the low magnitude of the reductions in night-time air temperature, sometimes within the measurement accuracy of the instruments highlight that meaningful nighttime cooling benefits from application of a reflective surface paint are unlikely. This conclusion was also reached in the study in Marrickville (Coutts et al. 2016).

Based on these results we recommend using other interventions to effectively cool ambient air temperatures in urban spaces. These include expanding green infrastructure, urban tree canopy cover and permeable surface area, introducing green walls and roofs, irrigation using rain and recycled water, air misting and others (WSROC 2021).

While some studies support a wider roll-out of cool pavement, wall and roof technologies to mitigate Urban Heat Island effects, the call to combine them with good knowledge about wind flows, sea breezes and thermal turbulence to increase their effectiveness is getting louder (e.g., He et al. 2020; Sen and Roesler 2020).

We cannot exclude that a more widespread application of CoolSeal or any other cool pavement technology leads to a reduction of air temperature variables. The Cool Roads Trial assessed microclimatic effects. Applying these technologies at larger scales might produce more uniform cooling outcomes and modelling studies have indicated this is the case (e.g., Mohegh et al. 2017). We recommend conducting detailed Cost-Benefit-Analyses that look at a range of cooling options prior to such interventions.

HUMAN THERMAL COMFORT BENEFITS

Studies that investigated the effect of cool pavement technologies on human thermal comfort have only surfaced recently (e.g., Li et al. 2016; Middel et al, 2020; Thalegani et al. 2016). Their results match findings presented in this report. Across all sites and measurement campaigns in 2020 and 2021, we found that CoolSeal increased black globe temperatures, whereby reducing human thermal comfort.

The effect of decreasing human thermal comfort is attributed to the capacity of the surface coat to reflect a large amount of incident solar radiation. After reflection, this energy is absorbed by the human body, represented by the black globe. The heating effect on the black globe by the reflected incident solar radiation was more intense compared to the radiant heat emitted from the surface. The fact that surface temperatures of coated surfaces were on average 6°C cooler emphasises the intensity of the heating effect from reflected solar energy.

The analyses of surface temperatures during the Cool Roads Trial have shown that temperatures of uncoated surfaces were higher. However, the resultant flux of sensible heat (i.e., emission of stored solar energy from the surface) had much less impact on human thermal comfort compared to reflected solar incident radiation. As shown in a study from Phoenix, Arizona, energy contained in this type of radiation reflected by high-albedo pavements was sufficiently intense to increase the energy needs for cooling a 4-story building by 11% (Yaghoobian and Kleissl 2012). Thus, the heating effect on humans should be no surprise.

Interventions that aim to improve human thermal comfort at the ground level should not increase albedo of ground surfaces. Other cool pavement technologies, like porous pavements and especially introduction of high-quality shade will generate the desired thermal benefits within streets, carparks and other public spaces.

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SUPPLEMENTARY INFORMATION

SUPPLEMENTARY TABLE 1: List of trial locations and approximate area covered with CoolSeal. Sites marked with '*' were intensive research sites where air temperature was recorded continuously from February 2020 until April 2020 and December 2020 until February 2021.

LOCAL GOVERNMENT AREA	SUBURB	STREET	TYPE	AREA (M^2)
City of Parramatta	Northmead	Roslyn Avenue*	residential	1,300
	Old Toongabbie	Renoir Street	residential	1,500
		Binnalong Park	carpark	820
	North Parramatta	Corry Court	residential	1,500
			carpark	600
City of Campbelltown	Campbelltown (Council Civic Centre Carpark)	Hurley Street	carpark	2000
	Campbelltown (HJ Daley Library)	Hurley Street*	carpark	2000
City of Blacktown	Ropes Crossing	Barlett Street	residential	940
		Burnet Court	residential	310
		Mortlock Avenue	residential	1,130
		O'Donoghue Street	residential	1,000
		Kobe Street*	residential	1,610
			Total area covered	**14,710**

SUPPLEMENTARY IMAGE 1: Cool Roads Trial site at Roslyn Avenue, Northmead. Image was taken on 15 April 2021. © Nearmap.

SUPPLEMENTARY IMAGE 2: Cool Roads Trial site at Renoir Street, Old Toongabbie. Image was taken on 15 April 2021. © Nearmap.

SUPPLEMENTARY IMAGE 3: Cool Roads Trial site at Binnalong Park, Old Toongabbie. Image was taken on 3 August 2021. © Nearmap.

SUPPLEMENTARY IMAGE 4: Cool Roads Trial site at Corry Court, North Parramatta. The image shows both, the residential street and the carpark sites. Image was taken on 3 April 2021. © Nearmap.

SUPPLEMENTARY IMAGE 5: Cool Roads Trial site at the Civic Centre, Hurley Street, Campbelltown. Image was taken on 3 April 2021. © Nearmap.

SUPPLEMENTARY IMAGE 6: Cool Roads Trial site at HJ Daley Library, Hurley Street, Campbelltown. Image was taken on 3 April 2021. © Nearmap.

SUPPLEMENTARY IMAGE 7: Cool Roads Trial sites at Barlett Street, Burnet Court, Mortlock Avenue and O'Donoghue Street, Ropes Crossing. Image was taken on 15 April 2021. © Nearmap.

SUPPLEMENTARY IMAGE 8: Cool Roads Trial site at Kobe Street, Ropes Crossing. Image was taken on 3 April 2021. © Nearmap.

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