Enhancing Thermal Properties of Asphalt Materials for Heat Storage & Transfer Applications

Andrew R Dawson[1], *Pejman Keikhaei Dehdezi[1, 2], Matthew R Hall[2], Junzhe Wang[3] & Riccardo Isola[1]

[1] Nottingham Transportation Engineering Centre, Division of Infrastructure and Geomatics, Faculty of Engineering, University of Nottingham, University Park, NG7 2RD, UK
telephone: +44 (0) 115 951 3902, e-mail: evxpk3@nottingham.ac.uk

[2] Nottingham Centre for Geomechanics, Division of Materials, Mechanics and Structures, Faculty of Engineering, University of Nottingham, University Park, NG7 2RD, UK

[3] BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK

* Corresponding author

ABSTRACT

The paper considers extending the role of asphalt concrete pavements to become solar heat collectors and storage systems. The majority of the construction cost is already procured for such pavements and only marginal additional costs are likely to be incurred to add the necessary thermal features. Asphalt concrete pavements are, therefore, designed that incorporate aggregates and additives such as limestone, quartzite, lightweight aggregate, copper slag and copper fibre to make them more conductive, or more insulative, or to enable them to store more heat energy. The resulting materials are assessed for both mechanical and thermal properties by laboratory tests and numerical simulations and recommendations are made in regard to the optimum formulations for the purposes considered.

BACKGROUND

Worldwide, asphalt pavement surfacings provide the vast majority of roads, parking lots and airport runways. Given their dark colour, asphalt pavements can heat up to 70°C due to solar irradiation in summertime because of their excellent heat-absorbing properties (Chen, Wei et al. 2009).

Many modern industrial and commercial buildings have a high heating and/or cooling load. This load has a high, potential, environmental impact. Therefore there is a strong pressure to obtain the necessary energy from a renewable source. Because such buildings frequently have large adjacent paved areas (roads, vehicle parking lots), there is great potential to collect and/or store solar energy using these adjacent surfaces which are already required and funded for operational purposes (e.g. from a transportation or parking budget). de Bondt (2003) reported a full scale trial of such a 'Pavement Energy System' (PES), installing pipes close to a pavement surface, thereby optimizing the pavement to collect solar energy in a Pavement Heat Collection (PHC) configuration.

Pavements, by installing loops at greater depths, might also be used as a heat source during winter and as a heat sink during summer (a similar application to Ground Source Heat Pump). Such Pavement-Source Heat Stores (PSHS) would exploit the fact that the seasonal temperature variation under the pavement is much less than the temperature fluctuation of ambient air because of the high thermal mass of the pavement.

Conceivably, the two arrangements could be combined to form a composite system in which solar heat, collected by the pavement surface in the summer, is transferred and stored at shallow depth for subsequent re-use (Carder, Barker et al. 2007). The heat passed to or from the pipes could also be used, directly or via a heat pump, for purposes such as:

- the de-icing of roads in winter,
- the reduction of the Urban Heat Island (UHI) effect,
- to reduce rutting of asphalt,
- to supply hot water,

- or to convert the energy to a transmittable form.

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

1) The ability of the pavement to absorb heat at/near the surface-air interface

2) The ability to conduct heat between the pavement surface and the pavement sub-surface

3) The depth of the embedded pipe network

4) The materials, geometry, spacing, and dimensions of the pipes

5) The type of working fluid within the pipes

6) The initial temperature and flow rate of the working fluid

7) The pavement material-pipe interface, i.e. the ratio of specific surface area to area in contact with the embedded pipe.

OBJECTIVE & SCOPE

Thus, to realize the potential benefits of the concept just described, it would be necessary to have pavement materials that continue to provide pavement functionality, but that would also be optimized for their thermal properties. In a companion paper (Keikhaei, Hall et al. 2010) several of the current authors have described the assessment of concrete pavement materials in the application just described. Therefore the objective of this paper is to investigate thermal improvements of, and potential for using, asphaltic materials for heat storage, transmission and/or insulation while still providing a useful paving function.

The pavement materials' thermo-physical properties will, clearly, play a major part in Factor 2 in the above list. For this reason, this paper studies the thermal properties of typical and modified asphalt materials. The three most important properties of a material in a thermal analysis are the thermal conductivity, specific heat capacity, and density. The rate of heat extraction, and ultimately the size of the embedded pipe loop and cost of the system must, inevitably, be influenced by the thermo-physical properties of the pavement materials. However, it is the least understood aspect of a PES design because there are many factors affecting the pavement's thermal properties and so little measured data available (ASHRAE 1995; Rawlings and Sykulski 1999).

The individual effects of a pavement's thermo-physical properties on the variation of maximum and minimum pavement surface temperature have been proven to be significant (Gui, Phelan et al. 2007). In this study, the thermo-physical properties of asphalt pavement mixtures consisting of conventional and unconventional components, for the first time, are measured using accurate and reliable methods such as a Heat Flow Meter (HFM) for measuring thermal conductivity and a Differential Scanning Calorimeter (DSC) to measure specific heat capacity. The thermo-physical properties, measured in this study, could also be used for the other applications where these parameters are critical, e.g. predicting freeze-thaw cycles in a pavement due to fluctuating environmental conditions (Dempsey and Thompson 1970; Mrawira and Luca 2002); predicting the

Urban Heat Island (UHI) effect (Gui, Phelan et al. 2007; Mallick, Chen et al. 2009); and road-condition forecasting for timely application of deicing and anti-icing salt for winter road maintenance.

LITERATURE REVIEW

A first application of pavement solar collectors in the literature seems to be that of Sedgwick and Patrick (1981). They experimentally studied swimming pool heating in summer by use of a grid of plastic pipes laid at 20 mm under an asphalt surface in a tennis court in the UK. The air temperature and solar radiation for the period of the experiment reached 22°C and 610 W/m^2, respectively. They found that the system can provide heating to swimming pools which are usually operated at between 20°C and 27°C, hence, concluded that the system was technically feasible, for UK conditions, and cost effective compared to a conventional swimming pool solar heater. Turner (1986; 1987) studied, theoretically, the performance of a pavement heat collector in winter (maximum pavement surface temperature of 15°C) and summer (maximum pavement surface temperature of 70°C) for applications varying from de-icing of roads and bridges to water heating for heat pumps and swimming pools. He did some analysis (using a simple 1D steady-state model) and found that pavement heat collector systems may be suitable for the application he was considering. Nayak et al. (1989) carried out experimental studies on a roof solar concrete collector, with glazing at the top, used for providing domestic hot water. They embedded PVC tubes at 10mm under the concrete which was painted black to increase its solar absorptivity. They concluded that solar concrete collectors can be used as a cost-effective alternatives to conventional systems (e.g. flat-plate collectors) under the climate where the experiment was performed (maximum air temperature and solar radiation reached 35°C and 1000 W/m^2 respectively). Similarly, Chaurasia (2000) experimentally studied the performance of a concrete solar collector by laying down a network of aluminium pipes in a building's roof (with no glazing at the top) in India (maximum air temperature and solar radiation reached 27°C and 650 W/m^2 respectively) to supply hot water for domestic use. They concluded that, for an inlet water temperature of 15°C-28°C, hot water at temperature 36°C to 58°C could be obtained during the daytime in winter. Hasebe et al. (2006) experimentally investigated an asphalt solar collector to produce electric power. The electric power was produced by temperature differences between warm water (coming out of the embedded pipe in the pavement) and cool water (supplied from a river) as a thermoelectric generator. They investigated the effects of outlet temperature of the warm water on generated electricity and found that the output power significantly increases as outlet water temperature increases.

Studies in recent years have aimed to improve the efficiency of pavement heat collector systems. Mallick et al. (Mallick, Chen et al. 2009) experimentally and theoretically studied asphalt pavement for applications of harvesting energy and reducing the UHI effect. They showed, using a finite-element model, that near-surface air temperature could be reduced as much as 10°C by running water through the embedded pipes placed at about 40 mm under the pavement. In addition, they performed small-scale laboratory testing on asphalt pavement samples. Their results showed that black acrylic paint on the asphalt surface and replacing limestone aggregates with aggregates containing high percentages of quartz could increase the efficiency (rise in water temperature) of the system by 50% and 100%, respectively. Wu et al. (2011) performed a similar study on small-scale asphalt pavement slabs and concluded that the pavement surface temperature could be significantly reduced as water flows in the embedded pipes. In another study, Wu et al. (2009) experimentally investigated the use of graphite powders in asphalt pavement to improve the thermal conductivity and energy exchange efficiency. They concluded that the addition of graphite could slightly increase the outlet water temperature however, but realised that longer piping and a larger area of heat transfer is necessary to realize a meaningful temperature rise. In addition, the lubricant effect of graphite may have a negative effect on the mechanical performance of the asphalt pavements.

Road Energy Systems®' (RES) asphalt solar collector (see Figure 2), is a system for extracting energy from asphalt pavements. This system have been developed and partly commercialised in the Netherlands by Ooms Avenhorn Holding bv (de Bondt 2003; Sullivan, de Bondt et al. 2007). The RES heats building and roads in winter and cools both in summer when it collects heat that is then stored at about 70m below ground. The water circulating is the groundwater (de Bondt 2003).

In order to commercialise the RES system, Ooms have conducted different experiments to investigate possible detrimental effects of pipes on the lifetime of the pavement as well as the effect of the asphalt compaction process on the (plastic) pipes. van Bijsterveld and de Bondt (2002) experimentally showed that the presence of pipes in the asphalt has negative effects on the durability of the asphalt structure because of concentrated stresses near the pipes which can lead to crack initiation. To prevent this phenomenon, they developed a three-dimensional reinforcing grid to fix and protect the pipes during the laying and compaction of the asphalt mixture and to reduce the stresses around the pipes. In addition, a special polymer modified bitumen was developed to achieve high quality asphalt mixture in between the pipes and the grid. The RES has been successfully installed in the Netherlands and UK (Sullivan, de Bondt et al. 2007).

Another major instrumented trial of the solar energy collector from asphalt pavements was undertaken by IcaxTM Limited ((Carder, Barker et al. 2007)) in the UK. The Icax system is very similar to the Ooms system since both of the systems can be considered as ‘composite systems’ (collect the solar energy and store it until required). In the Icax system heat, absorbed by the asphalt pavement, will be collected through upper loops installed below the asphalt surface. The warm water in the upper loops will then be circulated and stored through lower loops installed below the asphalt surface. Carder et al. (2007) found that at the end of a full season of heat recovery (from May to September), ground temperature in the centre of the heat store remained about 9°C higher than that of the control area of the pavement (i.e. without any loops and insulation). Moreover, they carried out winter maintenance of the pavement from the heat recovered in the heat store. They found that the heated section of the road was maintained at a temperature about 3°C higher than the unheated area.

EXPERIMENTAL PROGRAMME

In the present study, a wide range of heavy-weight, light-weight, and normal aggregates, as well as other additives, were considered as potential inclusions within asphalt, being those that might deliver beneficial thermo-physical properties. Those considered in detail were limestone (as reference aggregate), quartzite, sintered pulverised fuel ash lightweight aggregate (known as Lytag®), air cooled copper slag, and copper fibre (see Table 2). All the asphalt specimens were subjected to thermal conductivity test, specific heat capacity test, Indirect Tensile Stiffness Modulus (ITSM), Indirect Tensile Fatigue Test (ITFT) at different stress levels, and Repeated Load Axial Test (RLAT) (see British Standards 1993, 1996 & 2003).

Mix Design

The aggregate gradation and mix design was selected in accordance with the Construction Support Team (Defence Estates 2008), for a wearing course using macadam concrete, as shown in Table 1.

The specifications listed in Table 1 are particularly for limestone, there being no specification for the other aggregates used in the project. To generate alternative mix designs, the asphalt mixtures for the other aggregates were generated by replacing the limestone with the same *volume* of the replacement aggregates while keeping the remaining parameters (bitumen type and content, and aggregate grading) constant. Due to the non-availability of the larger sizes of Lytag and copper slag replacement aggregates, the asphalt mixes were produced according to Table 2. Although, the bitumen content and aggregate grading needs to be modified for each mix according to the aggregate type used in the mix, since the main focus of this paper was to study the effect of aggregate alteration on the thermal performance of the asphalt mixtures, hence, it was decided to keep the other parameters (e.g. grading, bitumen content and type) constant in order to eliminate the effect of such parameters on the thermal performance of asphalt mixes. The study doesn’t attempt to define material co-optimized for thermal and mechanical behaviour as it would be difficult to define successful co-optimization let alone achieve it. Instead it aims to demonstrate that significantly improved thermal properties can be obtained with mixes that are still mechanically satisfactory for pavement application.

Two slabs each, with dimensions of 300mm × 300mm in area and around 60mm thick, were manufactured for all mixes. The slabs were compacted until the target density was reached (as determined by slab volume) using a laboratory roller compactor. All the slabs were first subjected to thermal testing and then were cored across the plane of compaction and trimmed to produce specimens (100mm diameter with mean thickness of 40mm) for the mechanical test evaluations. The core specimens were, first, subjected to the ITSM test which is non-destructive test, next, the same specimens were subjected to the ITFT at different stress levels. In addition, three specimens (100mm diameter with mean thickness of 40mm) for each mix were also produced in order to perform the RLAT.

Mechanical Assessment

The Nottingham Asphalt Tester is well-known test equipment which is used to carry out various performance tests on bituminous materials. It consists of a temperature controlled cabinet containing a load frame, a sample support and instrumentation cradle, and a loading system comprising a pneumatic load actuator with load cell.

Indirect Tensile Stiffness Modulus (ITSM) test

Stiffness in a pavement material is the principal measurement used to indicate the ability of a material to spread the traffic loading over an area. For comparative purposes a fixed temperature of 20°C was used and the test performed according to the 1993 British Standard (British Standards Institution 1993). The stiffness modulus, S_m (in MPa), can be calculated using Equation 1 (British Standards Institution 1993):

$$S_m = \frac{F}{(D \times t)} \times (\nu + 0.27) \qquad \text{Eq.1}$$

where

F = the peak value of the applied vertical load (N) with rise time of 124 milliseconds

D = the peak horizontal diametral deformation resulting from the applied load (mm)

t = mean thickness of the test specimen (mm)

ν = value of Poisson's ratio, (0.35 for bituminous mixtures)

Indirect Tensile Fatigue Test (ITFT)

Fatigue is the condition whereby a material cracks or fails as a result of repeated (cyclic) loading (stress or strain) applied below the ultimate strength of the material. For the purposes of evaluating the asphaltic specimens in this study, the test was performed according to DD ABF (British Standards Institution 2003) using the stress mode. The maximum horizontal tensile stress and the maximum horizontal strain for each specimen can be calculated from Equations 2 and 3 respectively.

$$\sigma_{\max} = \frac{2P}{\pi . d . t} \qquad \text{Eq.2}$$

$$\varepsilon_{\max} = \frac{\sigma_{\max} \times (1 + 3\nu)}{S_m} \qquad \text{Eq.3}$$

where

P = applied compression load

d = specimen diameter

Repeated Load Axial Test (RLAT)

Resistance to the development of permanent deformation is a property that is directly related to the stability of the aggregate skeleton. A highly deformation-resistant mixture requires a dense and well interlocked aggregate skeleton. In this study, the repeated load axial test was performed to assess this resistance according to the British Standard (British Standards Institution 1996).

Thermal Assessment

Thermal conductivity, λ, of the asphalt specimens were determined by the Heat Flow Meter (HFM) technique using a computer-controlled P.A. Hilton B480 that complies with ISO 8301(ISO 8301 1996). The slab specimens were placed inside the apparatus between a temperature-controlled hot plate and a water-cooled cold plate. More details about the test can be found in previous publications (Keikhaei, Hall et al. 2010). Two slabs were prepared for each mix design, and then the mean value of three independent readings was obtained for each slab specimen.

The specific heat capacity of each mix design, c_p, was calculated as the sum of the heat capacities of the constituent parts weighted by their relative proportions, each being measured using a Differential Scanning Calorimetry (DSC) (TA Instruments Model Q10 DSC). The overall specific heat capacity of asphalt can then be calculated from Equation 4:

$$c_p = \frac{1}{m_{total}}\left[m_{Aggregate} \times c_{Aggregates} + m_{Bitumen} \times c_{Bitumen} + m_{Additive} \times c_{Additive}\right] \qquad \text{Eq.4}$$

where

m = mass of each constituent in kg,

c = specific heat capacity of each constituent in J/kg K.

Thermal diffusivity (α) is the coefficient that expresses the rate of heat energy diffusion (m^2/s) throughout a material when it is exposed to a fluctuating thermal environment and is calculated as:

$$\alpha = \frac{\lambda}{\rho \times c} \qquad \text{Eq.5}$$

where

α = thermal diffusivity (m/s)

λ = thermal conductivity (W/m K)

ρ = density (kg/m^3);

c = specific heat capacity of each constituent in J/kg K.

RESULTS AND DISCUSSIONS

The test results of asphalt mixtures made with the limestone, copper slag, and quartzite are presented and analysed as a group, while the results for Light Weight Asphalt (LWA) are discussed separately.

ITSM Results

Figure 3 shows the mean measured stiffness of all five mixes. Limestone has the highest stiffness modulus value of 2014 MPa, followed by copper slag, and quartzite mixtures. The addition of metallic fibre seems to improve the stiffness by about 68% compared to the mix with no fibre (i.e. 100% quartzite mix). Criteria and limits for asphaltic concrete wearing course AC14 with conventional aggregates requires a value for stiffness ranges 1500 to 2000 MPa at 20°C (Thom 2008; Kridan, Arshad et al. 2010). Thus all alternative mixtures perform rather poorly compared with this value.

The low value for the stiffness of quartzite asphalt may be partly attributable to the relatively smooth faces of the quartzite aggregates as revealed by its low roughness value. For this reason, aggregate surface texture was measured using a surface profilometer (2D Mitutoyo Surftest SV 662 profiler). The roughness average (R_a) is the most commonly used parameter for expressing measurements of surface contour. The value represents the arithmetic average of the height of the roughness irregularities above the mean line along the sampling length and is normally measured in microns. The average readings for five profiles of the roughness (R_a) values for limestone, copper slag, and quartzite were 10.87µm, 8.63µm, and 5.52µm, respectively. The lower ability of quartzite aggregates in absorbing bitumen may also cause the reduction in the stiffness. Since the binder content for all the mixes is the same, lower bitumen absorption could cause a softer mix due to the excess of bitumen. The effect of copper fibres on the stiffness improvement of the mix may be due to the increased interconnection between fibres.

ITFT Results

Fatigue life is commonly defined as the number of load cycles to fail the asphalt concrete specimen at a certain stress or strain level. The specimens were subjected to the ITFT at different stress levels namely; 100, 150, 175, 200, 250, 300, 350, 375, 425, 500 MPa. A fatigue regression analysis was performed using the relationship:

$$N_f = k_1 \left(\frac{1}{\varepsilon} \right)^{k_2} \qquad \text{Eq.6}$$

where:

N_f = Number of Load application to failure;

k_1 ,k_2 = Constants depending on the mixture characteristics;

ε = Resultant strain due to applied stress;

The fatigue lines are plotted in Figure 4, with the enumerated values of Eq.6 for the five materials given on the figure. The similarity of the values of k_2 reflect the parallel nature of the five lines while the small differences in k_1 reflect the small spacing of the lines with respect to each other. From Figure 4 it can be seen that the asphalt mix containing copper fibre showed the best resistance against fatigue. Both quartzite mixes (i.e. partial & full aggregate replacement) achieved almost the same fatigue line, and the copper slag mix performed slightly better than the limestone mix. The higher fatigue life of the fibre mixture is most likely due to the high level of fibre interconnection. Thus all of the unconventional mixtures show a fatigue relationship that is likely to represent satisfactory in-situ performance. Given the lower stiffness modulus of the quartzite asphalt, the greater fatigue life is somewhat surprising. However, a lower stiffness layer would be expected to strain more in-situ for the same level of system loading, hence, the actual fatigue life might be similar.

RLAT Results

Figure 5 presents the average axial permanent strain curves obtained from the results of the RLAT tests for the five mix materials. It can be seen that they exhibit a similar response during the loading. The permanent strains all increase rapidly at the beginning, followed by a progressively reducing strain rate per cycle. The deformation occurring in the first 500 cycles is 69%, 69%, 85%, 82% and 83%, respectively for the limestone, copper slag, quartzite (partially replaced), quartzite+2%fibre, and quartzite (fully replaced) asphalts. The quartzite asphalt experienced by far the largest permanent strain. Once again, this could be due to its smooth surface resulting in poor bond with bitumen. Although the addition of fibres in the asphalt mix slightly improved the permanent deformation, compared with the mix with no fibres, it did not result in a significant reduction of permanent deformation. This may be due to the horizontal fibre orientation (perpendicular to the direction of loading and, thus, probably largely ineffective as reinforcing elements) in the asphalt mix as it is shown in Figure 6 in next section.

Test Results of Thermal Properties

Thermo-physical properties of the asphalt mixtures are presented in Table 3. Table 3 shows that, fully replacing limestone aggregates with quartzite can enhance the thermal conductivity by about 135%. Surprisingly, the addition of copper slag in asphalt mixtures did not increase the thermal conductivity and the thermal conductivity of fibre-modified asphalt was only enhanced by about 13%. This increase is unlikely to deliver a significant economic benefit given the typical cost associated with the purchase of copper fibre. The authors in another study (Keikhaei, Hall et al. 2010) along with other researchers (Cook and Uher 1974) found that the addition of copper fibres in concrete mixes could significantly increase the thermal conductivity of the asphalt mixes. Ineffectiveness of the fibre addition on the thermal conductivity of the asphalt mix might be related to the fibre orientation in the asphalt mix. Figure 6 is a 3D image reconstructed from the 2D slices taken across the height of the fibre-modified asphalt specimen at 1mm slice spacing. Figure 6 shows many fibres, possibly during the compaction process, are lying close to the horizontal direction (perpendicular to direction of heat flow) and hence might not be able to convey heat as efficiently as possible in a fibre-modified asphalt mix.

Table 3 also shows that, thermal diffusivity of the asphalt mixes reduces due to the reduction of thermal conductivity as well as increase in volumetric heat capacity ($\rho \times c$). Values for thermal properties (i.e. thermal conductivity and specific heat capacity) of unconventional aggregates (i.e. quartzite, lytag, copper slag) were not found in the literature. However, the thermal conductivity and specific heat capacity of the reference asphalt (i.e limestone mix) are in good agreement with the finding reported in the literature. Yavuzturk et al. (2005) and Gui et al. (2007) reported a value of 1.3 W/m K, 880 J/kg K and 1.21 W/m K, 921 J/kg K for thermal conductivity and specific heat capacity of Hot Mix Asphalts, respectively.

<u>Tests Results of Light Weight Asphalt (LWA)</u>

The slabs generated with LWA were very weak. The aggregates did not bond well with the binder, especially at the corner of the slabs. Due to the poor quality, there were no meaningful results obtained for the ITSM. Two samples were selected and tested under 200kPa and 100kPa for fatigue in order to give a general idea about the fatigue resistance of this mixture. As shown in Table 4, its performance is far behind the other materials. In terms of RLAT, the LWA experienced a deformation of 0.98% in strain, only a little higher than that of the quartzite asphalt. Though it is still the poorest performing, in terms of mechanical properties, it might have a useful role in forming a stabilized sub-base layer. One possibility to improve the performance of LWA could be to increase the binder content, since due to the higher porosity of LWA, a binder content of 4.9% (used in this study) seems not enough to provide an appropriate bond in the asphalt mixture. For thermo-physical properties, one slab was tested and the results are shown in Table 3. The thermal conductivity was approximately half that of the value obtained for the copper slag asphalt, reflecting the potential of LWA asphalt to act as an insulating layer. Given that one would not want to use an insulative layer at the surface of the pavement, but rather just above a lower pipe array (as in Figure 1, PSHS or composite), then the stiffness, fatigue and deformation values would be unlikely to hinder its use at such a depth.

Numerical Analysis of Thermally Enhanced Pavement

<u>Materials design enhancement for PHC applications</u>

In order to simulate the relative effects of pavements materials on surface temperature and temperature depth profile development in the pavements, a one-dimensional finite difference transient heat transport model was used. The model is accurate to within 2ºC variation, and was found to give results at least as accurate as other similar models (Yavuzturk, Ksaibati et al. 2005; Gui, Phelan et al. 2007). The details of the model and its validation can be found in (Keikhaei, Hall et al. 2010; Hall, Keikhaei Dehdezi et al. 2012) and a brief description is given here.

The factors influencing the pavement surface energy balance, as well as the heat transport processes that occur within a pavement, are short wave and long wave solar radiation, convection heat due to wind, and conduction heat into the pavement. The absorbed short-wave radiation on the pavement surface, is simply equal to $\alpha \cdot q_{solar}$, where α is an absorptivity coefficient. Thermal (long-wave) radiation heat flux between the pavement surface and surrounding matter (i.e. the lower atmosphere, other buildings/objects) can be calculated as:

$$q_{thermal} = \varepsilon\sigma\left(T_{surr}^4 - T_0^4\right) \quad \text{Eq.7}$$

where

ε = emissivity (-)

σ = Stefan-Boltzmann constant= 5.67×10^{-8} W/m^2 K^4

T_0 = surface temperature (K)

T_{surr} = surrounding temperature (K)

The empirical Bliss equation which estimates the surrounding conditions in the form of a hypothetical 'sky temperature' used (an approximation of T_{surr}) used where (Yavuzturk, Ksaibati et al. 2005; Gui, Phelan et al. 2007):

$$T_{sky} = T_{air}(0.8 + \frac{T_{dp}}{250})^{0.25} \quad \text{Eq.8}$$

where

T_{dp} = dew point temperature (°C)

T_{air} = air temperature (K)

One-dimensional vertical heat transport by transient conduction through the pavement can simply be modelled as a response to absorbed/desorbed energy at the pavement surface using an explicit form of the finite difference (FD) method. The cross-sectional pavement profile and the sub-soil beneath it can therefore be considered as a semi-infinite medium extending downward from d = 0 (pavement surface) to d = x, at which point ΔT → 0. In reality, at a critical depth (usually several meters) the ground temperature is approximately constant as a result of thermal mass and so is largely unaffected by heating/cooling cycles at the pavement surface. In the finite difference method, the pavement is comprised of a column of nodes. The temperature at each boundary node is given by the energy balance equations as summarised in Table 5.

The boundary equations (summarised in Table 5) are solved by iteration in order to predicatively compute the temperature depth profile evolution at a given time interval. The environmental input parameters required for the model are hourly (or more frequently) solar irradiation, dry bulb air temperature, relative humidity (or dew point temperature) and mean wind velocity. The inputs were interpolated linearly across the hour period in order to achieve the interval required for the model. In addition to surface absorptivity and surface emissivity, the pavement material thermo-physical properties required are experimentally determined.

The climatic data and pavement section for simulation were extracted from the Seasonal Monitoring Performance (SMP) conducted under the Long-Term Pavement Performance (LTPP) program (US Department of Transportation–Federal Highways Administration 2009) for the state of Arizona, USA. This was chosen as it is a prime location for a PHC installation where solar radiation exceeds 1000 W/m^2 in summer, and approaching a 'best case' performance scenario. The Arizona LTPP pavement climatic data were collected at weather station number 0100, between 01/06/1996 to 31/08/1996. The pavement section consisted of a 100mm wearing course on top of a granular base. Figure 7 shows the predicted surface temperature variations for two cases;

1) where the pavement wearing course was constructed using limestone aggregates (Mix No.1 (See Table 3) used in the model)

2) where the pavement wearing course was constructed using quartzite aggregates (Mix No.4 (See Table 3) used in the model).

As can be seen from Figure 7, the maximum surface temperature can be reduced when quartzite aggregates are used in the wearing course of the pavement. The maximum surface reduction is approximately 4ºC with an average reduction of more than 2ºC of the peak temperature. The reduction in surface temperature is because of the higher thermal conductivity of quartzite mix that could increase the rate of heat transfer towards the bottom of the pavement. Reductions of pavement surface temperature could, potentially, minimise the rutting in asphalt pavements and extend their life. The UHI effect could also be minimised as a result of pavement surface temperature reduction and subsequently air temperature reduction in the adjacent urban area.

Figure 8 shows the temperature variations at 50mm depth for the two pavements mentioned in above from 01/06/1996 to 01/07/1996 (top) and 01/10/1996 to 01/11/1996 (bottom). Figure 8 shows that using the quartzite mix could increase the average temperature by more than 2ºC at 50mm depth in the pavement. This is because, when the pavement is a net heat recipient from the environment, a highly conductive surface material facilitates heat movement within the pavement away from the surface to the interior. This could, potentially, increase the performance of an installed PHC system.

<u>Materials design enhancement for PSHS applications</u>

In order to show the effects of pavement materials on heat storage in the pavement (i.e. PSHS), two pavement cross sections were considered as follows:

1) The conventional pavement consisted of 100mm limestone as a surface on top of a 200mm compacted aggregate as a base.
2) The modified pavement consisted of 100mm copper slag mix (Mix No.3) on top of a 200mm Lytag mix (Mix No.6) as a base.

Figure 9 shows the temperature distribution in a typical summer day (top) and winter day (bottom) within conventional and modified pavements. Figure 9 shows that under the modified pavement the temperature remains lower in summer and higher in winter by about 1.6ºC. The stable temperature at shallower depth is due to the use of low thermal diffusivity pavement, which can be achieved by using high volumetric heat capacity aggregates and/or low conductivity aggregates. A more stable temperature at shallower depth enabling easier heat storage in the pavement as well as minimising the risk of damage due to freeze-thaw cycling in cold climates.

Mechanical Analysis of Thermally Enhanced Pavement

In order to investigate the structural performance of a quartzite asphalt layer (Mix No. 4) compared to a limestone asphalt layer (Mix No. 1), Shell Pavement Design Method software (SPDM) Version 3.0 have been used. The analyses performed with the SPDM were an estimation of the asphalt thickness required to withstand fatigue and rutting under a certain traffic and climate. Although SPDM was never intended to work with the ITFT data, here it is employed to permit comparison of pavements with different materials. Thus the relative performance estimate should be valid even if the absolute values must be read with caution. To take into account the effect of climate, the software requires the monthly mean air temperature for one year and applies correction factors to estimate the resultant temperatures within the asphalt layer. Therefore, mean air temperature (in °C) multiplies by the correction factor of 1.47 for the rutting calculation and by 1.92 for the fatigue calculation (Brown, Brunton et al. 1985). In order to recognize that the two pavements have different thermal properties, the air temperatures for the SPDM input were calculated by dividing the previously calculated average asphalt temperatures (See Figure 7) by 1.47 for the rutting calculation and by 1.92 for fatigue.

Fatigue simulation

The ITSM tests performed on the limestone and the 100% quartzite mixes have shown that both are not particularly resistant to fatigue (Thom 2008), hence the pavements simulated were subjected to a relatively low design traffic of one million equivalent standard axles over a design period of 5 years.

Four different structures were simulated namely; Limestone over 200MPa and 800MPa sub-base (L200, L800) and Quartzite over 200MPa and 800MPa sub-base (Q200, Q800). The stiffness value and fatigue line for limestone and quartzite asphalt layers (i.e. Mix No 1 and Mix No 4) were imported to the model from Figure 3 and 4 respectively while other inputs have been kept constant (See Table 6). The results from simulation L800 and Q800 show that the limestone mix would need a thickness of 220mm while the quartzite mix would only need 207mm. This is probably due to the fact that, for these first examples, a stiff sub-base is employed which, in the case of the quartzite, might be bearing most of the stresses. If the stiffness of the sub-base is lowered from 800MPa to 200MPa (simulations L200 & Q200), the limestone would require a thickness of 400mm against the 520mm of the quartzite, which reflects the difference in stiffness.

Rutting simulation

The structures that were obtained from the fatigue simulations have also been investigated from the rutting point of view, with the addition of two new structures. As can be seen from Table 7, two quartzite structures have been given the same asphalt thickness as the limestone structures in order to isolate the effect of materials on rutting (i.e., since the thicknesses are the same the only differences observed will be due to the thermal properties of the two materials). These six structures were simulated by keeping a large number of parameters constant. These general settings for the rutting simulations are summarised in Table 7.

The results from these simulations are shown in Table 5. As can be seen, the quartzite is constantly performing better than the limestone thanks to its superior thermal properties. Although a thicker asphalt layer would always be a disadvantage in terms of total rutting compared to a thinner one, it can be seen that even in the case of structure Q200, the total rutting still remains lower. As can be expected, this is even more evident for L800 and Q800 where the quartzite layer does not need to be as thick as the limestone one.

CONCLUSIONS

The study has investigated the desirable mechanical and thermo-physical properties of asphalt concrete pavement materials, their effects on the evolution of temperature depth profile and the implications for mechanical pavement design and performance. The following conclusions can be drawn on the basis of the results and analysis presented in this study.

1. Fully replacing limestone aggregates with quartzite can enhance the thermal conductivity by about 135%. In addition, the quartzite mixture improved the fatigue performance while showing a negative effect on the stiffness.
2. The addition of copper fibre improved the thermal conductivity slightly, while it offered a significant improvement in the stiffness and fatigue performance.
3. The use of Light Weight Asphalt (LWA) and copper slag decreased the thermal diffusivity of asphalt pavements, inducing a more stable temperature at shallower depth which would enable easier heat storage in the pavement as well as lowering the risk of damage due to freeze-thaw cycling.
4. Quartzite asphalt mixes showed the potential to reduce the maximum surface temperature, by up to 4°C. This could, potentially, lessen rutting and the Urban Heat Island (UHI) effect, while increasing the performance of the installed Pavement Heat Collections (PHC).
5. Comparison of the quartzite and limestone wearing courses for their structural performance revealed that the quartzite mix would experience less rutting; however, it would need to be placed thicker in order to compensate for its lower stiffness.

Figure captions

Figure 1: Asphalt solar collector operational modes (from Road Energy Systems®)

Figure 2: Applications of thermally enhanced pavements (Adapted from (Keikhaei, Hall et al. 2010))

Figure 3: Mean stiffness of different mixtures

Figure 4: Number of load cycles to failure versus strain

Figure 5: Vertical permanent strain variations with number of cycles

Figure 6: Digitally processed X-ray CT image of a 100mm diameter core of asphalt containing copper fibres

Figure 6: Predicted surface temperatures for limestone (Mix No 1) & quartzite (Mix No 4)

Figure 7: Predicted temperatures at 50mm depth for limestone & quartzite asphalt mixes

Figure 8: temperature distribution in a typical summer day (top) and winter day (bottom) within conventional & modified pavements.

Tables

Table 1 Specification for Wearing Course AC14 (Defence Estates 2008)

Aggregate Grading	
Sieve Size (mm)	Mass passing given sieve size (%)
14	100
10	77-83
6.3	52-58
2	25-31
1	14-26
0.063	4.5-6.5
Target binder content	**Air Voids in Total Mix**
4.9±0.4%	4±1.5%
Paving grade of bitumen	
100/150	

Table 2 asphalt mixes used in the study

Mixes	descriptions
Limestone (Control)	All the aggregates in the mix were limestone
Quartzite (partially replaced)	Limestone smaller than 10mm was replaced with quartzite (80% vol quartzite, 20% vol limestone)
Copper slag (partially replaced)	Limestone smaller than 10mm was replaced with copper slag (80% vol copper slag, 20% vol limestone)
Quartzite (fully replaced)	All the aggregates in the mix were quartzite
Quartzite +2%Cu-	All the aggregates in the mix were quartzite. In addition 2% copper fibre (1mm

fibre (fully replaced)	in diameter and 50mm long) were added to the mix.
Lytag (partially replaced) / LWA	Limestone smaller than 10mm was replaced with Lytag (80% vol Lytag, 20% vol limestone)

Table 3 Thermo-physical properties of asphalt mixtures

Mix No	**Mix type**	**Thermal conductivity λ (W/m K)**	**Specific heart capacity c_p (J/ kg K)**	**Density ρ (kg/m^3)**	**Volumetric heat capacity α (×10^{-7}) (m^2/s)**	**Achieved air void (%)**
1	Limestone (Control)	1.21	919	2382	5.53	4.1
2	Quartzite (partially replaced)	1.46	880	2351	7.06	4.1
3	Copper slag (partially replaced)	1.05	814	3088	4.15	3.7
4	Quartzite (fully replaced)	2.47	870	2314	12.30	4.9
5	Quartzite +2%Cu-fibre (fully replaced)	2.82	836	2477	13.64	3.7
6	Lytag (partially replaced)	0.46	863	1504	3.54	4.9

Table 4: Cycles to failure under 100kPa and 200kPa

	Limestone	**Copper slag**	**Quartzite**	**LWA**
200kPa	915	1289	841	76
100kPa	13781	7924	8728	738

Table 5 TITLE NEEDED

$T_0^{i+1} = \frac{2\Delta t}{\rho_d c_p \Delta z}\left[a q_{solar} + h_c(T_{air} - T_0) + h_{rad}(T_{sky} - T_0) + \lambda \frac{T_1^i - T_0^i}{\Delta z}\right] + T_0^i$	Surface node
$T_m^{i+1} = \frac{\alpha \Delta t}{\Delta z^2}\left[T_{m-1}^i - 2T_m^i + T_{m+1}^i\right] + T_m^i$	Interior node
$T_m^{i+1} = \frac{\frac{\lambda_1}{\Delta z} T_{m-1}^i + \frac{\lambda_2}{\Delta z} T_{m+1}^i - \left[\frac{\lambda_1}{\Delta z} + \frac{\lambda_2}{\Delta z} - \frac{\rho_{d1} c_{p1} \Delta z}{2\Delta t} - \frac{\rho_{d2} c_{p2} \Delta z}{2\Delta t}\right] T_m^i}{\frac{\rho_{d1} c_{p1} \Delta z + \rho_{d2} c_{p2} \Delta z}{2\Delta t}}$	Interface node
$T_m^{i+1} = \frac{2\alpha \Delta t}{\Delta z^2}\left(T_{m-1}^i - T_m^i\right) + T_m^i$	Bottom node

where

λ= thermal conductivity (W/m K)

α= thermal diffusivity (m^2/s)

m= number of nodal points (1, 2 …n)

i= counter for time step (i=0 corresponding to specific initial condition)

Δt= time step (s)

ρ_d= dry density (kg/m^3)

c_p= specific heat capacity (J/kg K)

Δz= node distance

h_{rad}= radiation heat transfer coefficient (W/m^2 K)=$\varepsilon\sigma(T_0 + T_{sky})(T_0^2 + T_{sky}^2)$

T_1= temperature at first node beneath the surface node (K)

a= solar absorptivity

h_c= convective heat transfer coefficient (W/m^2 k)=
h_c =5.6+4.0×v_w For $v_w \leq 5m/s$
h_c =7.2× $v_w^{0.78}$ for $v_w > 5m/s$

Table 6 General inputs for Fatigue & Rutting simulations

Fatigue simulations		Rutting simulations	
Daily Equivalent Standard Axles	400	Daily Equivalent Standard Axles	400
Design Period	5 years	Axle Load	80KN
Lateral Distribution Factor	2	Design Period	5 years
Healing Factor*	5	Wheels per Axle	4
Sub-base Thickness	600mm	Contact Stress	570kPa
Sub-base Poisson’s Ratio	0.35	Sub-base Thickness	600m
Subgrade Stiffness	150MPa	Sub-base Poisson’s Ratio	0.35

Subgrade Poisson’s Ratio	0.35	Subgrade Stiffness	150MPa
Mass % of Binder	5	Subgrade Poisson’s Ratio	0.35
Volume % of Voids	4	Mass % of Binder	5
Asphalt Poisson’s Ratio	0.35	Mass % of Aggregate	95
-	-	Asphalt Poisson’s Ratio	0.35
-	-	Bitumen Creep Characteristic Q	0.42
-	-	Bitumen Creep Characteristic B	0.60MPa

* Allows for recovery on-site between loads and for beneficial effects of wheel wander

Table 7 Rutting simulations labels and asphalt layer thicknesses

Structure	Thickness (mm)	Rutting depths (mm)
L800	220	21.6
L200	400	25.3
Q800	207	18.8
Q200	520	22.2
New_Quartzite on 200MPa	220	18.2
New_Quartzite on 800MPa	400	23.0

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of this research by the Engineering and Physical Sciences Research Council (EPSRC) and East Midlands Airport.

REFERENCES

ASHRAE (1995). Commercial/institutional ground source heat pump engineering manual. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

British Standards Institution (1993). Method for Determination of the Indirect Tensile Stiffness Modulus of Bituminous Mixtures. Draft for Development DD 213.

British Standards Institution (1996). Method for Determining Resistance to Permanent Deformation of Bituminous Mixtures Subject to Unconfined Dynamic Loading. Draft for development DD 226.

British Standards Institution (2003). Method for Determination of Fatigue Characteristics of Bituminous Mixtures Using Indirect Tensile Fatigue. Draft for development, DD ABF.

Brown, S. F., J. M. Brunton, et al. (1985). "The Analytical Design of Bituminous Pavements." Proc. I.C.E **79**(2): 1-31.

Carder, D. R., K. J. Barker, et al. (2007). "Performance of an interseasonal heat transfer facility for collection, storage, and re-use of solar heat from the road surface." Transport Research Laboratory, Published Project Report PPR 302.

Chaurasia, P. B. L. (2000). "Solar water heaters based on concrete collectors." Energy **25**(8): 703-716.

Chen, M. Z., W. Wei, et al. (2009). "On Cold Materials of Pavement and High-Temperature Performance of Asphalt Concrete." Materials Science Forum **620 - 622**: 379-382.

Cook, D. J. and C. Uher (1974). "The Thermal Conductivity of Fibre-Reinforced Concrete." Cement and Concrete Research **4**: 497-509.

de Bondt, A. (2003). "Generation of Energy Via Asphalt Pavement Surfaces, Prepared for Asphaltica Padova, Netherland, 2003. Also available online at: http://www.roadenergysystems.nl/pdf/Fachbeitrag%20in%20OIB%20-%20de%20Bondt%20-%20English%20version%2013-11-2006.pdf."

Defence Estates (2008). Hot Rolled Asphalt and Asphalt Concrete (Macadam) for Airfields. UK, Ministry of Defence.

Dempsey, B. J. and M. R. Thompson (1970). "A Heat-Transfer Model for Evaluating Frost Action Temperature-Related Effects in Multilayered Pavement System." Transportation Research Record: Journal of the Transportation Research Board **342**: 39-56.

Gui, J., P. E. Phelan, et al. (2007). "Impact of Pavement Thermophysical Properties on Surface Temperatures." Journal of Materials in Civil Engineering **19**(8): 683-690.

Hall, M., P. Keikhaei Dehdezi, et al. (2012). "Influence of the thermo-physical properties of pavement materials on the evolution of temperature depth profiles in different climatic regions." Journal of Materials in Civil Engineering **24**(1): 32-47.

Hasebe, M., Y. Kamikawa, et al. (2006). Thermoelectric Generators using Solar Thermal Energy in Heated Road Pavement. Thermoelectrics, 2006. ICT '06. 25th International Conference on.

ISO 8301 (1996). Thermal Insulation – Determination of Steady-State Thermal Resistance and Related Properties – Heat Flow Meter Apparatus, International Organization for tandardization, Genève, Switzerland.

Keikhaei, D. P., M. Hall, et al. (2010). "Thermo-Physical Optimisation of Specialised Concrete Pavement Materials for Surface Heat Energy Collection and Shallow Heat Storage Applications." Transportation Research Record: Journal of the Transportation Research Board **2240**(1): 96-106.

Kridan, F. A. M., A. K. Arshad, et al. (2010). "Development of Warm Mix Asphalt and Compliance with the Requirements Set by Specifications." European Journal of Scientific Research **48**(1): 118-128.

Mallick, R. B., B.-L. Chen, et al. (2009). "Harvesting energy from asphalt pavements and reducing the heat island effect." International Journal of Sustainable Engineering **2**(3): 214-228.

Mrawira, D. M. and J. Luca (2002). "Thermal properties and transient temperature responses of full-depth asphalt pavements." Transportation Research Record **1809**(1): 160.
Nayak, J. K., S. P. Sukhatme, et al. (1989). "Performance studies on solar concrete collectors." Solar Energy **42**(1): 45-56.
Rawlings, R. H. D. and J. R. Sykulski (1999). "Ground source heat pumps: A technology review." Building Services Engineering Research and Technology **20**(3): 119-129.
Sedgwick, R. H. D. and M. A. Patrick (1981). The Use of a Ground Solar Collector for Swimming Pool Heating. Proceedings of ISES, Brighton, England.
Shaopeng, W., C. Mingyu, et al. (2011). "Laboratory investigation into thermal response of asphalt pavements as solar collector by application of small-scale slabs." Applied Thermal Engineering **31**(10): 1582-1587.
Sullivan, C., A. H. de Bondt, et al. (2007). Innovation in the Production and Commercial Use of Energy Extracted from Asphalt Pavements. 6th Annual International Conference on Sustainable Aggregates, Asphalt Technology and Pavement Engineering. Liverpool.
Thom, N. (2008). Principles of Pavement Engineering. London, Thomas Telford Ltd.
Turner, R. H. (1986). Concrete slabs as winter solar collectors. Proceedings of the ASME Solar Energy Conference (SED), California.
Turner, R. H. (1987). Concrete Slabs as Summer Solar Collectors. Proceedings of the International Heat Transfer Conference, California.
US Department of Transportation–Federal Highways Administration (2009). LTPP Seasonal Monitoring Programme (SMP): Pavement Performance Database (PPDB), DVD Version, Standard Data Release 23.0, USA.
van Bijsterveld, W. T. and A. H. de Bondt (2002). Structural Aspects of Asphalt Pavement Heating and Cooling Systems. Third International Symposium on 3D Finite Element Modeling, Design and Research. Amsterdam, Netherland.
Wu, S., M. Chen, et al. (2009). "Laboratory Study on Solar Collector of Thermal Conductive Asphalt Concrete." International Journal of Pavement Research and Technology **2**(4): 130-136.
Yavuzturk, C., K. Ksaibati, et al. (2005). "Assessment of Temperature Fluctuations in Asphalt Pavements Due to Thermal Environmental Conditions Using a Two-Dimensional, Transient Finite-Difference Approach." Journal of Materials in Civil Engineering **17**(4): 465-475.