TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING

ISSN 1021-2019

Vol 64 No 2, June 2022, Pages 2–12, Paper 0862

Light-coloured concrete surfacing for urban heat-island mitigation in Southern Africa

T P Mlilwana, E P Kearsley

THULANI MLILWANA is a civil engineer with experience in interdisciplinary infrastructure projects in Southern Africa and Eastern Europe. His research focuses on climate resilience and the sustainable development goals. He has served as a senior lecturer at the University of Johannesburg and is an advisor for international programmes run by WaterAid. He holds a BEng in Civil Engineering and an MEng in Structural Engineering from the University of Pretoria, and is currently pursuing a Master's in Business Administration.

Contact details:
Department of Civil Engineering
University of Pretoria
Private Bag X20
Hatfield
0028
South Africa
E: thulanimlilwana@gmail.com

PROF ELSABE KEARSLEY (Pr Eng, FSAICE) graduated with a degree in Civil Engineering from the University of Pretoria in 1984 and holds a PhD from the University of Leeds. She worked as a Structural Design Engineering in both South Africa and the United Kingdom before becoming a staff member at the University of Pretoria. She served as the 2009 President of the South African Institution of Civil Engineering (SAICE). For the last 26 years she has been involved with cement and concrete materials research, and her current research is aimed at reducing the environmental impact of cement and concrete products.

Contact details:
Department of Civil Engineering
University of Pretoria
Private Bag X20
Hatfield
0028
South Africa
T: +27 12 420 2176
E: elsabe.kearsley@up.ac.za

Keywords: Portland cement concrete, thermal performance, heat island, thermal mass

Global population growth and rapid urbanisation have resulted in the rapid transformation of natural topographies that are now dominated by engineering materials and structures. It is widely recognised that economic development is largely attributable to infrastructure development. However, this development has come about with adverse consequences. In this paper, the effects of surface characteristics, climatic parameters and material properties on the thermal environment and near-surface heat islands in urban areas were investigated. An experiment was conducted in which simple concrete structures with varying surface characteristics were constructed and instrumented. The effect of solar absorptivity was clearly visible, with structures surfaced with low absorptivity materials exhibiting lower surface and effective temperatures. Following the experimental programme, numerical simulations of the simple concrete structures were performed using finite element modelling. The analyses showed that the thermal environment of concrete structures is sensitive to changes in solar absorptivity, climatic parameters, cross-sectional dimensions, and material properties. It was found that the use of low absorptivity or highly reflective surfacing and the selection of appropriate dimensions can be used to significantly reduce the temperatures of concrete infrastructure, including buildings and pavements, thereby providing an evidential basis for the use of low absorptivity surfacing materials to mitigate climate change in Southern Africa.

INTRODUCTION

The growth of the global economy has increased the demand for affordable construction materials and the proliferation of construction methods. Presently, concretes produced with Portland cement are the most widely used construction materials in the world in terms of volume. The development of infrastructure, industry and housing is largely attributable to readily available raw materials, and the strength and durability characteristics of concrete. However, these manufacturing and development activities are climate-forcing, as the production of Portland cement contributes up to 5% of all anthropogenic carbon dioxide emissions (Damtoft *et al* 2008). It is also known that concrete has substantial heat capacity and is thus able to store large amounts of energy. This energy is released thermally into the atmosphere, further influencing the climate-change conundrum.

Sustainable development has been defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their needs*" (Brundtland 1987). In developing nations, sustainable development activities are often disregarded as a result of the urgent demand for basic economic growth that is facilitated by the provision of economic infrastructure or "*investments and related services that raise the productivity of other types of physical capital, e.g. education, power, water system, communication …*" (Perkins *et al* 2005). Currently, South Africa, which is a member state of the United Nations, The African Union and the Southern African Development Community, is a signatory of various treaties and resolutions implemented by these organisations for the achievement of sustainable development goals (AUC 2015). In the continental context, South Africa leads the implementation of continental initiatives for growth and sustainable development.

In this paper, the thermal behaviour of simple concrete structures exposed to the Southern African climate is studied. The research presented seeks to make a meaningful contribution to the development of climate change mitigation strategies. It

Mlilwana TP, Kearsley EP. Light-coloured concrete surfacing for urban heat-island mitigation in Southern Africa.
J. S. Afr. Inst. Civ. Eng. 2022:64(2), Art. #0862, 11 pages. http://dx.doi.org/10.17159/2309-8775/2022/v64no2a1

is proposed that the use of light-coloured surfacing materials, which absorb minimal quantities of solar radiation, and the inclusion of thermal parameters in the design of concrete structures could be effective measures for the reduction of urban air temperatures, thereby reducing cooling demands. If such measures are widely implemented they would contribute to the development of key infrastructure in Southern Africa in a sustainable manner.

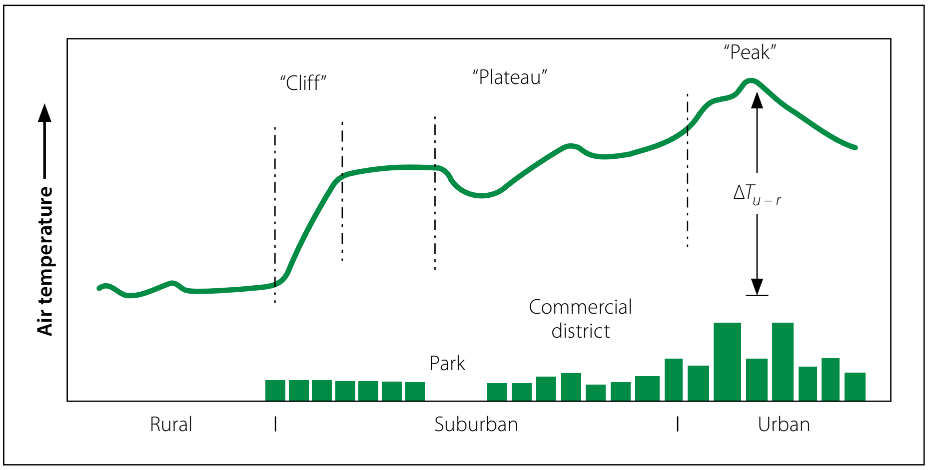

Figure 1 Generalised cross-section of an urban heat island (adapted from Oke 2002)

BACKGROUND

Since the early 1960s, the response of concrete structures to climatic parameters such as ambient temperature, solar radiation and wind speed have been investigated. However, many of these studies were either performed in relatively cold European climates, or climate-change-related factors were not considered. Consequently, the recommendations obtained several decades ago require validation due to increases in the average global temperature and increased variability in regional climates. In addition to the change in global climates, in recent times Southern African climatic conditions have exhibited greater variability between extremes due to El Niño oscillations (Hulme *et al* 2001). Under the Paris Agreement, 197 countries agreed to limit the increase in the global average temperature to *"well below 2°C above pre-industrial levels"* (UNFCCC 2015). The Intergovernmental Panel on Climate Change (IPCC) developed a special report on the impacts of global warming of 1.5°C above pre-industrial levels and related greenhouse gas emissions. The report indicated that the occurrence and intensity of extreme events would substantially worsen if the global average temperature increased by 1.5°C, and that this limit could be exceeded as early as 2030 or by 2038 if CO_2 emissions did not decrease. Beyond the 2°C threshold, the impacts of climate change would become irreversible (IPCC 2018).

Urban heat islands

The urban heat island is a microclimatic phenomenon that occurs within urban areas in which the ambient and near-surface temperatures are warmer than the suburban and rural surroundings. This is primarily due to convective heat transfer from the surfaces of two engineering materials – concrete and asphalt. These construction materials are the dominant materials in urban areas, with pavement materials making up between 29% and 45% of urban footprints (Akbari 2012). Concrete is a thermal mass material that has high volumetric heat capacity. The increased storage and release of thermal energy result in an increase of the surrounding air temperature throughout diurnal cycles. The increase in air temperature is more pronounced at night when concrete releases the energy absorbed during the day. As a result of the heat-island effect, cooling requirements increase, and energy consumption increases by 2% to 4% for every 1°C rise in the daily maximum air temperature above a threshold of 15°C to 20°C (Akbari 2009). Additionally, these high urban temperatures are associated with increased production of ozone, which presents environmental, health and economic challenges (Rosenfeld *et al* 1996). Figure 1 (Oke 2002) shows a cross-section of a city in which the greatest increase in temperature occurs in the transition zone from rural to suburban spatial planning as vegetation and open greens are reduced. These ambient temperatures are maintained in suburban areas and reach peak temperatures above urban areas where the largest difference between urban and rural temperatures (ΔT_{u-r}) is observed.

While heat islands are localised in nature they are, however, a global challenge that disproportionately affects urban centres in developing countries where economic and social infrastructure are required on an urgent basis and where sustainability has thus far been neglected by planners and policymakers. In research by Power and Mills (2005) it was found that the increased production of smog in Southern Africa had resulted in drastic climatic changes and subsequently increased energy use in major South African cities including Bloemfontein, Cape Town, Durban, Johannesburg and Pretoria. Smog promotes atmospheric warming, thereby increasing the demand for mechanical cooling that is powered by combusting fossil fuels which in turn increase atmospheric carbon (Power & Mills 2005).

Cooling technologies

The demand for cooler cities has resulted in increased research and development of cooling technologies which include blue roofs, sky gardens, cool pavement technology, and the usage of light-coloured surfacing on concrete structures. These technologies have been found to reduce ambient and structural temperatures, but the capital and maintenance costs often render such methods unfeasible. In studies performed in North American cities, it was found that cooling a city by 3°C would reduce smog by 12%, resulting in annual energy savings of US$360 000 000 ($579 983 000), of which US$76 000 000 ($122 440 000) was a result of cooling the pavements (Rosenfeld *et al* 1996). The net values in May 2019 of the aforementioned monetary savings are parenthesised. Increasing the reflectivity of buildings by whitewashing can result in direct energy savings of up to 14% and 19% on cooling peak power and electrical cooling energy respectively (Taha *et al* 1988). These researchers showed that the use of reflective materials to cool urban areas is not only feasible but would result in significant future economic benefits.

Solar absorptivity

Solar radiation has the largest effect on temperature distributions in concrete structures. Air is transparent to light and allows approximately 90% of the visible light and some of the infrared fractions of the electromagnetic spectrum to pass through it. The solar absorptivity of a surface is a non-dimensional parameter which determines the quantity of visible light or global radiation that is absorbed by the surface. This property is measured relative to the reflectivity of a black body which would absorb all visible light wavelengths on the electromagnetic spectrum. During the day, the thermal balance of a construction material is determined by the reflection and absorption of solar radiation. The use of low absorptivity materials results in reduced absorption of thermal energy which is characterised by lower surface and mean temperatures during the day, and lower air temperatures at night, as less thermal energy is stored and subsequently released as longwave radiation.

Interaction of structures and climatic parameters

It is widely accepted that climatic parameters contribute to the deterioration of buildings, pavements and other types of concrete structures, as temperature variations contribute to several distress modes, including fatigue, deflection and block cracking. They are of interest in structures with large horizontal surface areas such as pavements and the superstructures of bridges and buildings where temperature variation can result in adverse volumetric movement. Movement due to thermal loading is primarily of interest in instances such as the following:

- Where the cross-section varies, differences in thermal gradients can lead to transverse cracking in extreme conditions.
- In integral structures, where expansion and contraction of the bridge superstructure lead to stresses in the deck and rotation of the piers and/or abutments.
- In continuously reinforced concrete pavements, where cracking and local buckling can be caused by large temperature changes.

In general, concrete structures undergo three types of temperature-induced volume change – uniform expansion of an entire cross-section due to uniform increase in the temperature, linear expansion and contraction whereby volume change occurs equally but in opposite directions around a neutral axis, and lastly, non-linear changes due to uneven heating and cooling through a cross-section (Larsson & Thelandersson 2011; Elbadry & Ghali 1983). The linear and non-linear components of expansion cause rotational changes in the form of warping, even in simply supported superstructures.

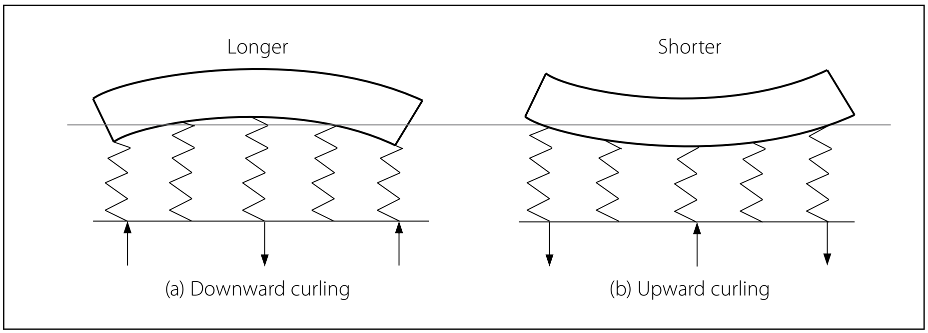

Figure 2 Curling of concrete pavement structures (Huang 1993)

If these movements are restrained, compressive and tensile stresses will be generated in the case of expansion and contraction respectively. In most structural applications this restraint occurs due to changes in cross-section or thermal gradients. In concrete pavement structures, which have large horizontal surfaces and are exposed to climatic actions, temperature variations can result in curling. Curling occurs due to temperature differences between the top and bottom of the pavement as shown in Figure 2. During summer months, daytime gradients cause downward curling, while upward curling is observed at night.

In a study investigating temperature distributions in asphalt and concrete pavements in Southern Africa by Williamson and Marais (1975) it was found that the mean temperature range at the surface of concrete pavements varied annually by between 11°C and 31°C, and that of asphalt pavements varied by 10°C to 15°C. The measured temperature gradients in concrete pavements were approximately half of those measured in asphalt pavements, while the minimum surface temperatures experienced by concrete pavements were higher than those in asphalt pavements. The authors attributed this temperature variation to the lower emissivity of mass concrete which was 0.68 compared to 0.87 for bituminous surfaces. A review of the thermal characteristics of concrete indicates that this difference was more likely due to the differences in solar absorptivity and the superior volumetric heat capacity of concrete.

It is evident from the aforementioned research that climate change is an unequivocal global challenge that will have catastrophic effects on the economies of developing countries by 2030 if adequate mitigation measures are not implemented with immediacy. The economical and sustainable design of future infrastructure requires the simultaneous consideration of climatic loading and climate change mitigation measures. Engineers should consider the surface characteristics of concrete, namely solar absorptivity and emissivity, and influence the energy balance within and surrounding the structure or element. In particular, this should be applied on structures with large horizontal components, such as pavements, bridges and buildings.

The research presented in this paper includes a study of the effect of solar absorptivity, climatic parameters, cross-sectional dimensions and material properties in order to form a basis for climate change mitigation strategies in infrastructure development. Physical modelling is conducted to monitor thermal performance of simple concrete structures and quantify the effect of solar absorptivity, followed by numerical simulation using finite element modelling to verify the observed results and extend the range of cross-sectional dimensions and materials considered. Comparisons are made between surface colours, dimensions and aggregates, in conjunction with brief discussions of the practical application of these results.

Table 1 Mix design

Component	Relative density	Quantity (kg/m^3)
CEM II 52.5N	3.02	382
Dolomite stone (9.5 mm)	2.84	880
Dolomite crusher sand	2.84	1004
Water	1.00	210
Theoretical concrete density	2.48	2476

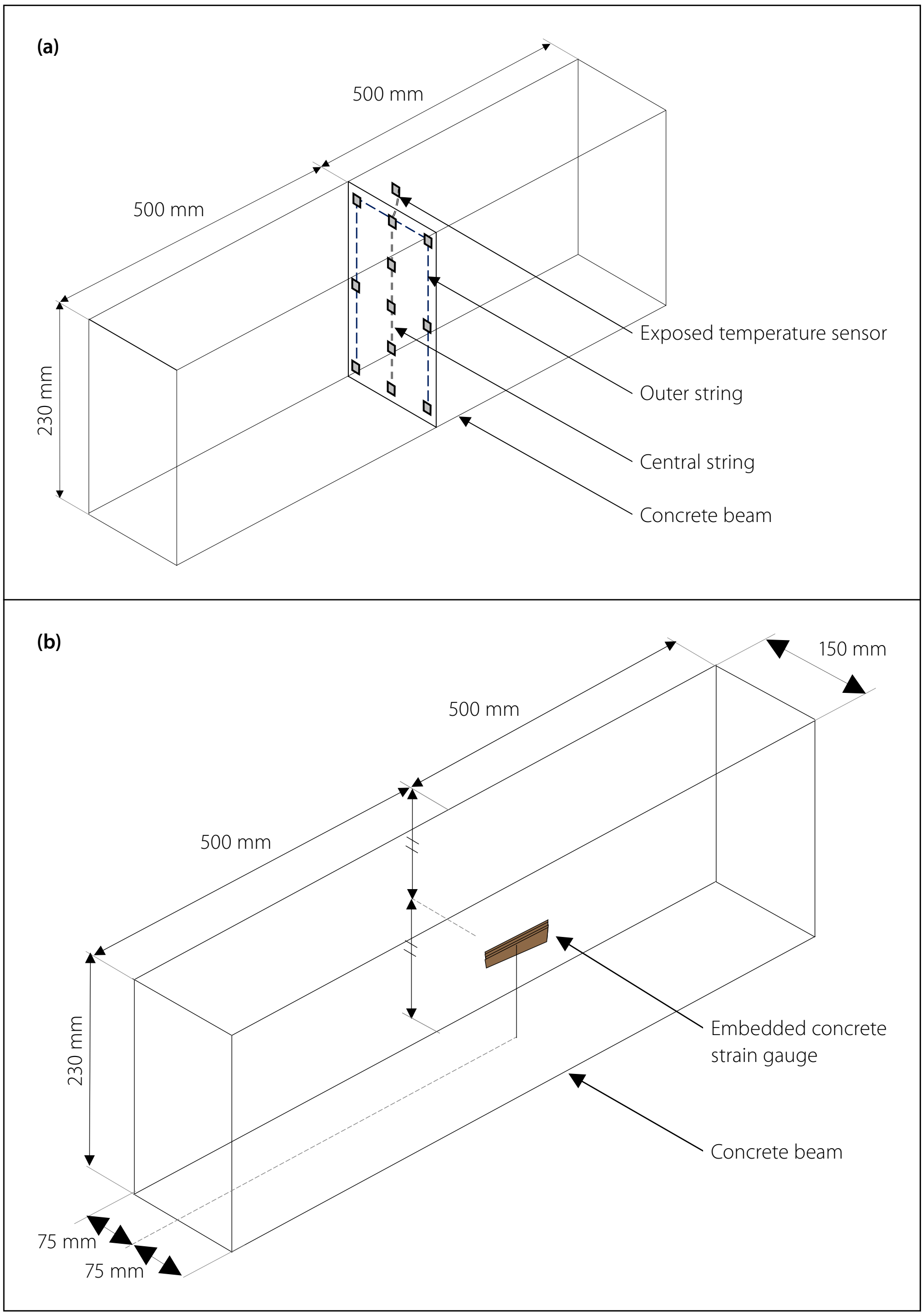

Figure 3 Instrumentation of concrete structures

EXPERIMENTAL PROGRAMME

The experimental programme was conducted for two primary purposes – firstly to investigate the thermal response of simple concrete structures exposed to climatic parameters in Southern Africa, and secondly to aid the development and validation of numerical simulations that would be used to expand the research scope.

Materials and mix design

Simple concrete structures were instrumented and constructed using normal-weight concrete produced with locally available materials. Table 1 shows the relative densities and quantities per m^3 of the materials used. These materials were selected as they were readily available and of high quality. The mix design was developed to produce normal-weight concrete with a 28-day target compressive strength of 40 MPa, which is a typical compressive strength used for a wide range of structural applications in Southern Africa

Construction of test structures

Three simple concrete structures were instrumented and cast in the University of Pretoria Concrete Laboratory using normal-weight concrete produced with the abovementioned mix design. The rectangular structures were 1 000 mm long, 230 mm wide and 150 mm deep without any steel reinforcement provided. In order to develop experimental data that was comparable to real concrete structures and previous research relevant to this paper, a depth similar to that of conventional rigid pavements was used. To simulate the behaviour of the homogenous concrete material that

Figure 4 Curing of concrete structures

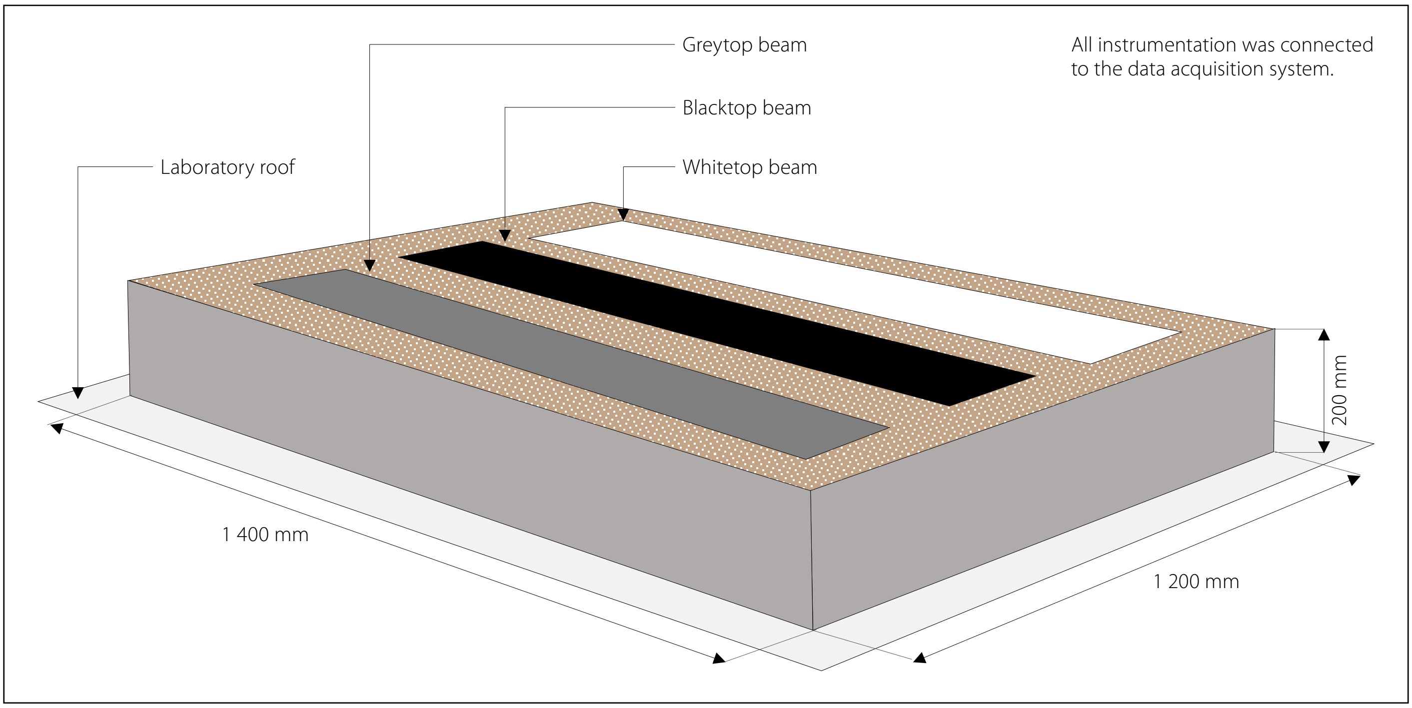

Figure 5 Schematic presentation of experimental set-up

would be used in numerical simulations, no steel reinforcement was used in the test structures. Prior to the casting of the concrete, various instruments were installed throughout the structure cross-section at the mid-point to measure the thermal performance of the concrete structures.

In each structure, 11 temperature sensors (negative resistance thermistors) were provided internally to determine internal temperature distributions and effective temperatures, while one temperature sensor was provided externally 25 mm from the top surface to measure the temperature of the surrounding medium (see Figure 3 on page 5). During the manufacturing process, verification of each sensor was performed using the base resistance of 5 000 Ω at 25°C in a LAUDA-Brinkmann® RP 1840 water bath using a steady-state verification time of twenty minutes. Vishay Precision Group, Inc EPG-Series 350 concrete embedment strain gauges were provided along the centre line of each structure to investigate early age and long-term thermal movement under climatic loading (see Figure 3). The instrumentation was connected to a data acquisition unit, where data was collected at 15-minute intervals throughout the study.

Conventional rotary drum mixers were used to produce the concrete which was placed and compacted using industrial poker vibrators. Immediately after placing, plastic sheeting was provided for 48 hours to prevent moisture loss, after which they were stored under laboratory conditions for seven days (see Figure 4 on page 5).

Experimental set-up

An experimental set-up was designed to empirically investigate the thermal performance of the structures, which were painted with white, grey and black acrylic paints. The concrete structures were embedded in silica sand, which served as a thermal sink as well as prevented the heating of the non-horizontal surfaces (see Figures 5 and 6). That is, for each structure only a single horizontal surface measuring 1.00 m × 0.23 m was directly exposed to climatic factors. A geotextile layer was provided below the sand layer to allow for the free drainage of rainwater which was allowed to run off as the experimental set-up was elevated from the supporting surface.

The experimental set-up was located on the roof of the University of Pretoria Concrete Laboratory. This roof was selected as it satisfied several criteria, including:

- An unobstructed horizon
- Realistic exposure to solar radiation
- Free atmospheric moisture movement.

Data acquisition system

Temperature and strain data was measured and recorded throughout the casting, curing and longterm monitoring of three concrete beams. These measurements were recorded

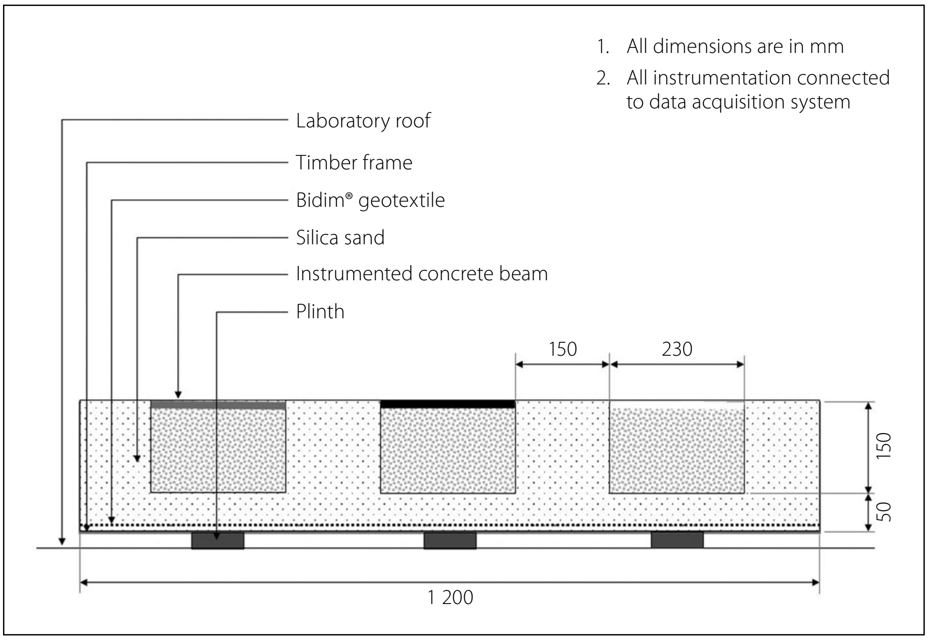

Figure 6 Section through experimental set-up

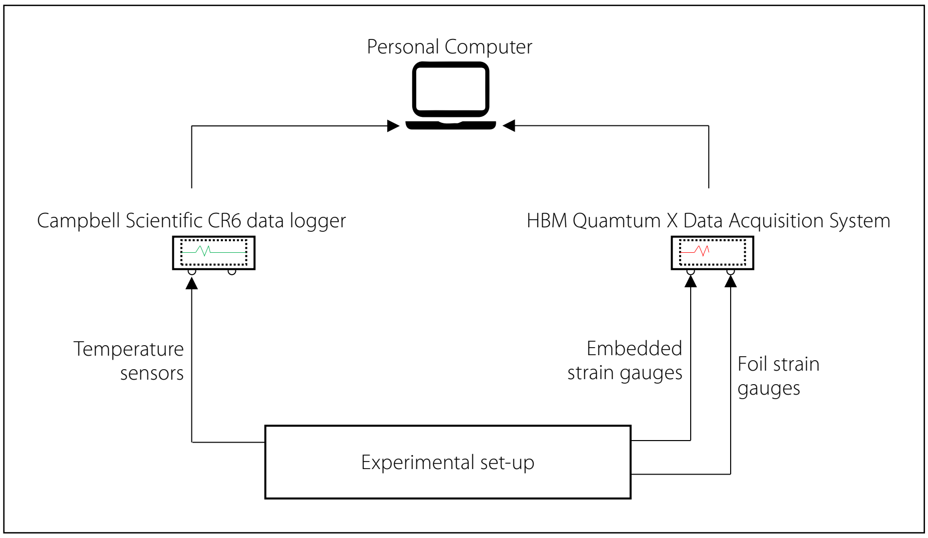

Figure 7 Schematic presentation of data acquisition system

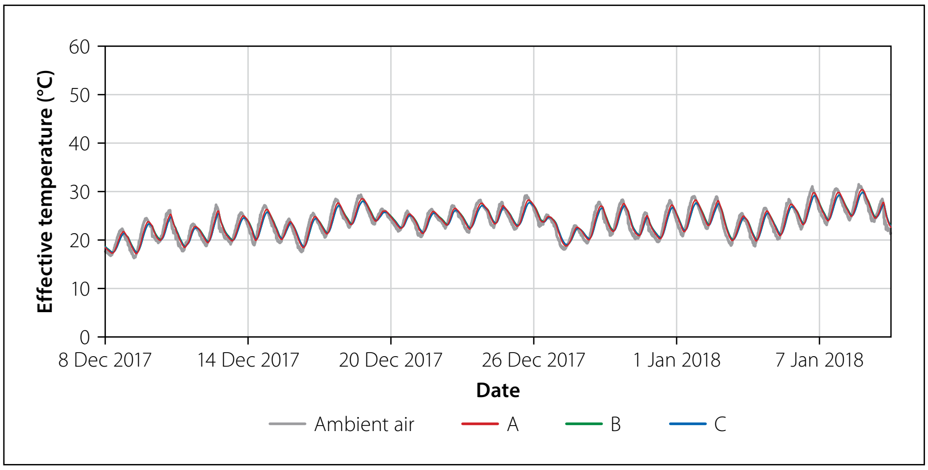

Figure 8 Ambient and effective temperature in Phase I

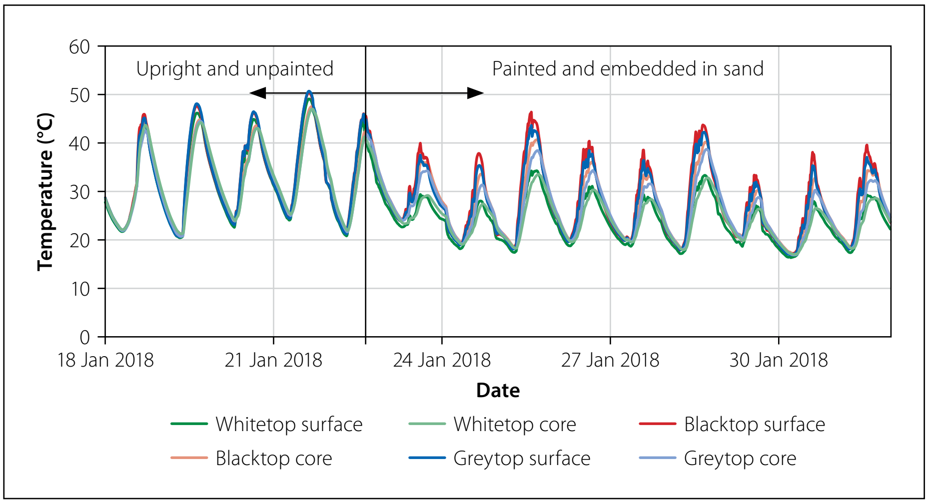

Figure 9 Influence of orientation and surface colour

through an acquisition system with a total of 42 individually logged channels. A schematic layout of the data acquisition system is shown in Figure 7. The temperature data was recorded through a Campbell Scientific CR6 data logger, while the embedded and surface strain gauge data was recorded with Catman® data acquisition software using HBM QuantumX strain gauge amplifiers. The aforementioned logging systems were controlled using a personal computer that was located in the adjacent laboratory.

Climatic data was obtained from a weather station located on the roof of a building which has good solar exposure and largely unobstructed horizons on the University of Pretoria Hatfield campus.

EXPERIMENTAL RESULTS AND DISCUSSION

Early-age thermal behaviour

In Phase I, the three concrete structures were cast and cured in the laboratory for seven days, after which they were transferred to an outdoor testing facility at the University of Pretoria where they were stored for a further six weeks from December 2017 to January 2018. The purpose of the latter stage of Phase I was to ensure that the structures would reach a constant hygrothermal state that would be comparable for each structure since the exposure conditions were identical. The effective temperature or weighted mean temperature of the structural cross-section was used as the thermal response indicator for the duration of the experimental phase. Figure 8 shows the ambient air and effective temperatures measured in each structure during Phase I.

Following Phase I, the concrete structures were moved to the University of Pretoria Concrete Laboratory roof where they were stored in an upright position for seven days. The structures were then embedded in sand and painted. Figure 9 shows the influence of orientation and surface colour. In an upright position, all four sides of the structures were exposed to solar radiation, resulting in high effective temperatures. The effect of surface colour was immediately visible with lower albedo surfaces showing a large reduction in effective temperatures in less than 24 hours after the paint had been applied.

Long-term thermal performance

Table 2 shows the climatic conditions measured during the experimental phase. The monthly maximum, minimum and average monthly range in temperature measured during the experimental phase

Table 2 Climatic conditions in Pretoria

Variable	Summer	Winter
Maximum daily average solar intensity (W/m^2)	1 020	660
Time at sunrise	05:00	06:00
Time at sunset	18:30	17:00
Maximum ambient air temperature (°C)	33.8	21.9
Minimum ambient air temperature (°C)	13.4	2.5

Table 3 Extreme temperatures measured during experimental study

Month	Whitetop (°C)			Blacktop (°C)			Greytop (°C)		
	Max	Min	Range	Max	Min	Range	Max	Min	Range
January	34.8	16.6	18.2	46.3	17.0	29.3	44.4	16.7	27.7
February	36.1	16.4	19.7	47.5	17.0	30.5	45.0	16.9	28.1
March	36.6	13.9	22.7	48.0	14.9	33.1	45.4	14.9	30.5
April	25.9	11.4	14.5	36.4	12.3	24.1	33.9	12.2	21.7
May	21.3	6.1	15.2	29.6	6.6	23.0	27.6	6.6	21.0
June	16.7	3.9	12.8	23.3	4.7	18.6	21.8	4.7	17.1
July	14.3	1.6	12.7	19.8	2.4	17.4	18.4	2.4	16.0

Table 4 Comparison of concrete pavement temperatures

Month	Concrete pavement 1972 (°C)			Greytop beam 2018 (°C)		
	Maximum	Minimum	Full depth range	Maximum	Minimum	Full depth range
April	34	23	12	33.9	23	13
June	21	17	9	21.8	19.4	13

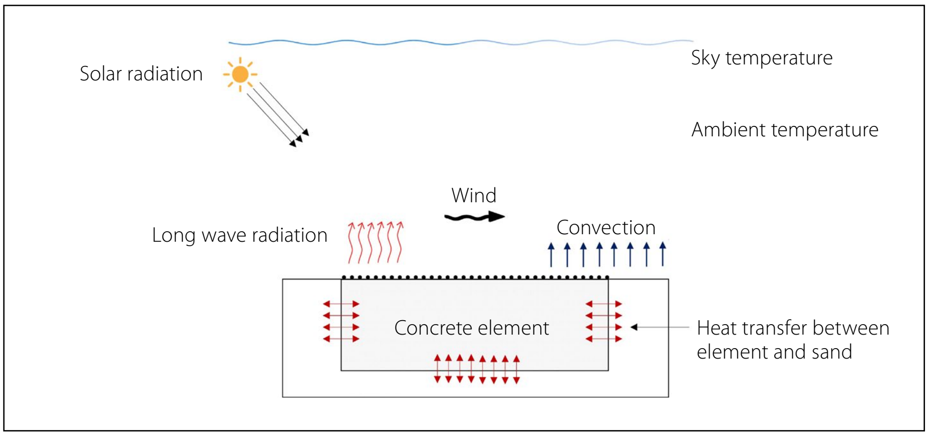

Figure 10 Energy balance of heat transfer model

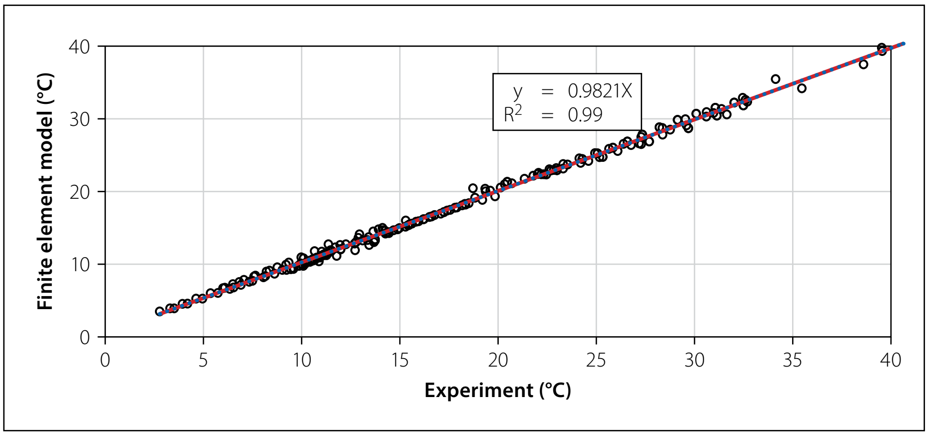

Figure 11 Relationship between experimental and simulated results

Table 5 Model parameters

Attribute	Value
Stephan-Boltzmann constant (W·m^{-2}· K^{4})	5.67 × 10^{-8}
Absolute zero (°C)	–273.15

Table 6 Material properties

Property	Range	Value used
Conductivity (W/m·°C)	2.2 – 2.7	2.5
Density (kg/m^{3})	2 400 – 2 600	2 460
Specific heat (J/kg·°C)	800 – 1 000	880

for each concrete structure are shown in Table 3. While the temperatures decreased from summer to winter, the reduction in maximum and minimum temperatures, as well as the monthly range, was lower for low albedo surfaces. These results support the use of light-coloured surfaces for reducing temperature differentials and near-surface ambient temperatures.

Table 4 shows a comparison between the results measured in the concrete structure with grey paint and experimental data measured by Williamson and Marais (1975). These results indicate that simple structures can be used to simulate the behaviour of concrete structures such as pavements. It can be seen that the use of light-coloured surfacing on a full-scale pavement would result in decreases in the pavement temperature and near-surface air temperature.

NUMERICAL SIMULATION

Numerical simulation was used to extend the study beyond the limitations of physical modelling, namely time and financial cost. The commercially available suite of finite element packages, Abaqus, was used to develop a two-dimensional heat transfer model for normal-weight concrete sections. The Abaqus/Standard analysis module that was used to develop a two-dimensional heat transfer model makes use of a backwards difference algorithm programmed in the Complete Abaqus Environment (Simulia 2011). Data obtained from the experimental programme was used to develop and validate the heat-transfer model. The objective of the numerical simulations was to develop a model that could simulate daily and seasonal temperature variation and thermal gradients in concrete sections by taking into account climatic factors, surface characteristics and conductive heat transfer within the material.

Material and model properties

The thermal characteristics of concrete were assigned to the model using a homogenous two-dimensional solid material. Table 5 shows the physical constants assigned to the model, namely the

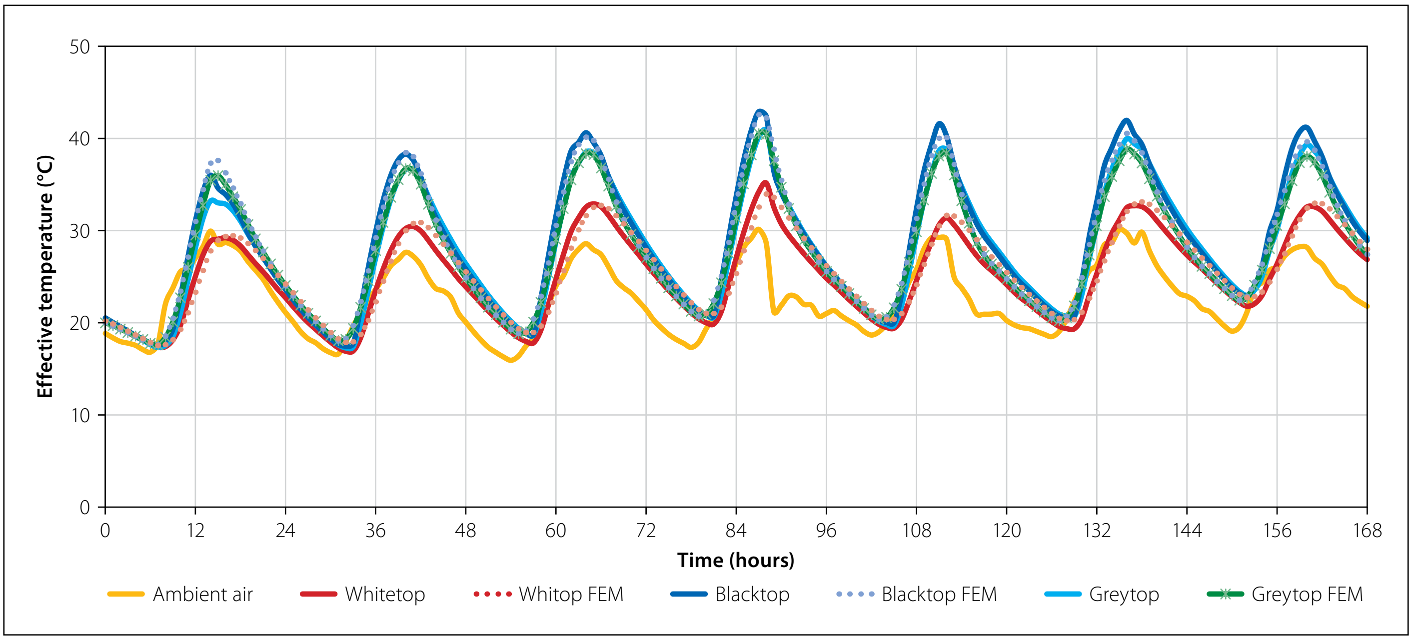

Figure 12 Comparison of experimental and simulated temperature variation

Stefan-Boltzmann constant which governs radiative heat transfer from the solid material, as well as the reference or absolute zero temperature.

Table 6 shows the material properties used to develop the model. The density of concrete was determined experimentally from 200 mm diameter cylinders that were produced with the same concrete used to cast the main concrete structures, while the remainder of thermal properties were obtained through an extensive literature study. To incorporate the effect of moisture changes under wetting and drying cycles, a partition was made at mid-depth with wet and dry thermal characteristics applied to either section.

Energy balance

In order to accurately simulate climate factors in a two-dimensional model, the climatic factors considered in the study were applied to the model as loads and interactions on the various model boundaries. Figure 10 shows the climatic factors and heat transfer mechanisms used in the model.

Model discretisation and validation

The solid material used to develop the heat transfer model was discretised using quadratic C2D4R Abaqus/Standard heat transfer elements with 1:1 aspect ratio. These are two-dimensional continuum (solid) elements with four nodes. Heat transfer occurs linearly by diffusion in both directions across each element (Simulia 2011). The mesh fineness was determined iteratively to determine a constant solution or an absolute error of less than 0.1%, as shown in Figure 11. A final element size of 2.5 mm × 2.5 mm was selected for model implementation.

Figure 12 shows a comparison between measured and simulated results under summer climatic conditions from 1 March to 8 March 2018. The effective temperature or weighted mean temperature of the structure cross-section was used as the thermal response indicator. These results show a good correlation between effective temperatures in the physical model and finite element model with absolute errors of less than 2°C for each surface colour.

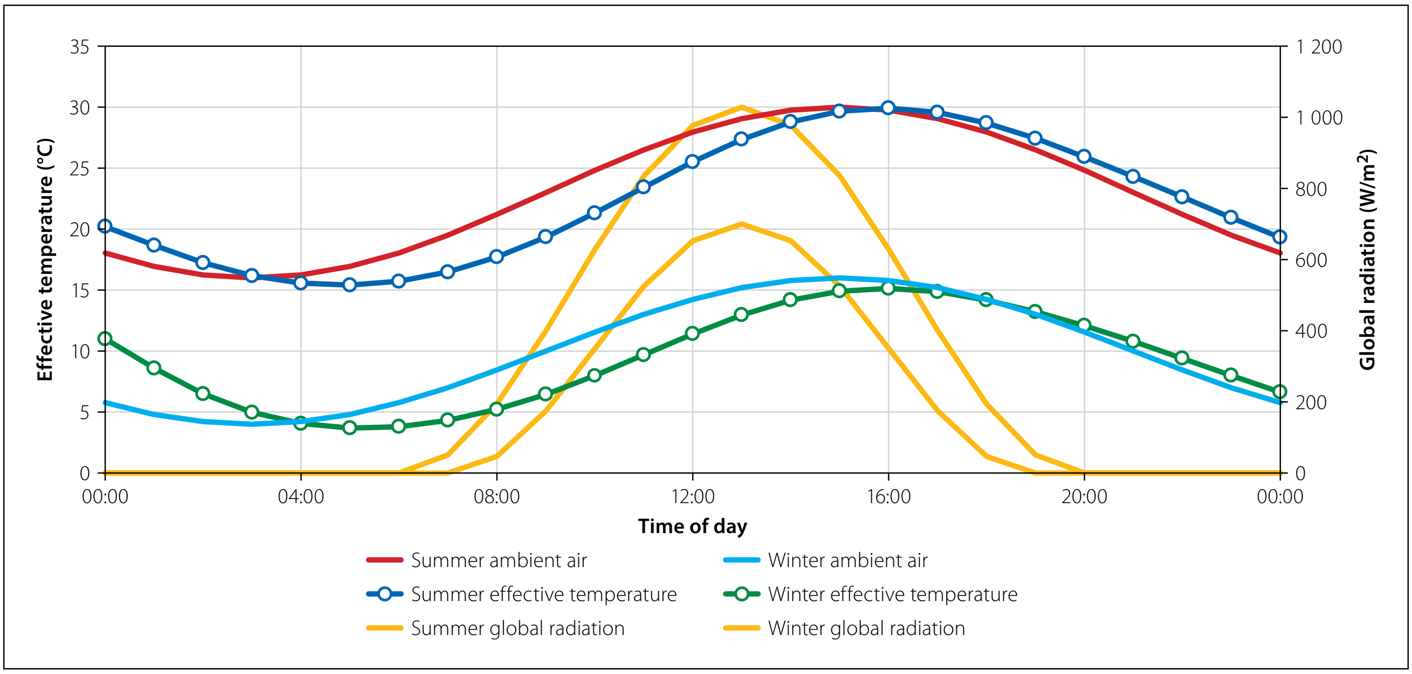

Figure 13 Simulated climatic parameters

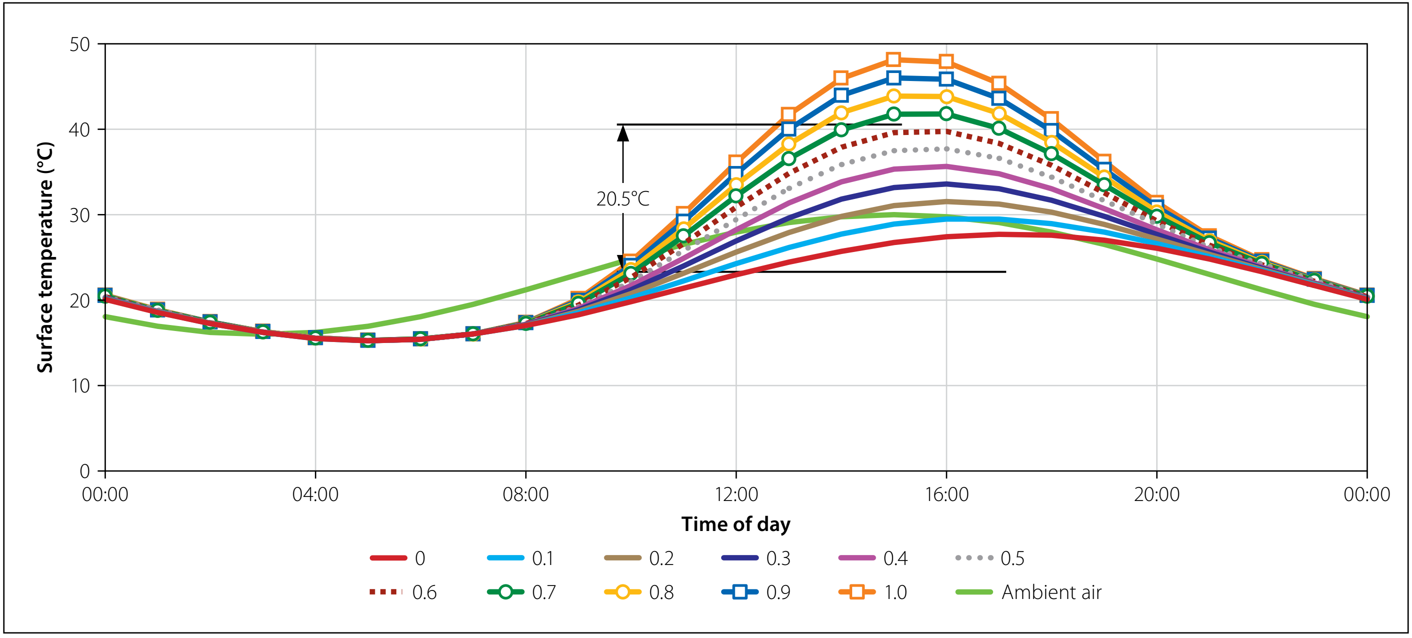

Figure 14 Influence of surface reflectivity on surface temperatures

Numerical simulations

Idealised climatic input data was used to simulate summer and winter climatic conditions. Figure 13 (page 9) shows the idealised ambient temperature and solar radiation data used. Figure 14 shows the influence of albedo on the surface temperatures of concrete structures. It can be seen that, for a concrete section with the surface characteristics of white paint, the effective daily temperature follows a sinusoidal function similar to that of the ambient temperature. These results provide further support for the use of light-coloured surfacing materials to mitigate the effects of climate change and reduce the urban heat-island effect.

Effect of cross-sectional dimensions

Figure 15 shows the effect of cross-sectional dimensions on the effective temperature of concrete sections with whitetop surface characteristics. It can be seen that increasing surface areas and overall volume results in reduced effective temperatures. This is due to:

- Increased reflection/absorption of solar energy
- Increased transfer of thermal energy from surface by conduction
- Increased insulation of the structure with increasing width.

The aggregate type used in concrete determines the thermal properties of concrete due to its large volumetric proportions. Figure 16 shows the influence of aggregate type on the thermal response of concrete. Dolomite and granite aggregate were used with assumed thermal conductivities of 2.7 W/m.C° and 2.6 W/m.C° respectively. With increasing conductivity, energy is transferred from the warm surface to the cooler parts of the concrete structure by conduction. It can be seen that the use of high conductivity aggregates could be a useful measure for reducing the surface temperatures of concrete structures.

Figure 17 shows the relative effects of the climatic, material and geometric parameters investigated using numerical simulation. These results show that the surface colour and cross-sectional depth

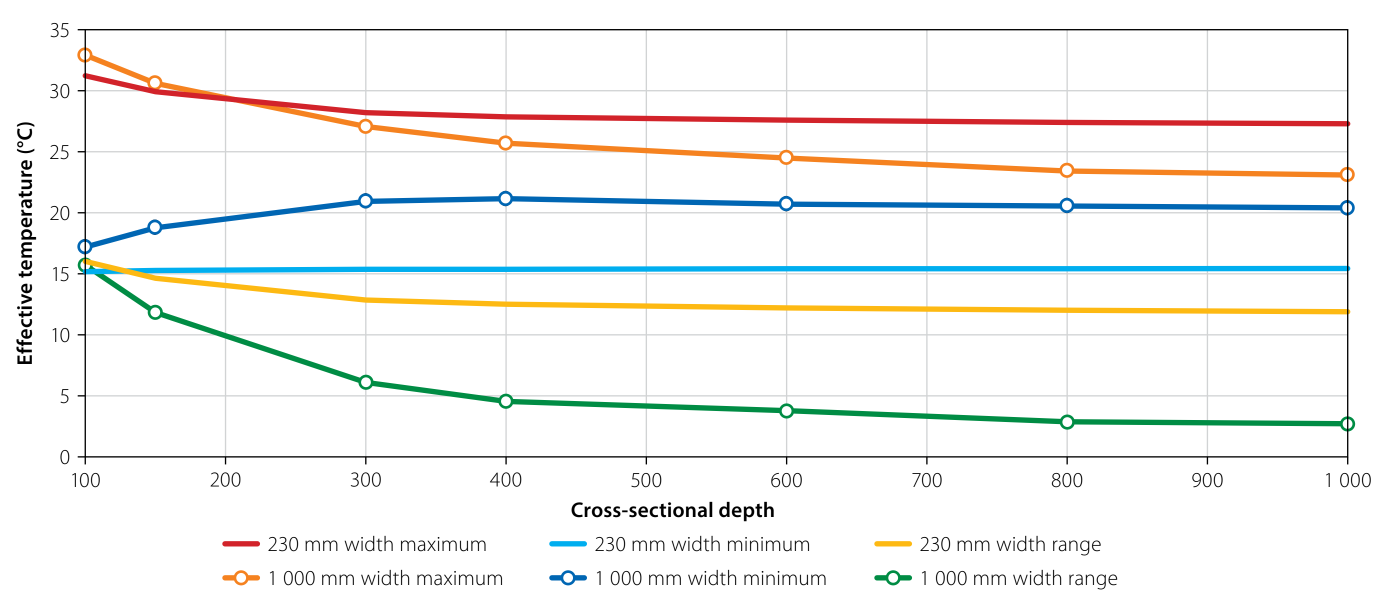

Figure 15 Influence of concrete structure depth and width on effective temperature

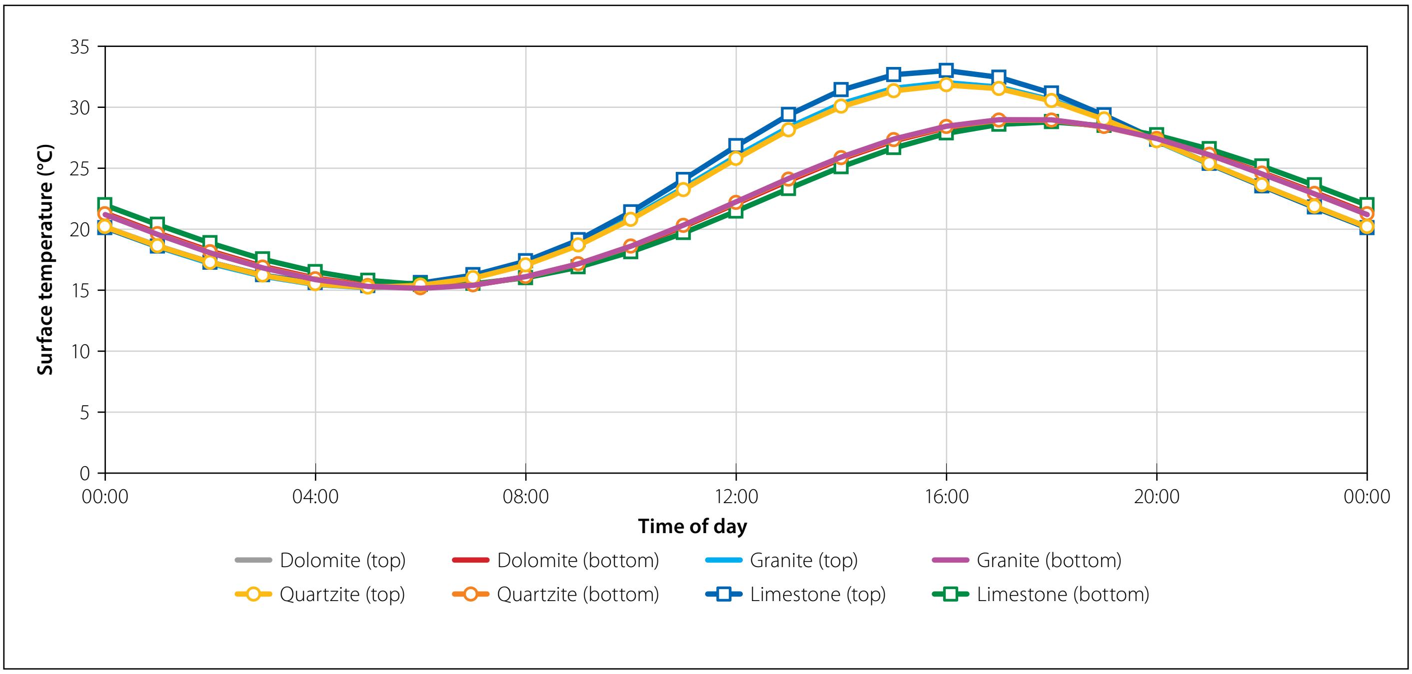

Figure 16 Influence of aggregate type on surface temperatures

have the largest influence of temperature differentials in concrete structures. Increasing absorptivity or reducing albedo and increasing depth resulted in significant increases in the temperature differentials and linear thermal gradient. Increases in wind speed and moisture were found to increase the loss of thermal energy from the radiated surfaces by convection to the surrounding air and conduction to the surrounding materials respectively.

CONCLUSIONS

An experimental study was conducted to determine the effect of surface colour on the thermal response of concrete structures exposed to climatic loading. The use of light-coloured surfacing as a cost-effective measure to mitigate the urban heat-island effect and climate change in Southern Africa was investigated. This was followed by numerical simulation of the concrete structures using finite element methods. The verified numerical model was then extended to include the effects of cross-sectional dimensions and thermal characteristics of normal-weight concrete produced with South African aggregates. The following conclusions were drawn:

- High albedo surfacing effectively reduced the surface temperatures of concrete surfaces by between 60% and 75% when compared to highly absorptive surfaces. The mitigation of global climate change and the reduction of air temperatures in urban areas require the use of innovative materials and construction methods.

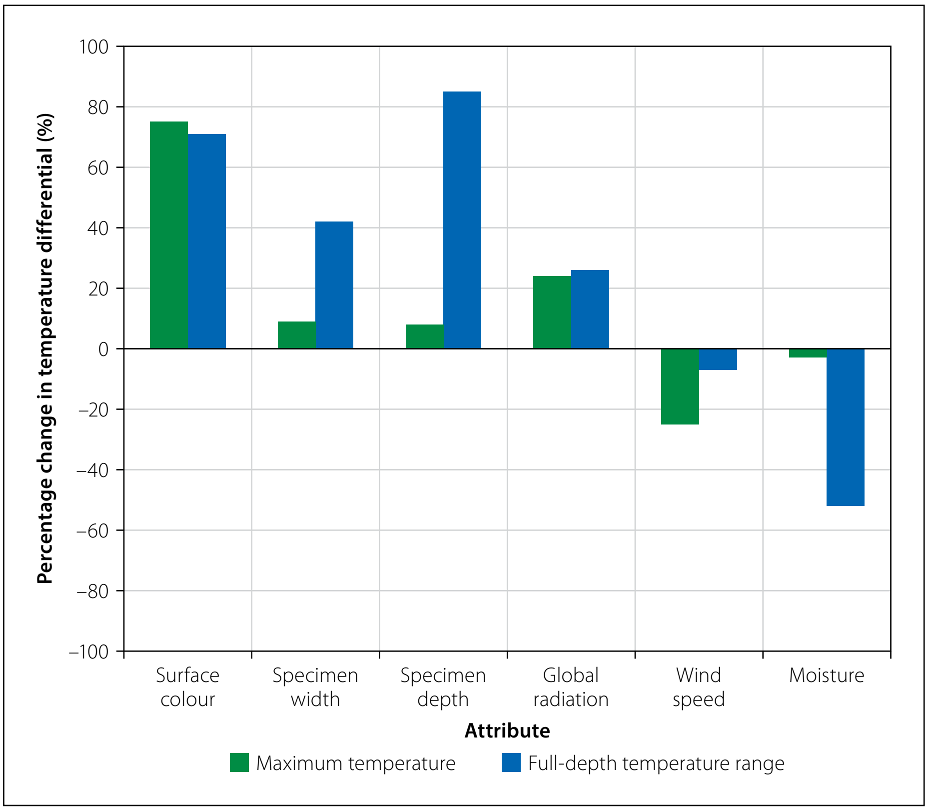

Figure 17 Influence of various parameters on maximum effective temperatures and full-depth temperature ranges

- The implementation of the above-mentioned climate change and heat-island mitigation measure could be implemented at low cost through the whitewashing of building structures, replacement of roofing and façade covers with high-albedo alternatives during scheduled maintenance periods, and the use of light-coloured compound pigments during the production of cement and concrete.
- Increasing cross-sectional width resulted in increased surface temperatures due to the increased absorption of global radiation, while increasing cross-sectional depth resulted in a reduction in the effective temperature within concrete structures, regardless of the surface colour.
- Concrete structures with cross-sectional widths greater than or equal to 600 mm could be modelled as having adiabatic

boundaries. As such, heat transfer on the vertical faces of the structures or edge effects could be neglected for such widths. The aforementioned conclusion was true for concrete structures with a maximum depth of 1 000 mm.

- Wind speed, represented by a convective heat-transfer coefficient, resulted in the reduction of surface temperatures in concrete structures. The influence of the above wind speed was, however, negligible for speeds in excess of 10 m/s. Through a parametric investigation it was found that wind aids the cooling of surfaces, with potential reductions of up to 25% in the maximum surface temperatures for average wind speeds in unobstructed areas.
- The effects of rainfall and variations in atmospheric relative humidity were not investigated explicitly in this research; however, the effects of moisture variation were investigated. In practice, such variations would occur as a result of precipitation in urban infrastructure and varied exposure in partially submerged hydraulic structures. It was observed that the increase in thermal conductivity due to increased moisture resulted in the increased uniformity of thermal gradients. Thus, the increase in moisture has temporary beneficial effects; however, the subsequent drying would likely cause internal restraint and surface cracking if the tensile capacity of concrete is exceeded. Thus, wetting and drying cycles could increase the rate of deterioration of concrete structures and other structures.

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