Thermophysical Optimization of Specialized Concrete Pavement Materials for Collection of Surface Heat Energy and Applications for Shallow Heat Storage

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Great potential exists to use pavement structures to collect or store solar energy for heating and cooling of adjacent buildings, for example, airport terminals and shopping malls. Therefore, pavement materials comprising both conventional and unconventional concrete mixtures with a wide range of densities, thermal conductivities, specific heat capacities, and thermal diffusivities were investigated. The thermophysical properties were then used as inputs to a one-dimensional transient heat transport model to evaluate temperature changes at various depths at which heat might be abstracted or stored. Results indicated that a high diffusivity pavement (e.g., one that incorporated high conductive aggregates or metallic fibers, or both) could significantly enhance heat transfer as well as reduce thermal stresses across the concrete slab. However, a low diffusivity concrete could induce a more stable temperature at shallower depths and enable easier heat storage in the pavement, which would help to reduce the risk of damage caused by freeze–thaw cycling in cold regions.

Many buildings that have a high heating or cooling load are built adjacent to roads, aircraft stands, car parks, and other places (e.g., airport terminals, shopping malls, factories, warehouses, and retail outlets). Therefore, great potential exists to collect or store solar energy using the large adjacent pavement surface areas that are already required for operational reasons. Such pavement structures, equipped with fluid-filled pipes (known as loops), are called solar pavements here.

As shown in Figure 1, solar pavements could be used either by installing loops close to the pavement surface to collect the solar energy [pavement heat collectors (PHCs)], or by installing loops at shallow depths, to use the pavement as a heat source during winter and as a heat sink during summer [pavement-source heat stores (PSHS)]. The two systems might be combined or linked together as a hybrid system in which the solar heat collected by the pavement surface in the summer is transferred and stored in shallow insulated ground heat stores for subsequent reuse (1). In all applications, the transmitted heat to the loops could also be used, either directly or in conjunction with a heat pump, for different purposes such as deicing of roads in winter, to reduce the urban heat island effect, to reduce asphaltic pavement rutting, to heat or cool adjacent buildings, to supply hot water, or to convert the energy to a transmittable form (1, 2). If such a system were installed at the time of pavement construction, it might incur only a marginal cost, for the cost of the pavement construction would probably be already funded from a separate budget (i.e., budget for transportation rather than energy purposes).

The thermophysical properties of pavement materials along with an effective loop component design (e.g., depth of pipe burial, type and length of pipes, type of fluid) are key parameters to design solar pavements. Previous studies have shown that thermophysical properties of pavement materials have a significant effect on temperature distribution within the pavement (3–5).

OBJECTIVE

The objective of this paper is to study the thermophysical properties of concrete pavement materials and determine their effects on the performance of PHC and PSHS and other implications to help pavement design. Thermophysical properties of concrete pavements with acceptable mechanical qualities for different structural applications (e.g., roads, aircraft stands, car parks) were used in a one-dimensional transient heat transport model previously developed and verified (5).

THERMAL, PHYSICAL, AND MECHANICAL PROPERTIES OF MODIFIED PAVEMENT MATERIALS

A wide range of heavyweight, lightweight, and normal aggregates, as well as other additives, were used to produce concrete that might deliver beneficial thermophysical properties. Replacement components included limestone, quartzite, natural sand, sintered pulverized fuel ash lightweight aggregate (known as Lytag), crumb rubber, cooled iron shot (known as Ferag), air cooled copper slag, incinerator bottom ash, furnace bottom ash, and copper fiber. Pavement quality concrete and lean mix concrete mixes were designed according to airfield concrete pavement design (6). The control mix for pavement quality concrete used is a 10/20 single-sized limestone aggregate and 4-mm down natural sand in compliance with BS EN 12620 as well as high-strength portland cement (CEM I, 52.5 N/mm²). The control mix for lean mean concrete used is an all-in limestone aggregate and
CEM I, 52.5 N/mm². Particle density and water absorption coefficients of the materials were experimentally determined according to BS EN 1097-6. On the basis of these values, the volumetric replacement method was used in calculating the mixture proportions. All concrete specimens were first air cured for 24 h in laboratory conditions, and then for a period of 28 days in water at a temperature of 20°C ± 2°C.

Five 100-mm cubes were used for determining the unconfined compressive strength (fc), according to BS EN 12390-3. Apparent porosity (AP) of specimens was assessed with the following expression:

\[
AP(\%) = \frac{w_d - w_s}{w_s} \times 100
\]

where

- \(w_s\) = weight of specimen at saturated condition,
- \(w_d\) = dry weight of specimen when dried to constant mass at 105°C ± 5°C for 24 h, and
- \(w_e\) = weight of specimen in water under saturated conditions.

The thermal conductivity of the concrete specimens, following immersion in water (\(\lambda_s\)) and oven-dried (\(\lambda\)) conditions, was experimentally determined using a computer-controlled P. A. Hilton B480 uniaxial heat flow meter apparatus with downward vertical heat flow, which complies with ISO 8301. The concrete slab specimens were placed inside the apparatus between a temperature-controlled hot plate \((T_{hot})\) and a water-cooled cold plate \((T_{cold})\) connected to a separate chiller device. Under steady-state conditions, the thermal conductivity of the specimen is calculated using the following:

\[
\lambda = \frac{1}{\rho c_p} \int \left[ \frac{k_1 + (k_2 \cdot T)}{(T + k_3) \cdot \text{HFM}} \right] \frac{dT}{dT}
\]

where

- \(l\) = thickness of specimen,
- \(k_1\) to \(k_6\) = calibration constants of apparatus determined separately,
- \(T = T_{hot} + T_{cold}/2\) = average temperature of hot and cold plates,
- \(\text{HFM} = \text{heat flow meter output measured in mV, and}
- dT = T_{hot} - T_{cold}\)

The values for the calibration constants of the apparatus \(k_1\) to \(k_6\) inclusive are determined separately. Steady-state conditions are deemed to occur when the percentage variation in heat flux throughout the sample is ≤3%. The sample interval of the heat flow meter is given by the greater of 300 or as follows:

\[
pC/\lambda R
\]

where

- \(\rho\) = density of specimen,
- \(C_s\) = specific heat capacity of specimen, and
- \(R\) = specific thermal resistance of material.

Two slabs with dimensions of 300 × 300 mm, and a thickness of approximately 65 mm, were prepared for each mix design, and then the mean value of three independent readings was obtained for each slab specimen at oven-dried and water immersed states. For thermal conductivity measurement in the wet state, the concrete slabs were removed from the curing tank water at the end of their 28-day curing period and sealed in a vapor-tight envelope to prevent a change in moisture content. The influence of the thin envelope on the thermal conductivity of the slab specimens was found to be negligible when thermal conductivity was measured at a steady-state variance of ±2% to 3%, as prescribed by ISO 8301. In the dry state, all the specimens were dried in an oven at 105°C ± 5°C, until the mass changes by less than 0.2% in 24 h, and then cooled in a desiccator. More details about the test can be found in a previous publication (5). The mean values of compressive strength and apparent porosity along with saturated surface dry density (\(\rho_{sat}\)) and dry density (\(\rho_d\)) of the concretes are presented in Table 1.

The specific heat capacity of each mix design was calculated as the sum of the heat capacities of the constituent parts weighted by their relative proportions. Therefore, the specific heat capacity of hardened cement paste (HCP) was first measured. Then the specific heat capacity of coarse aggregates (CA), fine aggregates (FA), and additives (ADD) were added proportionally; it was assumed that air in the samples had a negligible contribution to the heat capacity of the total concrete since it has a density of approximately 1.205 kg/m³ at ambient temperatures compared with 2,300 kg/m³ for the concrete solids. The specific heat capacity of concrete in both the dry (\(c_p\)) and wet (\(c_p'\)) states is calculated from Equations 4 and 5, respectively.

\[
c_p = \frac{1}{w_{total}} \left[ w_{HCP}c_{HCP} + w_{CA}c_{CA} + w_{ADD}c_{ADD} \right]
\]

\[
c_p' = c_p \times \frac{\rho_{sat}}{w_{water}} \times c_{water}
\]

where \(w\) is mass of each constituent in kg and \(c\) is specific heat capacity of each constituent in J/kg K.
A differential scanning calorimeter (TA Instruments Model Q10 DSC) was used to determine the specific heat capacity of the concrete constituents. The mean value of five readings taken across the range $-13^\circ$C to $57^\circ$C is presented for each component in Table 2.

Thermal diffusivity ($\alpha$) is the coefficient that expresses the rapidity of temperature change when a material is exposed to a fluctuating thermal environment and is calculated as follows:

$$\alpha = \frac{\lambda}{\rho_c c_p}$$  \hspace{1cm} (6)

Thermal effusivity ($\beta$), also known as the coefficient of heat storage, is a measure of ability of a material to exchange heat with its surroundings and is calculated as follows:

$$\beta = \sqrt{\rho_c c_p}$$  \hspace{1cm} (7)

The wet-state thermal diffusivity ($\alpha^*$) and thermal effusivity ($\beta^*$) of concretes were also calculated by inserting the wet values in the foregoing equations. The mean values of measured and calculated thermal properties of modified concrete pavements are presented in Table 3.
TABLE 2  Mean Value of Specific Heat Capacity of Concrete Components

| Temperature (°C) | HCP | CS | Lytag | NS | Quartzite | Limestone | IBA | FBA | Iron Shot | Rubber |
|------------------|-----|----|-------|----|-----------|-----------|-----|-----|-----------|--------|
| −13              | 807 | 522| 546   | 495| 450       | 793       | 599 | 571 | 401       | 960    |
| 0                | 1,021| 670| 712   | 637| 629       | 838       | 748 | 678 | 552       | 1,292  |
| 7                | 1,094| 679| 741   | 655| 642       | 859       | 787 | 703 | 562       | 1,326  |
| 17               | 1,241| 691| 767   | 679| 659       | 878       | 850 | 732 | 575       | 1,369  |
| 27               | 1,458| 701| 778   | 698| 675       | 892       | 917 | 751 | 586       | 1,406  |
| 37               | 1,714| 712| 787   | 711| 693       | 904       | 956 | 768 | 589       | 1,444  |
| 47               | 1,978| 723| 799   | 721| 709       | 917       | 978 | 782 | 609       | 1,485  |
| 57               | 2,300| 734| 812   | 734| 724       | 931       | 984 | 793 | 618       | 1,523  |

NOTE: Measured in J/kg K.

PREDICTIVE NUMERICAL MODELING TOOL

A one-dimensional transient heat transport model is used in this paper to predict the response of pavements constructed with some of the novel materials listed in Tables 2 and 3 (5). The model was previously developed to predict pavement temperature profile evolution at various depths in response to the climatic variables period. Keikha et al. validated the model using data provided by the Seasonal Monitoring Program database of the Long-Term Pavement Performance program project (5, 6). The model is accurate to within 2°C variation and was found to give results at least as good as for other similar available models (3–5).

FACTORS AFFECTING CONCRETE THERMAL PROPERTIES

It is evident from data presented in Table 3 that the degree of saturation correlates to a significant increase in the thermal conductivity for each concrete material that was tested. This can be attributed to changes in air voids filled with water, whose thermal conductivity is superior to that of air. However, it was also observed that the thermal conductivity of the concrete was directly and positively related to that of the aggregate. Quartzite aggregate, for example, has a conductivity from 5.5 to 7.5 W/m-K and produced concrete with a conductivity of 2.8 W/m-K in this study, whereas limestone that has a conductivity of 45 W/m-K at 25°C (11). This is also the case for synthetic alternative aggregates such as Lytag and crumb rubber. Other reasons probably exist for change in thermal conductivity which may be as or more significant than changes in the thermal conductivity of the aggregate. For example, crumb rubber–modified concrete is known to have problematic interfacial transition zones, which are likely to augment reductions in thermal conductivity (12). Figure 2 shows an inverse relationship between the apparent porosity and both the dry and saturated thermal conductivity for Lytag- and crumb rubber–modified concretes. This might occur as a result of enhanced interparticle contact when the void ratio is minimized.

Interestingly, the addition of cooled iron shot particles had minimal effect on the thermal conductivity of the pavement quality concrete. The thermal conductivity of cast iron is known to be approximately 45 W/m-K at 25°C (13). However, when loose cooled iron shot particles were tested using a Setaram TCI modified transient plane source device, the thermal conductivity was determined to be only 1.4 W/m-K in the dry state. This reduction must be a reflection of the limited interparticle contact. Figure 3a provides a cross-sectional image through the concrete containing cooled iron shot particles produced with a Venlo H 225/350 X-ray computer tomographic scanner at 83-μ resolution and 340 kV accelerating voltage. It shows that even though there are some clusters of iron shot that might deliver a conductivity of 1.4 W/m-K, these clusters are not well interconnected, further reducing their opportunity to convey heat energy effectively through concrete. Comparison of λ-values in Table 3 for with and without iron shot particles (see sample numbers 24 and 10, respectively) will illustrate this.

However, results of experiments carried out by Cook and Uher proved that the addition of steel and copper fibre in concrete can significantly improve the thermal conductivity of the concrete (7). Figure 3b shows that the addition of metallic fiber in concrete can develop many continuous highly conductive paths that, as expected, increase the thermal conductivity of the concrete. This effect can be seen in Table 3 comparing values of λ for mixes 4 through 9, which are those with increasing copper fiber content.

OPTIMIZATION OF MATERIAL DESIGN FOR PHC APPLICATIONS

The efficiency of a PHC system in transporting large quantities of heat from the pavement surface to the embedded pipe network depends on several key factors:

1. Ability of the pavement to absorb heat at or near the surface–air interface;
2. Ability to conduct heat between pavement surface and pavement subsurface;
3. Depth of the embedded pipe network;
4. Materials, geometry, spacing, and dimensions of the pipes;
5. Type of working fluid within the pipes;
6. Initial temperature and flow rate of the working fluid; and
7. Ratio of specific surface area to area in contact, that is, pavement material–pipe interface.

Factors 1 to 3 are the focus of this study, for they are related to the design of civil engineering materials issues and have received little attention to date. Factors 4 to 7 are mechanical systems engineering issues relating to the operation of the system and the working fluid and, while they have been the focus of much previous research, significant potential exists for collaboration combining the work presented...
| Sample No. | Concrete | CA  | FA      | \(\lambda\) (W/m-K)\(^a\) | \(\lambda^*\) (W/m-K)\(^a\) | \(C_p\) (J/kg-K)\(^b\) | \(C_p^*\) (J/kg-K) | \(\alpha\) (\(\times 10^{-7}\)) (m²/s) | \(\alpha^*\) (\(\times 10^{-7}\)) (m²/s) | \(\beta\) (J/s²m²-K) | \(\beta^*\) (J/s²m²-K) |
|-----------|----------|-----|---------|-----------------|-----------------|----------------|----------------|----------------------------|----------------------------|----------------|----------------|
| 1         | Limestone| NS  |         | 1.12            | 1.36            | 953            | 1,114          | 5.37                      | 5.26                      | 1,529          | 1,875          |
| 2         | Quartzite| NS  |         | 2.64            | 2.81            | 860            | 1,031          | 13.64                     | 11.42                     | 2,260          | 2,630          |
| 3         | Quartzite| NS  | Quartzite| 2.98          | 3.08            | 852            | 948            | 15.42                     | 13.87                     | 2,400          | 2,616          |
| 4\(^c\)  | Gravel   | Sand|          | 1.53            | —               | 1,080          | —              | 6.57                      | —                         | 1,887          | —              |
| 5\(^c\)  | Gravel   | Sand+0.5% Cu-Fiber| 2.096          | —               | 1,070          | —              | 8.86                      | —                         | 2,226          | —              |
| 6\(^c\)  | Gravel   | Sand+1% Cu-Fiber| 2.677          | —               | 1,060          | —              | 11.22                     | —                         | 2,527          | —              |
| 7\(^c\)  | Gravel   | Sand+2% Cu-Fiber| 3.251          | —               | 1,040          | —              | 13.30                     | —                         | 2,819          | —              |
| 8\(^c\)  | Gravel   | Sand+4% Cu-Fiber| 5.980          | —               | 995            | —              | 25.04                     | —                         | 3,779          | —              |
| 9\(^c\)  | Gravel   | Sand+8% Cu-Fiber| 10.71          | —               | 920            | —              | 44.95                     | —                         | 5,052          | —              |
| 10        | CS       | NS  |         | 1.18            | 1.29            | 854            | 986            | 5.23                      | 4.75                      | 1,630          | 1,872          |
| 11        | CS       | NS  | CS      | 0.81            | 0.94            | 837            | 958            | 3.24                      | 3.16                      | 1,423          | 1,672          |
| 12        | CS       | NS  | 20% rubber+80% CS| 0.64          | 0.75            | 863            | 995            | 2.62                      | 2.55                      | 1,251          | 1,485          |
| 13        | CS       | NS  | 50% rubber+50% CS| 0.57          | 0.71            | 908            | 1,060          | 2.44                      | 2.47                      | 1,154          | 1,428          |
| 14        | Limestone| NS  | 80% NS+20% rubber| 0.81          | 0.97            | 987            | 1,180          | 3.95                      | 3.68                      | 1,289          | 1,598          |
| 15        | Limestone| NS  | 50% NS+50% rubber| 0.44          | 0.61            | 1,043          | 1,263          | 2.19                      | 2.30                      | 940            | 1,271          |
| 16        | Limestone| NS  | 20% NS+80% rubber| 0.27          | 0.40            | 1,110          | 1,369          | 1.42                      | 1.54                      | 716            | 1,020          |
| 17        | Limestone| Rubber|         | 0.22            | 0.36            | 1,160          | 1,444          | 1.24                      | 1.44                      | 625            | 948            |
| 18        | 80% limestone+20% lytag| NS |         | 1.03            | 1.27            | 950            | 1,140          | 5.20                      | 4.99                      | 1,428          | 1,798          |
| 19        | 50% limestone+50% lytag| NS |         | 0.94            | 1.19            | 945            | 1,207          | 5.18                      | 4.65                      | 1,306          | 1,745          |
| 20        | 20% limestone+80% lytag| NS |         | 0.88            | 1.13            | 939            | 1,236          | 5.18                      | 4.51                      | 1,170          | 1,682          |
| 21        | Lytag    | Lytag|         | 0.81            | 1.07            | 935            | 1,285          | 5.10                      | 4.27                      | 1,134          | 1,637          |
| 22        | Lytag    | Lytag|         | 0.46            | 0.71            | 1,009          | 1,481          | 3.23                      | 2.81                      | 809            | 1,339          |
| 23        | Lytag    | CS   |         | 0.67            | 0.78            | 900            | 1,017          | 3.33                      | 3.30                      | 1,162          | 1,358          |
| 24        | CS       | Iron shot|         | 1.21            | 1.31            | 729            | 800            | 3.90                      | 3.76                      | 1,938          | 2,136          |
| 25        | IBA      | NS  |         | 0.86            | 1.18            | 968            | 1,108          | 4.20                      | 5.03                      | 1,328          | 1,664          |
| 26        | FBA      | NS  |         | 1.05            | 1.14            | 942            | 1,150          | 5.53                      | 4.92                      | 1,411          | 1,625          |
| 27\(^d\) | Limestone| Limestone|         | 0.92            | 1.16            | 983            | 1,227          | 4.34                      | 4.15                      | 1,397          | 1,800          |
| 28\(^d\) | Lytag    | Lytag|         | 0.56            | 0.88            | 953            | 1,574          | 3.75                      | 3.13                      | 915            | 1,574          |
| 29\(^d\) | CS       | CS   |         | 0.84            | 0.99            | 761            | 880            | 3.58                      | 3.51                      | 1,403          | 1,670          |
| 30\(^e\) | Crushed aggregate|         | 0.7            | 1.3             | 892            | —              | 3.58                      | —                         | 1,170          | —              |
| 31        | Loose lytag|         | 0.20            | 0.34            | 778            | —              | 3.21                      | —                         | 353            | —              |
| 32\(^f\) | Heavy soil (clay, compacted sand, loam)|         | 0.86            | 1.30            | 840            | 960            | 5.12                      | 6.45                      | 1,202          | 1,619          |
| 33\(^g\) | Light soil (loose sand, silt)|         | 0.34            | 0.86            | 840            | 1,040          | 2.79                      | 5.17                      | 643            | 1,196          |
| 34\(^h\) | Polystyrene|         | 0.034          | —               | 1,130          | —              | —                         | —                         | —              | —              |

Note: — = not applicable.

\(^a\)Values for \(\lambda\) were determined under steady-state conditions at 1% stability.

\(^b\)Values for \(C_p\) and \(C_p^*\) were calculated at 27°C.

\(^c\)Data from Cook and Uher (7).

\(^d\)Values are for lean mix concrete.

\(^e\)Data from Cote and Konrad (10).

\(^f\)Data from American Society of Heating, Refrigerating, and Air-Conditioning Engineers (9).

\(^g\)Data from Carder et al. (1).

\(^h\)Data from American Society of Heating, Refrigerating, and Air-Conditioning Engineers (9).
here with that of previous thermo-fluid research work, to deliver a comprehensive study simultaneously considering all of the factors.

The quantity of heat energy absorbed by the pavement is directly proportional to the pavement surface absorptivity, which is mainly related to the pavement surface color. Yavuzturk et al. reported that the maximum temperature change at the pavement surface is as high as \(10^\circ\text{C}\) when the absorptivity is altered between 0.5 and 0.99 (3). This work is focused on concrete pavement materials that would typically have a solar absorptivity of about 0.65, but with the addition of a high-absorptivity colored surface coating can achieve in excess of 0.9 (3, 14). To represent optimized heat collection conditions, the thermal model used a high value of 0.95 to simulate the best performance of PHCs.

Figure 4 shows the cross section of an existing pavement in Arizona and four other modified sections. The climatic data and pavement sections were extracted from the Seasonal Monitoring Program conducted under the Long-Term Pavement Program for the state of Arizona (12). These LTTP data were chosen because Arizona is a prime location for a PHC installation where solar radiation exceeds 1,000 W/m\(^2\) in summer and therefore represents a best case performance scenario. The Arizona Long-Term Pavement program pavement climatic data were collected at weather station number 0100 from January 1 to December 31, 1996.

Installing the pipe network close to the surface of the pavement (e.g., \(<50\text{-mm depth}\) obviously provides higher temperature heat energy for absorption by the working fluid. Ideally, sufficient depth is required to avoid reflection cracking under traffic loading (doing that has a detrimental effect on the lifespan of the pavement) and to enable future resurfacing without damaging the pipe network. With application of thermophysical properties of pavement layers in the thermal model, the mean maximum temperature for each month in Arizona has been plotted at two depths, 40 mm and 120 mm (see Figure 5). These depths were chosen on the basis of the embedded pipe depths in previous full-scale PHC trials by de Bondt and Ooms Avenhorn Holding and the Transport Research Laboratory respectively (1, 2).

Figure 5 shows that by using PHC Design 2, the same temperature can be achieved at a depth of 120 mm as at 40-mm depth in the unmodified reference pavement. The presence of a high thermal diffusivity pavement layer above a depth of 120 mm, combined with a high thermal resistance pavement layer below this depth (i.e., PHC Design 4), can significantly increase the temperature at pipe locations, as shown in Figure 5. Theoretically, this would result in a significant increase in efficiency of a PHC system. In addition, there is no significant difference between the temperatures at 40 mm and 120 mm in PHC Design 4 because the high diffusivity material layer allows heat to penetrate rapidly into the pavement.
One of the advantages of using high thermal diffusivity concrete pavement materials is to reduce the warping stresses that can occur owing to temperature differences between the top and bottom of the slab. To illustrate this, Figure 7 shows a comparison of the temperature distribution within the reference pavement, and PHC Designs 1, 2, and 3 at 4 a.m. and 4 p.m. in July. The concrete thermal diffusivity increases, the temperature gradient range across the slab (120-mm thickness) decreases considerably. Therefore, service life of the pavement can be prolonged as a result of reduction of thermal stresses. In addition, total temperature variations between 4 a.m. and 4 p.m. decrease as thermal diffusivity increases, a result that could minimize the likelihood of thermal cracking from expansion and contraction.

**OPTIMIZATION OF MATERIAL DESIGN FOR PSHS APPLICATIONS**

Ground source heat pumps rely on the fact that, at depth, the earth’s crust has a relatively constant temperature: warmer than the air in winter and cooler than the air in summer. A reversible heat pump
can transfer heat stored in the earth into a building during the winter, and transfer heat out of the building during the summer. Efficiency of ground source heat pumps can significantly increase if temperature variations at the pipe location(s) are minimized, as is the case for vertical ground source heat pumps that have significantly higher efficiency than horizontal ground source heat pumps do (12). Pavements are already required for essential infrastructure purposes, having a set of structural performance criteria to meet. Thus, they would need only a few thermally specific elements to be installed, to act as a thermal heat storage system, as is the case with conventional thermal energy use systems. However, thermal properties of the pavement constituent material have not previously been optimized for these purposes. Therefore, PSHS as an innovative technology might be designed to operate more cost-effectively than conventional ground source heat pumps do.

Five pavement cross sections with different thermophysical properties are considered (see Figure 8), and the mean February and July temperature distributions within these pavements have been predicted using the numerical model mentioned earlier. The pavement cross sections represent an airport apron since that is a key potential application for this technology. Airport buildings typically have high cooling loads and energy demands, and they are immediately adjacent to large areas of pavement surface. They are also of a similar arrangement throughout the world. Climatic data for this PSHS simulation were collected from the University of Nottingham weather station at Sutton Bonington, Leicestershire, United Kingdom (52.58°N, 1.38°W), close to East Midlands Airport.

The critical depth ($d_{\text{crit}}$) below the surface at which minimal seasonal temperature fluctuation occurs is defined by the point of convergence between seasonal minima and maxima. From previous research conducted by the authors, this is known as positively correlated to the thermal diffusivity of pavement materials (BS EN 1260:2002+ A1:2008). The effect of the pavement’s thermal diffusivity on $d_{\text{crit}}$ is shown in Figure 9. Figure 9 data show that as the thermal diffusivity decreases, $d_{\text{crit}}$ also decreases. This is
because the material with higher volumetric heat capacity, equal to $\rho_c$, and lower thermal conductivity will reduce the temperature fluctuation at a lower depth within the pavement.

Figure 10 shows the temperature fluctuation from January 1 to December 12, 2007, at a depth of 1.5 m. Temperature fluctuation at this depth is minimized as pavement thermal diffusivity decreases (see Figure 8 for PSHS design). Less temperature fluctuation will improve the efficiency of the system because in winter the pavement stays at a higher temperature, and vice versa. Although the lower thermal diffusivity layer above the embedded pipe array will improve the efficiency of the PSHS, the pavement materials that surround the pipes themselves must also have a suitably high thermal effusivity (see Table 3) to allow rapid heat transfer from the pipe material.
The same findings might also have an application to pavements in cold regions, which are subjected to annual freeze–thaw cycles and deep frost penetration. Data from Figures 9 and 10 show that pavements with a lower thermal diffusivity could help to reduce the risk of damage resulting from freeze–thaw cycling by achieving a more constant temperature at shallower depth (Figure 9) and less temperature fluctuation (Figure 10).

Changing concrete composition to modify the thermal properties of the mix cannot be performed in isolation from an effect on other properties of the concrete—specifically on the mechanical properties. Thus, thermally desirable changes to the makeup of concrete could have a deleterious effect on the strength of the concrete mixture. However, all mixes used in PHC Designs 1 through 4 (see Figure 4) and PSHS Designs 1 through 5 (see Figure 8) meet mechanical requirements to be an airfield pavement (6). The same materials as introduced in this paper have also been subjected to a mechanical testing program. When this program is complete, plans are for the results to be published in a future paper. At present, it seems that thermal modification can be achieved and mechanically adequate performance retained, although not always easily. It is probable that some compromise between the two goals will be necessary, or that the thermally modified materials used in a pavement sequence will be adapted in a way to employ them successfully.

CONCLUSIONS

The study has determined the thermophysical properties of concrete pavement materials and their effects on the performance of PHC and PSHS and other implications to help pavement design. The following conclusions can be drawn from the results and analysis proposed in this study:

1. The thermal conductivity of the concrete was directly and positively related to its degree of saturation as well as the thermal conductivity of its aggregates. However, it was negatively related to concrete porosity.

2. The thermal conductivity of concrete can be significantly increased by generating a continuous highly conductive path (e.g., addition of metallic fibers).

3. High thermal diffusivity concrete, which can be achieved by incorporating high conductive aggregate or addition of metallic fibers, can significantly enhance heat transfer to the embedded pipe networks.

4. Warping stresses that result from temperature differences between the top and bottom of the slab can be reduced with the use of high diffusivity concrete in hot climates.

5. Low thermal diffusivity concrete, which can be achieved with the use of high volumetric heat capacity aggregates or low conductivity aggregates, or both, can induce a more stable temperature at shallower depths and promote easier heat storage in the pavement.

6. The risk of damage caused by freeze–thaw cycling can be minimized with the use of low diffusivity concrete in cold climates.

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