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Influence of early colour degradation of asphalt pavements on their thermal behaviour

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Abstract

Environmental goals such as the reduction of fossil fuel consumption or greenhouse gas (GHG) emissions through the development of new renewable energy sources have led to the emergence of the so called asphalt solar collectors. Moreover, in recent years, engineers are devoting increased interest to the effect of the thermal loads on the mechanical behaviour of pavements. Several approaches to these topics can be found in the literature. However, a study of the influence of the colour degradation suffered by pavements on their thermal behaviour is still necessary since both the efficient application of the asphalt collectors and the proper study of the effect of the solar radiation on the asphalt pavement behaviour are directly affected by the loss of colour occurring as time goes by. Therefore, the thermal behaviour of two different asphalt mixes was studied before and after being subjected to a colour degradation process. The degradation of five different asphalt mixes was studied and the results were compared to those obtained in the access roads to seven low volume car parks. The final results show that there are large differences between the two asphalt mixes with different gradations and *densities*. The importance attributed by other authors to *conductivity* was also confirmed. Furthermore, the results showed that it was possible to simulate the early colour degradation suffered by a low volume road. Finally, a slight reduction in temperature and energy collection capacity was measured after the colour degradation process.

KEYWORDS: asphalt pavements, low volume road, colour degradation, temperature distribution, energy storage.

1. Introduction

The achievement of environmental goals such as the reduction of greenhouse gas (GHG) emissions, the decrease in fossil fuel consumption or the development of sustainable infrastructures have led researchers to study asphalt pavements as an energy storage element. Thus, the collection of renewable and cleaner energy by asphalt pavements subjected to solar radiation seems to be an appropriate solution taking into account the high temperatures reached by the surface of these pavements in summer [1].

The first application of energy collection in asphalts appearing in the technical literature is the patent obtained by Wendel in 1979 [2]. From then on and throughout the eighties and nineties, mathematical models, real scale tests and/or experimental installations were developed by several authors [3-10]. The systems SERSO [9] and GAIA [10], located in Switzerland and Japan, respectively, deserve special attention. In these two installations, the energy that increases the temperature in the road surface during the summer is absorbed by the water flowing through a pipe network placed underneath. This energy is used in winter to melt the snow and de-ice the road.

The thorough study carried out by Van Bijsterverld *et al.* at the beginning of the XXI century [11], in which data obtained by numerical simulation with finite element method (FEM) and an experimental field test were analysed, led to the development of a new type of asphalt collector: the Road Energy Systems (RES). More recently, Mallick *et al.* [12-13] carried out several studies in which small and large-scale asphalt samples with a copper pipe network embedded were used to analyse the influence of different parameters on their heat collection efficiency and the capacity of these systems to reduce the pavement temperature.

The results reported by Wu *et al.* [14-15] and Chen *et al.* [16] are also of great importance. Enhanced HMA slabs with u-shaped copper pipes inside were used to demonstrate the relevance of the use of thermally enhanced fillers in the heat collection efficiency of asphalt collectors. It was also demonstrated that the circulating water is able to decrease the temperature of the asphalt surface. Based on these results, Chen *et al.* [17] carried out a numerical and experimental investigation which confirmed the suitability of this type of asphalt collectors for melting snow or de-icing roads in winter.

Profound knowledge of the thermal behaviour of pavements is not only essential for sizing and building these asphalt solar collectors, but also because of the influence of the thermal loads on the mechanical behaviour of pavements. Hot mix asphalt (HMA) is a viscoelastic material whose behaviour under traffic loads depends on its temperature which in turn depends on the environmental conditions to which the HMA is subjected. During the winter months, when the pavement temperature is reasonably cold, the HMA behaves closer to an elastic solid able to recover small deformations. During the summer months, at high temperatures, the HMA behaves as a viscous material which flows when the traffic load is applied [18].

One of the first most important studies about asphalt pavement temperature prediction was performed by Solaimanian and Kennedy in 1993 [19]. These authors proposed a reasonably accurate and simple method to predict the maximum pavement surface temperature on the basis of the existing air maximum temperature and hourly solar radiation. A few years later, Ake Hermansson conducted a very interesting investigation in which a numerical model based on the energy balance on the pavement surface was developed to predict the asphalt pavement temperature at different depths during the summer and winter [20,21,22]. The model was previously calibrated with data from experimental field tests.

Several other models were developed based on the energy balance in the pavement surface and validated with data from experimental field tests. While Yavuzturk *et al.* [23] and Gui *et al.* [24] developed finite difference models, Minhoto *et al.* [25] developed a tridimensional FEM model. The input data required by all these models in order to predict the temperature distribution of the pavement with depth were: air temperature, wind speed and hourly solar radiation. After their validation with real data from instrumented road sections, the results from the models showed good accuracy and low computational errors.

Other authors opted for the development of prediction models based on the results obtained in laboratory tests. Thus, small- and/or medium-scale samples artificially subjected to the usual environmental conditions were used to collect real data instead of the instrumented roads. Bilgen and Richard [26] studied the radiation balance that exists in the surface of a concrete slab subjected to a rated heat flux from a halogen lamp in order to develop a finite difference model suitable for simulating its thermal behaviour. Chen *et al.* [27] proposed a study in which the temperature distribution in HMA samples with different base layers was measured in laboratory and modelled with the FEM. Finally, Xu *et al.* [28] developed an analytical model to predict the transient temperature distribution of asphalt pavements and determine their principal thermal properties.

Many factors have been studied in these and other references that affect the thermal behaviour of asphalt pavements and hence, their mechanical performance and their ability to collect energy: solar radiation, rain events, wind speed, snow and ice or surrounding air temperature [29]. However, colour degradation suffered by the asphalt pavements during the early stages of their lives due to traffic and the presence of dust has not been analysed yet. This phenomenon, which entails the partial loss of the characteristic black colour of the HMA, can be responsible for the reduction of the amount of energy absorbed by the pavements and hence, for the change in the temperature distribution within them. Eventually, this can result in a decrease of the energy efficiency of the asphalt collectors and also affect the mechanical behaviour of pavements. On the other hand, this phenomenon is also connected to the studies carried out at the *Lawrence Berkeley National Laboratory* concerning the advantages of reducing the energy absorbed by roofs and pavements (altering their albedo), like the reduction of the urban heat island effect, the increase of the air quality or the savings from the reduction of the air-conditioning costs [30,31].

In this paper, the temperature distribution and energy storage capacity of two different asphalt mixes subjected to the effect of a heat source able to emulate solar radiation are analysed before and after being subjected to a colour degradation process. The steps followed to define this process and the comparison between the degradation rates obtained in the laboratory samples and in the access roads to low volume car parks are explained in detail. The properties of the materials used in the research and the procedures necessary to run the tests are also fully described.

2. Research Methodology

Energy Balance

Several elements are included in the energy balance between the surface pavement and the surroundings. Thus, this balance is formed by [1]: the shortwave radiation from the sun (direct and diffusely scattered in the atmosphere) reaching the pavement; a portion of this radiation which is reflected back depending on the surface albedo; the outgoing longwave radiation emitted by the pavement; and the fraction of the longwave radiation leaving the pavement which is absorbed by the atmosphere and partly emitted back to the pavement. Besides, the different temperatures existing between the pavement surface and the adjacent air result in the convective heat flux from the pavement to the atmosphere. Finally, the heat absorbed by the pavement is transferred by conduction to deeper layers. The magnitude of this process depends on the temperature gradient and the thermal *conductivity* (λ) of the pavement [1].

Colour study of degraded asphalt pavements with spectrophotometer

A colour study enables the colour of any material to be quantified. This means that a numerical value related to a colour can be obtained for any material. The ***L*a*b**** colour space, defined by the *International Commission on Illumination (CIE 2000)*, is probably the most used and it describes all the colours visible to the human eye. In this space, the coordinate ***L**** represents the lightness of the colour and it ranges from ***L****=0 indicating black, to ***L****=100 indicating white. Coordinates ***a**** and ***b**** range from negative to positive values and indicate colours from green to magenta and from blue to yellow, respectively. Thus, every colour can be objectively measured by means of a spectrophotometer. The device used for this study was the *Konica Minolta CM-600d*, courtesy of the *Geosynthetics Laboratory* of the *University of Cantabria*.

The degradation was performed with a 200 W orbital sander. To enable a similar and uniform degradation, the same working parameters were assumed for each sample: type of sandpaper (Debray, very coarse, grit grade “4”); operation speed (2-3 cm/s) and direction; number of passes ***N*** over the sample; and laboratory technician. Apart from that, 0.04 g/cm^2 of limestone filler was spread over the surface of each sample and then brushed off with a soft haired brush in order to emulate the presence of the accumulated dust existing on the pavements. As was determined during the research, this process simulates the loss of colour suffered by a pavement during the first years, which is assumed to be the period in which the loss is more intense. No further effects can be emulated by means of this degradation process.

The degradation process carried out can be divided in three stages. In the first one, the aim was to determine the number of passes ***N*** to be made with the orbital sander over the surface of the HMA slabs. For this purpose, six Marshall samples (cylindrical samples with a nominal diameter of 101.6 mm) of a dense graded asphalt mix with the characteristics shown in Table 1 (M1) were made in the laboratory and four measurements of ***L**** were done with the spectrophotometer for each sample. Then the samples were subjected to 75 passes of the orbital sander, taking measurements of ***L**** every 15 passes. Prior to every measurement, the filler was spread and brushed off. The Box-and-Whisker plot in Fig. 1 shows the ***L**** values collected throughout the process. In spite of the few mild outliers, it can be seen from the plot that a uniform range of ***L**** values is obtained for values of ***N*** higher than 45. Therefore, for the second stage of the degradation process, a number of 50 passes will be assumed enough to provide the maximum colour degradation of the HMA samples for the current test methodology.

Table 1 – Properties of the asphalt mixes used in the degradation process

Mix	M1	M2	M3	M4	M5
Gradation	Dense	Dense	Semi-Dense	Semi-Dense	Open
Density	2271 kg/m^3	2383 kg/m^3	2320 kg/m^3	2108 kg/m^3	2083 kg/m^3
MAS	16 mm	16 mm	16 mm	11 mm	16 mm
Type of Aggregate	Ofite	Ofite	Limestone	Ofite	Ofite
Bitumen content [a]	4.70 %	4.53 %	4.78 %	5.20 %	4.68 %
Bitumen sp. gravity	1.03 g/cm^3	1.03 g/cm^3	1.03 g/cm^3	1.03 g/cm^3	1.03 g/cm^3
Bitumen Penetration (25ºC, 100g, 5s)	60-70 dmm	60-70 dmm	60-70 dmm	60-70 dmm	55-70 dmm

[a] Bitumen content by weight of total mix.

Once the number of passes ***N*** was determined, the next stage consisted in the colour study of four different asphalt mixes subjected to the previously established degradation process. The properties of these asphalt mixes can be seen in Table 1 (M2 to M5). Eight Marshall samples of each type of mixture were used and four measurements of ***L**** were taken in each sample before and after the colour degradation process. The parameter colour degradation ***ΔL**** was defined as the loss of colour suffered by a pavement due to traffic effects and accumulated dust during its first years in service. It was measured as the difference between the values of ***L**** obtained with the spectrophotometer on the surface of the newly made samples ($\boldsymbol{L_o}$*******) and the values obtained after the degradation process ($\boldsymbol{L_f}$*******).

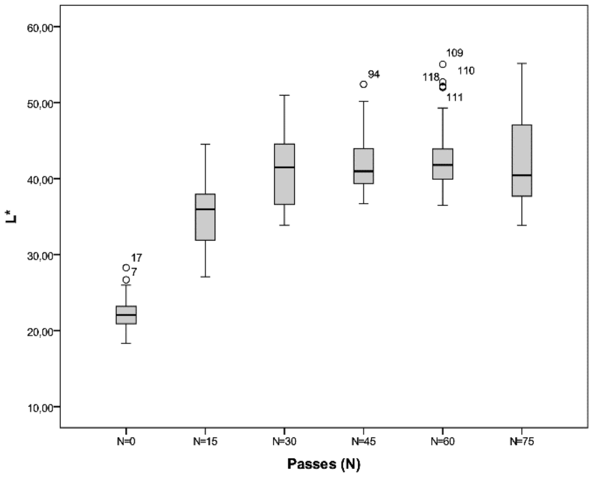

Fig. 1 - Results of the tests done to determine the number of passes (N) of the orbital sander.

Finally, in order to link the parameter ***ΔL**** measured in the laboratory samples with the age of a low volume pavement, the value of ***L**** was taken with the spectrophotometer in the surface of the access roads (not in the parking bays) to seven different small car parks with different ages and levels of colour degradation (Fig. 2). The main characteristics of these pavements are shown in Table 2. Sixteen measurements of ***L**** were taken in each of the car park roads that were used to perform a statistical analysis relating the colour degradation process in the laboratory and the real colour degradation undergone by this type of low volume roads.

Table 2 – Characteristics of the car parks where the L* values where measured with the spectrophotometer

Car Park	CP1	CP2	CP3	CP4	CP5	CP6	CP7
Mix Gradation [a]	Dense	Dense	Dense	Dense	Dense	Dense	Dense
Mix MAS	16 mm	16 mm	16 mm	16 mm	16 mm	16 mm	16 mm
Age	0.3 years	1.0 year	2.0 years	3.0 years	3.3 years	3.7 years	6.0 years
Total Surface [b]	1200 m^2	1900 m^2	1600 m^2	1400 m^2	1900 m^2	1600 m^2	1900 m^2
No. of Places	60	90	60	60	70	45	50

[a] The specific type of mixture is not known for all the car parks.
[b] This is an approximate value obtained with a SIG open application.

Fig. 2 - One of the car parks where measurements of colour degradation were taken.

Laboratory tests on new and degraded HMA slabs with solar radiation lamp

Solar radiation tests were carried out in the laboratory to analyse the temperature distribution and energy storage ability of new and degraded HMA slabs. Two different asphalt mixes were tested: a semi-dense (SDG) and an open graded (OG) asphalt mix. The main properties of these mixes are shown in Table 3.

Table 3 – Properties of the asphalt mixes used in the thermal analysis with solar radiation lamp

	Gradation	Semi-dense Graded	Open Graded
Mix	**Bitumen content** [a]	5.00 %	4.68 %
	Density	2181 kg/m^3	2034 kg/m^3
	Aggregate Type	Ofite	Ofite
Aggregate	**MAS**	16 mm	16 mm
	Bulk Specific Gravity	2.678 g/cm^3	2.900 g/cm^3
	Penetration (25ºC, 100g, 5s)	50-70 dmm	55-70 dmm
Bitumen	**Softening Point**	> 48 ºC	> 60 ºC
	Specific Gravity	1.03 g/cm^3	1.03 g/cm^3

[a] Bitumen content by weight of total mix.

The slabs used in these tests were 500 mm x 500 mm x 100 mm (length x width x depth). In order to measure the temperature distribution within the slabs, several thermistors (NTC 10K) were inserted at different depths. Thermal grease was spread around the thermistors so that the insulating effect of the air voids between them and the mix was decreased. Every sensor was connected to a data acquisition device that enabled continuous recording of the temperature. Apart from these measurements, a laser thermometer was used to measure temperature of the slab surface, and ambient temperature and humidity were also recorded. Finally, a pyranometer was used to evaluate the irradiance applied to the slabs during the tests.

The slabs were placed in a wooden mould that enabled bottom and lateral insulation with polyurethane foam [32] and made possible the application of the heat source just to the slab surface. The heat source was supplied by a solar radiation lamp (Fig. 3) made up of a steel structure with a 4x4 matrix of special radiator bulbs (OSRAM Ultravitalux 300 W) whose emission spectrum is similar to that of the sun. This structure enabled the variation of the lamp height, thus providing a wide range of irradiance (W/m^2) values. The same type of bulbs has already been used in other applications such as glass testing [33] or the simulation of atmospheric processes [34].

Once prepared, new and degraded slabs were placed under the solar lamp and subjected to an irradiance of 460 W/m^2 for 7 hours. Slab temperatures at increasing depths and ambient temperature and humidity were recorded using the previously mentioned measurement devices. The irradiance value corresponds to the average daily irradiance (considering only daylight hours) on horizontal plane on a clear sunny day of July in a Mediterranean population where part of this research was carried out [35].

With the data collected throughout these tests, it was possible to analyse the influence of the early colour degradation suffered by the asphalt mixes on the temperature distribution and ability of asphalt pavements to store solar thermal energy.

Fig. 3 - Solar simulator lamp used for the thermal (irradiation) tests of the asphalt s[illegible]

3. Results and Discussion

Results of the colour study of degraded asphalt pavements

The average values of L_o*, L_f* and ***ΔL**** obtained with the spectrophotometer f[illegible] every mix (M1 to M5) are shown in Table 4. The average values of ***ΔL**** for every sample are shown in Fig. 4. The data pertaining to mix M1 were obtained by interpolation between the L_o*, L_f* and ***ΔL**** values measured after 45 and 60 passes of the sander. The reason was that no measurement was taken after 50 passes when testing this mix.

Table 4 – Average values of L_o*, L_f* and ΔL obtained in the laboratory with the spectrophotometer

Mix	M1	M2	M3	M4	M5
L_o*	22.34	22.33	23.20	21.90	22.02
L_f*	42.48	45.39	49.85	42.02	44.15
ΔL	20.14	23.06	26.65	20.12	22.13

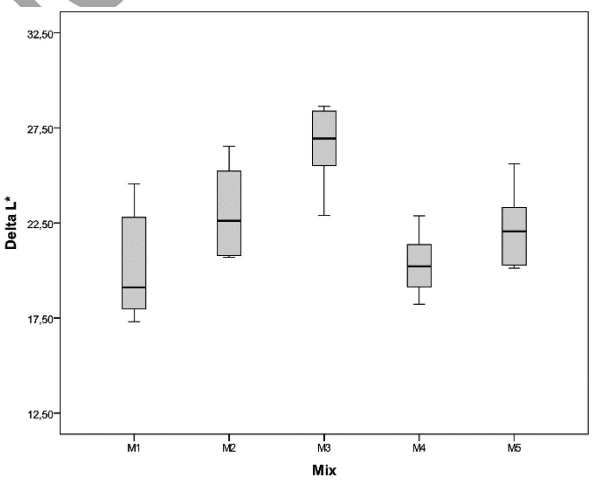

Fig. 4 - Average colour degradation of the mixes in which the degradation process was applied.

Only slight differences can be appreciated between the values of ***ΔL**** shown in Fig. 4, which means that most of the mixes suffered a similar colour degradation. Besides, no extreme outliers were found, which shows the reliability of the method. However, a clearer difference was observed between M3 and the rest of the mixes in terms of ***ΔL****. This deviation might be due to the properties of the different aggregate used to make the samples of the mix, limestone, whose colour is usually lighter than ophite and mostly whitish and greyish [36,37]. This would imply that once the bitumen was removed due to the degradation process, the limestone's lighter colour would be exposed to the spectrophotometer and would make the values of L_f* (and hence ***ΔL****) increase with respect to the asphalt mixes made with ophite.

A *Student's t-test* for independent samples was carried out that statistically demonstrated that a significant difference existed between M3 and the other mixes. Requisite conditions of normality and homocedascity were verified through the *Kolmogorov-Smirnov* and *Levene* tests, respectively. Therefore, the results of the *Student's t-test* confirm the influence of additional parameters (the type of aggregate in this case) that should be taken into account in further studies. This diagnosis can be also linked to the low value of R^2 obtained for the fitted curve of the average colour degradation of each type of mix as a function of its *density* (Fig. 5).

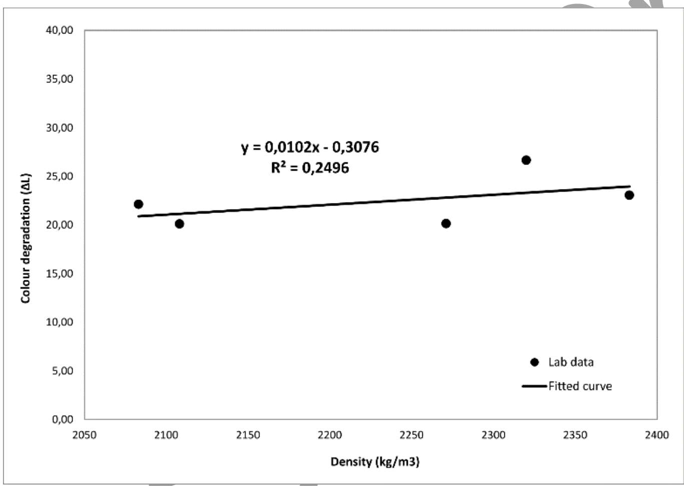

Fig. 5 - Fitted curve of the colour degradation measured in the mixes as a function of their density.

Regarding the data measured in the roads accessing the car parks, the values of L_f* obtained with the spectrophotometer are shown in Fig. 6 in the form of a Box-and-Whisker plot. As in previous plots, no extreme outliers were found. In this picture, a similar trend can be easily recognised in the pavements with ages over two years (CP3-CP7). In the same way, a clear difference can be perceived between the values of L_f* measured in the 0.3 year old car park (CP1) and the rest of them. For this reason, two *Student's t-tests* for independent samples were performed that statistically confirmed: a) the significance of the difference; and b) the non-existence of a significant difference between the values of L_o* measured in the newly made HMA laboratory samples (M1-M5) and the values of L_f* measured in CP1. Requisite conditions of normality and homocedascity were properly verified.

The results of these tests imply that: a) there is no colour degradation in this car park within the first 4 months after its opening; and b) the average value of L_f* in CP1 might be taken as the average value of L_o* for all the car parks. This means that it is possible to determine an average ***ΔL**** for the car parks, even though the real L_o* might not be measured. The values of ***ΔL**** for all the car parks are shown in Table 5.

Once the values of ***ΔL**** are calculated, it is possible to compare the colour degradation undergone by the HMA samples in the laboratory with the loss of colour undergone by the car parks. For this reason, although it seems from Tables 4 and 5 that a similar range of values has been obtained within the laboratory samples and the car parks, a final *Student's t-test* was carried out that determined significant differences between them. Nevertheless, this does not imply that the degradation process followed in the laboratory was incorrect. On the contrary, it means that this process is able to simulate at least the degradation suffered by a 6 year old low volume pavement, keeping further analysis on the safe side. Furthermore, based on these results, it can be said that several months after their opening, these pavements will suffer a degradation that makes them reach a value of ***L**** that will not be altered at least in the next 4 to 5 years. Maintenance routines to ensure pavement heat collection efficiency will have to be considered in accordance with these results.

Table 5 – Average values of L_f* and ΔL obtained in the car parks with the spectrophotometer

Mix	CP1	CP2	CP3	CP4	CP5	CP6	CP7
L_f*	21.85	33.56	42.80	38.86	41.72	42.42	39.82
ΔL	-	11.71	20.95	17.01	19.87	20.57	17.97

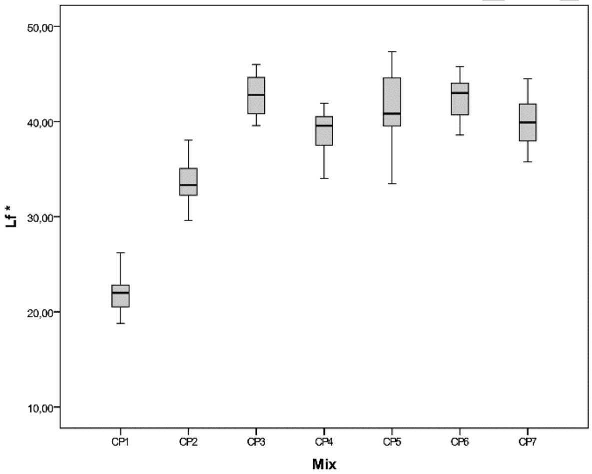

Fig. 6 - Values of L_f* measured with the spectrophotometer in the car parks here analysed.

Results of the thermal tests on slabs with solar radiation lamp

In Fig. 7 and 8, the results of the solar radiation tests carried out on the newly made HMA slabs are presented. The temperature distribution with depth and time for the semi-dense graded and open-graded asphalt slabs are shown in the form of contour plots. An initial temperature of 20±1 °C was set for all the tests in order to facilitate their comparison. Since the steady state was never reached, a temperature gradient existed over the depth during the tests and hence, a transient analysis has been done.

Generally speaking, the thermal behaviour of both mixes in terms of temperature distribution is rather different, as can be inferred from the distinct slope of the contour lines. Thus, different temperature gradients were obtained due to the different maximum and minimum temperatures arising in both types of mixes. On the one hand, the OG mix slabs reached slightly higher temperatures near the surface during the tests. However, as the depth increased, the temperature of the SDG mix slabs became considerably higher from the beginning to the end of the tests. All this means that although small differences in temperature can be found in asphalt layers near the surface, it is when the depth increases that greater differences arise between SDG and OG mixes.

Average minimum values of 49.82°C and 45.06°C were measured in SDG and OG mixes, respectively.

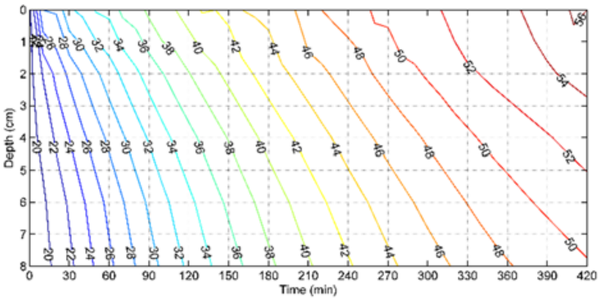

Fig. 7 - Contour plot of the temperature distribution in the new SDG HMA during the thermal test.

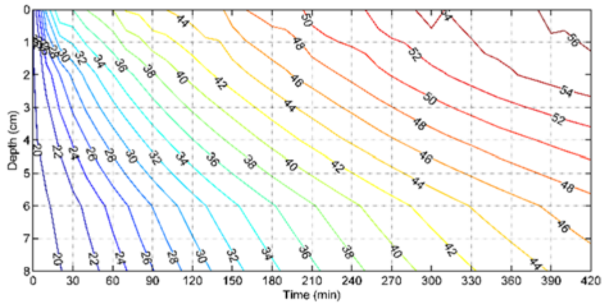

Fig. 8 - Contour plot of the temperature distribution in the new OG HMA during the thermal test.

Considering that the main difference between the two mixes is their *density* (Table 3), and that this parameter is very closely linked to their *conductivity*, these results confirm the influence of this parameter in the asphalt mixes' thermal behaviour. Thus, a higher or lower value of *conductivity* will lead to a smaller or larger temperature gradient between the surface and the bottom of a pavement. It should be noted that conductivity values of typical dense and semi-dense graded mixes range from 1.00 to 1.90 W/m·K [15,23,27], while conductivity values of open graded mixes are expected to be much lower. At the same time, the fact that the higher differences arise as the depth increases also confirms how exiguous the influence of the asphalt mix *conductivity* is at low (next to the surface) depths [23,27]. On the other hand, the smaller differences in temperature at the surface could also be explained in terms of *conductivity* due to the fact that a much lower value would lead to a lower heat absorption velocity and then to higher and lower temperatures at the surface and the lower layers of the asphalt mix, respectively [26].

The energy collected by the slabs of both asphalt mixes during the tests is shown in Fig. 9. As seen from the picture, the same energy was stored in both types of mixes within the first two hours of test, from which time, the energy stored in the OG mix was always lower. This is relevant only when the construction of an asphalt solar collector is considered, but it is not very important in terms of the mechanical behaviour of the pavements since even higher temperatures are reached at the surface of these mixes. On the other hand, the growing curves imply that the slabs did not reach their maximum storage capacity after 7 hours of tests, as could be expected considering that the steady state (and hence the maximum temperatures within all the asphalt layers) was not reached.

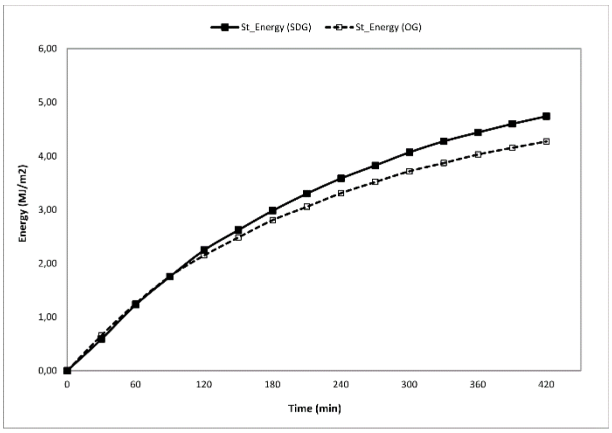

Fig. 9 - Curves of the stored energy in the new SDG and OG HMA during the thermal test.

The results of the loss of temperature and stored energy undergone by the SDG and OG asphalt mixes after being subjected to the previously mentioned degradation process are shown in Fig. 10 and 11. Probably, the most important consideration was the low magnitude of the temperature and energy storage capacity reduction for both types of mixes, with values of maximum reduction of 2.45 ºC for the SDG mix and 3.42 ºC for the OG mix. Concerning the energy, maximum reductions of the storage capacity of less than 8% and 4% were measured for the SDG and OG mixes, respectively.

Thus, a low reduction of temperature and energy has occurred which means that these types of mixes placed in low volume roads do not need to be maintained in terms of heat collection capacity, e.g. by re-painting them with a new black coating, at least within the first six years from their opening. Regarding the influence of the high thermal loads on the mechanical behaviour of pavements, the reduction of temperature measured in this research, although quite low, entails that a lower rutting damage would be suffered by a pavement as time goes by after its opening. Similarly, this reduction would help to decrease the urban temperature and, hence, mitigate the heat island effect.

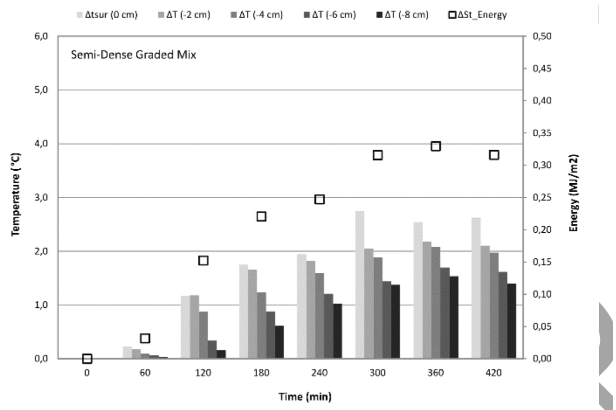

Fig. 10 - Temperature and energy storage capacity deviation between new and degraded SDG asphalt slabs.

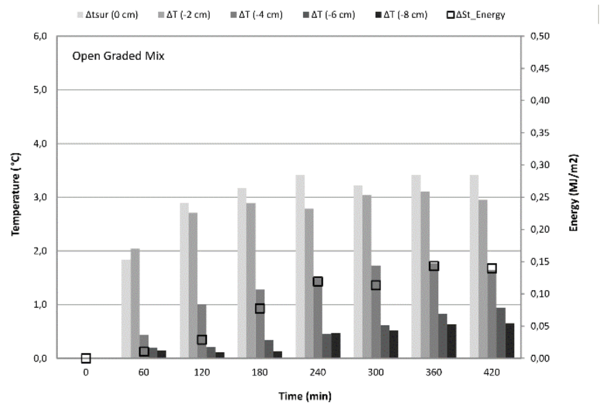

Fig. 11 - Temperature and energy storage capacity deviation between new and degraded OG asphalt slabs.

Furthermore, it can be seen from the graphs that this exiguous loss of temperature follows the same pattern as the previously analysed temperature distribution. Thus, the loss of temperature increases with time for both types of mixes. However, while in the SDG mix the loss of temperature is homogeneously distributed with depth, the loss suffered by the OG mix at depths under 6 cm is virtually negligible. This means that the degradation process carried out on the OG asphalt slabs did not have any effect on the temperature at lower depths. This is presumably the reason why the reduction in the heat storage capacity of the OG mix was considerably lower.

4. Conclusions

The influence of early colour degradation of two different asphalt mixes on their thermal behaviour was analysed in this paper through the development of a new degradation process carried out in the laboratory on five different asphalt mixes and its comparison with the colour degradation suffered on the access roads of seven low volume car parks. Several conclusions can be drawn from the results obtained:

- The colour degradation undergone by most of the different mixes analysed in the laboratory was very similar. However, other parameters such as the aggregate type have to be taken into account in further studies.
- The colour degradation on the access road of a low volume car park within the first years after its opening was successfully simulated in the laboratory according to the parameters

and conditions defined in this paper.

- The value of colour degradation reached after two years by the low volume car parks of the type studied here seems to be a relative maximum in the short-term and will not be altered at least within the following 4-5 years.
- There is a large difference in terms of thermal behaviour between semi-dense graded and open graded asphalt mixes.
- The increasing difference with depth in the temperature distribution of two asphalt mixes, with significantly different *densities* and hence *conductivities*, confirms the influence of these two parameters on the asphalt mixes' thermal behaviour at specific depths. The exiguous influence of the *conductivity* at depths near the surface was also confirmed.
- A very low reduction in the temperature and energy collection capacity was measured for the two mixes after being subjected to the colour degradation process. For the open graded mix, the difference in temperature at low depths between the newly made and degraded slabs was negligible.
- The low reduction of temperatures and energy storage capacity of asphalt mixes demonstrated in this paper would strongly affect the maintenance frequency of a potential asphalt solar collector. On the other hand, the beneficial influence of the temperature reduction on the mechanical behaviour of a regular asphalt pavement as well as on the urban heat island effect, although limited, should be considered.

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References

[1] Pascual-Muñoz, P., Castro-Fresno, D., Serrano-Bravo, P. and Alonso-Estébanez, A. Thermal and hydraulic analysis of multilayered asphalt pavements as active solar collectors. Applied Energy, 2013, 111 pp. 324-332.

[2] Wendel, I.L. Paving and solar energy system and method. United States Patent, Patent number 4.132.074,1979. U.S.

[3] Sedgwick, R. H. and Patrick, M. A. The use of a ground solar collector for swimming pool heating. Solar World Forum. Proceedings of ISES, Brighton (England), 1992, pp. 632-636.

[4] Turner, R.H. Concrete slabs as summer solar collectors. Proceedings International Heat Transfer

Conference, 1987, pp. 683-689.

[5] Bopshetty, S.V., Nayak, J.K. and Sukhatme, S.P. Performance analysis of a solar concrete collector. Energy Conversion Management, 1992, 33(11) 1007-1016.

[6] Sokolov, M. and Reshef, M. Performance simulation of solar collectors made of concrete with embedded conduit lattice. Solar Energy, 1992, 48(6) 403-411.

[7] Al-Saad, M.A., Jubran, B.A. and Abu-Faris, N.A. Development and testing of concrete solar collectors. Solar Energy, 1994, 16(1) 27-40.

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

[9] EGEC (2007). Geothermal snow melting and de-icing. European Geothermal Council. Brussels, Belgium.

[10] Morita and Tago (2000). Operational characteristics of the Gaia Snow-Melting System in Ninohe, Iwate, Japan. Proceedings World Geothermal Congress 2000, Kyushu-Tohoku (Japón).

[11] Van Bijsterveld, W.T., Houben L.J.M., Scarpas, A. and Molenaar, A.A.A. Using pavement as solar collector: effect on pavement temperature and structural response. Journal of Transportation Research Board, 2001, (1778) 140-148.

[12] Mallick, R.B., Chen, B.L., Bhowmick, S. and Hulen, M.S. Capturing solar energy from asphalt pavements. International ISAP Symposium on Asphalt Pavements and Environment. Switzerland, Zurich, 2008, pp. 161-172.

[13] Mallick, R.B., Chen, B.L. and Bhowmick, S. Reduction of urban heat island effect through harvest of heat energy from asphalt pavements. International Journal of Sustainable Engineering, 2009, 2(3) 214-228.

[14] Wu, S., Chen, M., Wang, H. and Zhang, Y. Laboratory study on solar collector of thermal conductive asphalt concrete. International Journal of Pavement Research and Technology, 2009, 2(4) 130-136.

[15] Wu, S., Chen, M. and Zhang, Y. Laboratory investigation into thermal response of asphalt pavements as solar collector by application of small-scale slabs. Applied Thermal Engineering, 2011, 31(10) 1582-1587.

[16] Chen, M., Wu, S., Zhang, Y. and Wang, H. Effects of conductive fillers on temperature distribution of asphalt pavements. Physica Scripta T, 2010, Vol. T139, art. no. 014046.

[17] Chen, M., Wu, S., Wang, H. and Zhang, Y. Study of ice and snow melting process on conductive asphalt solar collector. Solar Energy Materials and Solar Cells, 2011, 95(12) 3241-3250.

[18] Diefenderfer, B.K., Al-Qadi, I.L. and Diefenderfer, S.D. Model to predict pavement temperature profile: Development and validation. Journal of Transportation Engineering, 2006, 132 (2) 162-167.

[19] Kennedy, T. and Solaimanian, M. Predicting Maximum Pavement Surface Temperature Using Maximum Air Temperature and Hourly Solar Radiation. Transportation Research Record, 1993, (1417) 1-11.

[20] Hermansson, Ake. Simulation model for the calculation of pavement temperatures, including the maximum temperature. Transportation Research Record, 2000, 1699(19): 134-141.

[21] Hermansson, Ake. Mathematical model for calculation of pavement temperatures: comparison

of calculated and measured temperatures. Transportation Research Record, 2001, 1764(19): 180-188.

[22] Hermansson, Ake. Mathematical model for paved surface summer and winter temperature: comparison of calculated and measured temperatures. Cold regions science and technology, 2004, 40(1-2): 1-17.

[23] Yavuzturk, C., Ksaibati, K. and Chiasson, A.D. 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, 2005, 17(4): 465-475.

[24] Gui, J., Phelan, P.E., Kaloush, K.E. and Golden, J.S. Impact of pavement thermophysical properties on surface temperatures. Journal of Materials in Civil Engineering, 2007, 19(8): 683-690.

[25] Minhoto, M.J., Pais, J.C., Pereira, P.A.A. and Picado-Santos, L.G. Predicting asphalt pavement temperature with a three-dimensional finite element method. Transportation Research Record, 2005, 1919(11): 96-110.

[26] Bilgen, E. and Richard, M.A. Horizontal concrete slabs as passive solar collectors. Solar Energy, 2002, 72(5): 405-413.

[27] Chen, B., Rockett, L. and Mallick, R.B. A laboratory investigation of temperature profiles and thermal properties of asphalt pavements with different subsurface layers. Journal of the Association of Asphalt Paving Technologists (AAPT), 2008, Volume 77.

[28] Xu, Q. and Solaimanian, M. Modeling temperature distribution and thermal property of asphalt concrete for laboratory testing applications. Construction and building materials, 2009, 24(4): 487-497.

[29] Qin, Y. and Hiller, J.E. Modeling temperature distribution in rigid pavement slabs: impact of air temperature. Construction and Building Materials, 2011, 25(9): 3753-3761.

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

[31] Akbari, H. and Konopacki, S. Calculating energy-saving potentials of heat-island reduction strategies. Energy Policy, 2005, 33 (6):721-756.

[32] Wu, J.-W., Sung, W.-F. and Chu, H.-S. Thermal conductivity of polyurethane foams. International Journal of Heat and Mass Transfer, 1999, 42(12): 2211-2217.

[33] ISO 12543-4:2011. Glass in building. Laminated glass and laminated safety glass. Part 4: Test methods for durability.

[34] Bernard, F., Quilgars, A., Cazaunau, M., Grosselin, B., Daele, V., Mellouki, A., Winterhalter, R. and Moortgat, G. Ozonolysis of a series of biogenic organic volatile compounds and secondary organic aerosol formation. Geophysical Research Abstracts, Volume 12. European Geosciences Union (EGU), General Assembly 2010. May 2-7, Vienna-Austria.

[35] Šúri, M., Huld, T.A., Dunlop, E.D. and Ossenbrink, H.A. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy, 2007, 81(10): 1295-1305.

[36] Boynton, R.S. Chemistry and technology of lime and limestone. Interscience Publishers, New York (USA), 1966.

[37] Oates, J.A.H. Lime and limestone: chemistry and technology, production and uses. Wiley-VCH,

Weinheim (Germany), 1998.