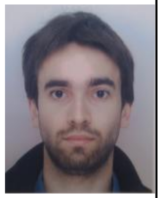

Characterization of the behavior of Parisian street materials

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1. Introduction

Materials used in urban environments have strong impacts on urban climates and consequently on pedestrian thermal comfort. Depending on their thermal properties, they contribute more or less to the urban heat island (UHI) effect (Asaeda, Ca, & Wake, 1996; Santamouris, 2013). Several UHI countermeasures involving cool materials, urban greening or urban watering have been studied (Akbari, Pomerantz, & Taha, 2001; Bowler, Buyung-Ali, Knight, & Pullin, 2010).

Previous work by the authors has focused on the field study of pavement-watering as a climate change adaptation measure for Paris against increasing and intensifying heat waves (Hendel, Colombert, Diab, & Royon, 2014, 2015a, 2015b). Testing over the summers of 2013 and 2014 has shown that the method reduces surface temperatures an average 13°C during pavement insolation in a N-S street paved with asphalt concrete. Air temperature reductions of up to 0.8°C as well as 2.4°C mean radiant and 1°C UTCI equivalent temperature reductions were found, while relative humidity was increased by 4%RH at most. Finally, the optimal watering rate was determined to be 0.16-0.21 mm/h during shading and 0.31-0.41 mm/h during pavement insolation.

These analyses also underlined the important role played by the materials being watered. Indeed, while a given watering frequency may be valid for asphalt road surfaces, they are unlikely to be valid for other materials with different water-holding capacities, albedo or other relevant properties. Given the wide variety of materials used in cities, it is important for decision-makers to be able to account for this when designing a city-wide pavement-watering strategy. Field trials however are expensive and impractical for this purpose.

This paper proposes a lab experiment that may be used to characterize the behavior of street materials with or without watering in heat-wave conditions. As a first step, this paper will focus on temperature observations made without watering for five pavement structures commonly used in Paris, France: asphalt concrete road surfaces, stabilized sand, asphalt and modular granite sidewalks and grass. Temperatures measured 6 cm, 14 cm, 25 cm and 32 cm deep will be discussed in particular. Previous work by the authors describes surface temperature and heat flux observations (Hendel, Grados, Colombert, Diab, & Royon, 2015a, 2015b).

2. Materials and methods

Five different street structures were compared, consisting of standard asphalt road and sidewalk structures as well as samples of cement-stabilized sand, granite-paver sidewalk and lawn structures. Each cylindrical sample is 32 cm tall and 16 cm in diameter. Fig. 1 describes the composition of the street structures constructed in the lab. Each sample was equipped with thermocouples and or flowmeters 0 cm, 6 cm, 14 cm and 25 cm deep. In addition, a thermocouple was positioned on the underside of the samples, 32 cm below the sample surface. The surface albedo was determined experimentally in previous work with the exception of the grass sample (Hendel, Grados, et al., 2015a). These albedo values are summarized in Table 1.

Once insulated with a polyurethane foam casing, each sample was submitted to identical a 24-hour climate cycle three days in a row. Air temperature and relative humidity were controlled by a climate chamber and insolation with a seven-bulb dichroic halogen lamp with a color temperature of 5,600 K. The characteristics of the climate cycles are described in Table 2, while Fig. 2 presents a diagram and photograph of the experimental setup.

Prior to the beginning of the three-day trials, each sample was stabilized for at least 24 hours in the climate chamber under nighttime conditions. In addition, the grass sample was sufficiently watered before the trials to ensure that evapotranspiration would not be interrupted over the course of the three day trial.

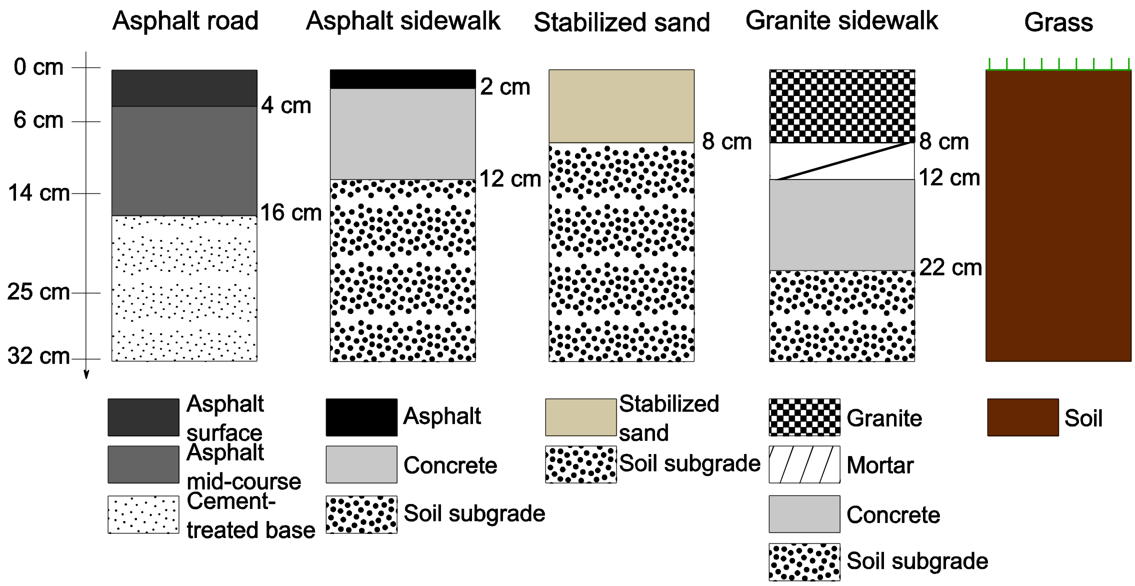

Fig. 1: Studied structure samples

Table 1: Albedo of the samples determined experimentally, except for the grass sample.

Asphalt road	*Asphalt sidewalk*	*Stabilized sand*	*Granite sidewalk*	*Grass*
0,098	0,155	0,369	0,313	0,25-0,30

Table 2: Daytime and nighttime conditions

	Day	*Night*
Duration	8h	16h
Air temperature	35°C	25°C
Relative Humidity	35%	70%
SW Radiation	1 320 W/m²	0
LW Radiation	230 W/m²	440 W/m²

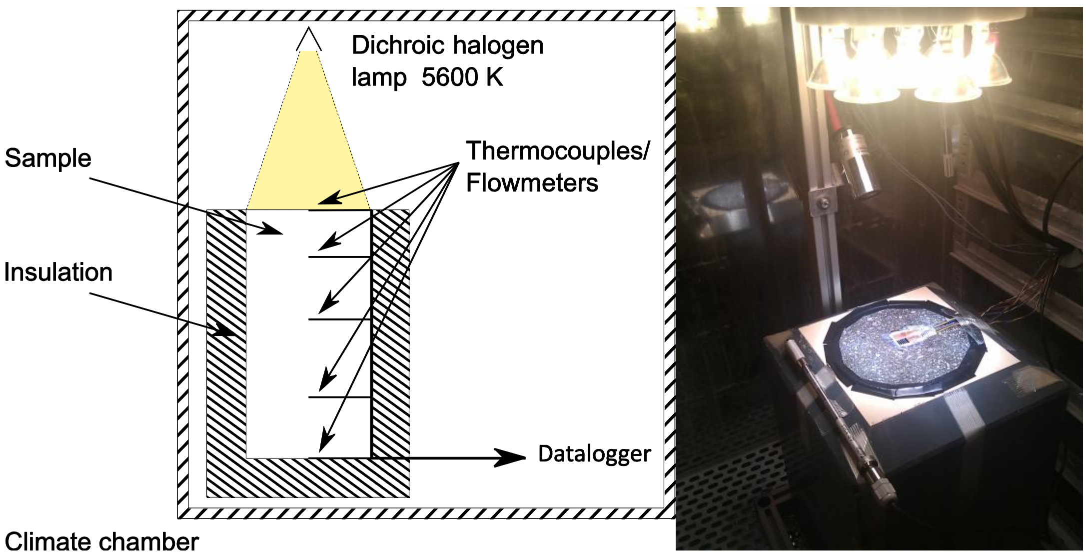

Fig. 2: Diagram (left) and photograph (right) of experimental setup.

3. Results and discussion

We begin by describing the temperature observations at the studied depths.

3.1. Results

Fig. 3 illustrates temperature measured 6 cm deep inside each sample. As can be seen, temperatures range from 23.3° to 50°C over the course of the three days, except for the grass sample whose initial temperature is 22.3°C. This is likely due to the additional latent cooling that the sample benefits from as a result of evapotranspiration.

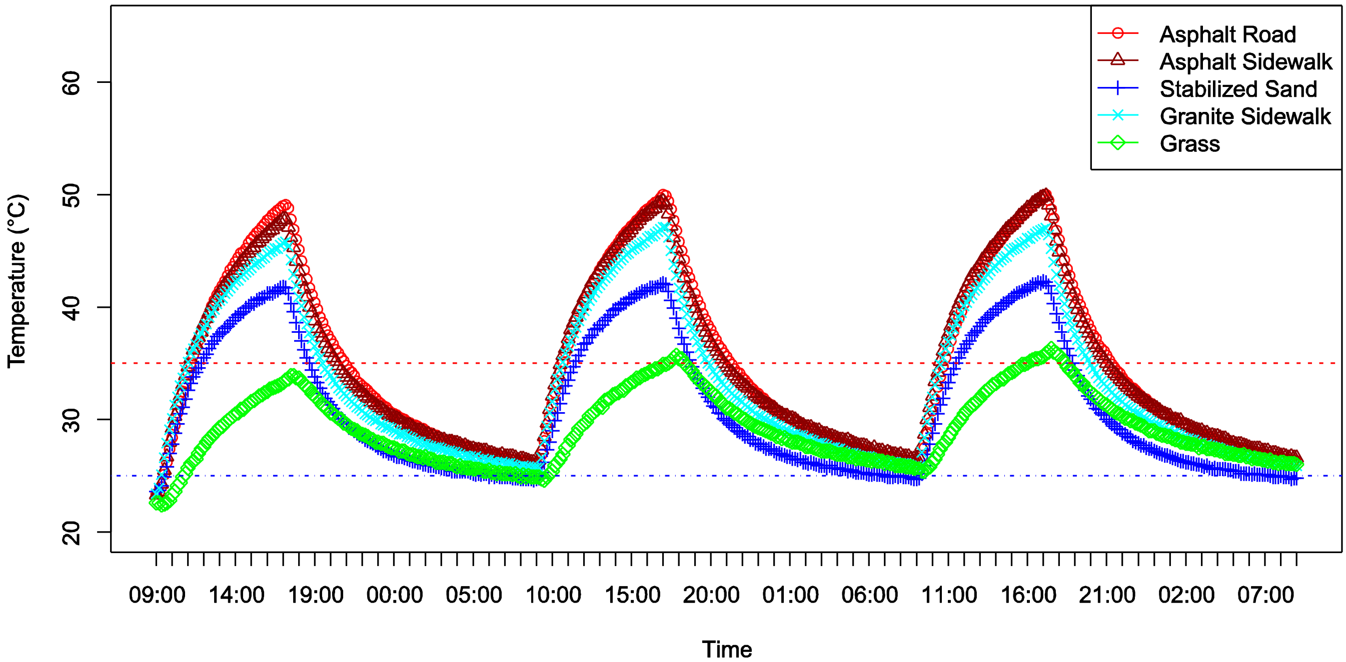

Fig. 3: Temperature measured 6 cm deep over 72 hours. The dotted red and blue lines respectively indicate the day and night setpoint temperatures inside the climate chamber.

The asphalt road and sidewalk structures are the warmest over the trial period, closely followed by the granite sidewalk structure, while the stabilized sand and grass samples are significantly cooler. The stabilized sand is warmer than the grass sample during the day, but at night it becomes cooler after the first two hours. After 24 hours, temperatures remain a few degrees warmer than the initial state.

Additionnally, inertial effects are manifested by the gradual increase in temperatures over the course of the three-day trial. While, the daily maximum temperature of the asphalt road and the stabilized sand samples increases by less than 1°C, it increases by 1.3°C for the granite sidewalk sample and by 2.2°C for the asphalt sidewalk and grass samples.

Fig. 4 illustrates temperatures measured 14 cm deep, which range from 23°C (22.3°C for the grass sample) to 42.9°C.

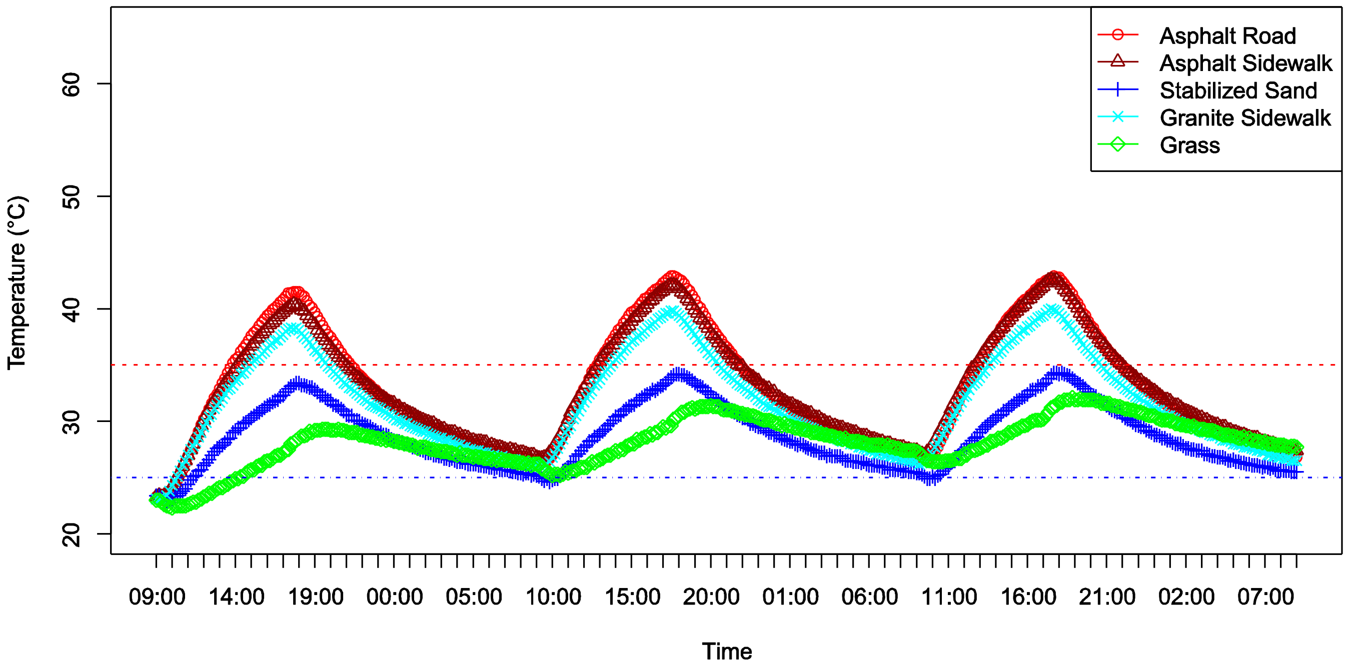

Fig. 4: Temperature measured 14 cm deep. The dotted red and blue lines respectively indicate the day and night setpoint temperatures inside the climate chamber

As was the case for temperatures measured 6 cm deep, the asphalt road and sidewalk samples are the warmest, closely followed by the granite sidewalk structure, with the stabilized sand and grass samples being the coolest. Once more, the stabilized sand sample is warmer than the grass during the day, but becomes cooler six hours into the night phase. Compared to the temperature shifts observed 6 cm deep, those 14 cm deep occur approximately one hour later. The thermal inertia of the samples is visible at this depth as well, the grass sample exhibiting a nearly 3°C increase in daily maximum temperature over the course of the trial, followed by the asphalt and granite sidewalk structures with approximately 2°C.

Fig. 5 illustrates temperature measurements 25 cm deep.

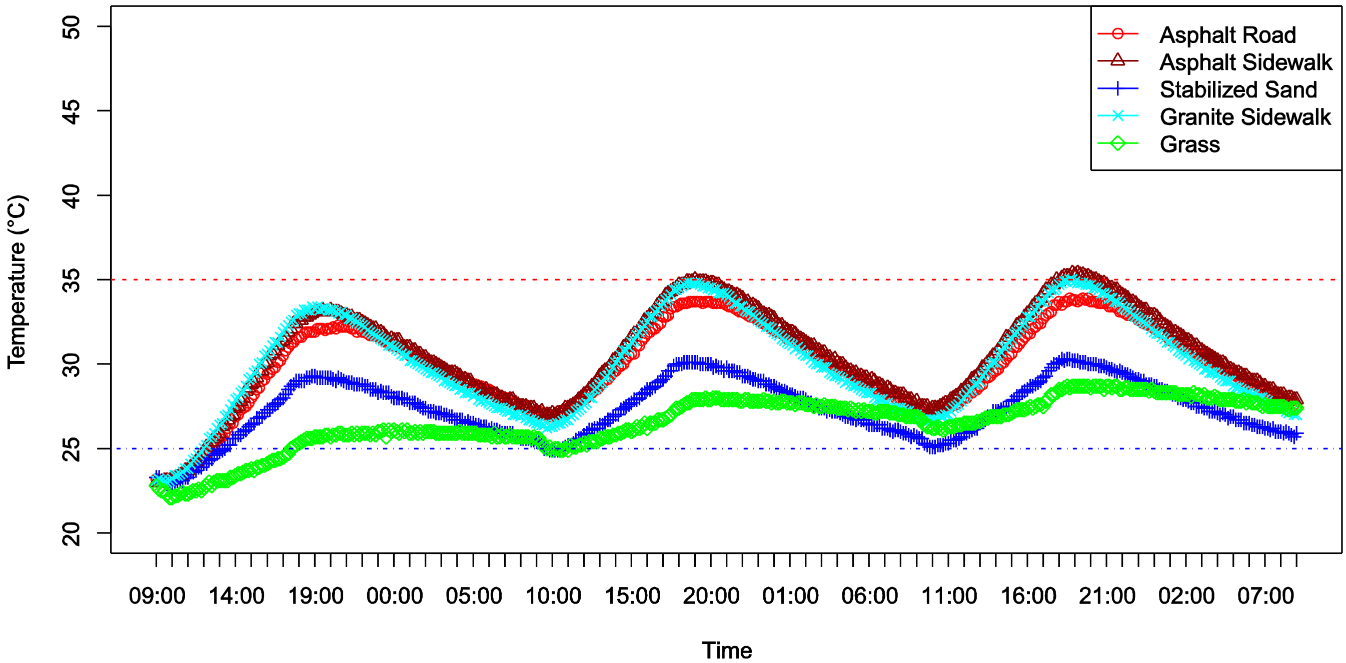

Fig. 5: Temperature measured 25 cm deep. The dotted red and blue lines respectively indicate the day and night setpoint temperatures inside the climate chamber.

Temperatures 25 cm deep range from 23° (22.1° for grass) to 35.4°C and no additional lag is visible compared to the 14 cm observations. For the first time, the granite sidewalk is warmer or nearly as warm as the asphalt road and sidewalk structures. All samples exhibit visible inertial effects, greatest for the asphalte sidewalk and grass structures (+2.2°C and +2.7°C daily maximum temperature increase resp.).

Fig. 6 illustrates temperatures measured 32 cm deep.

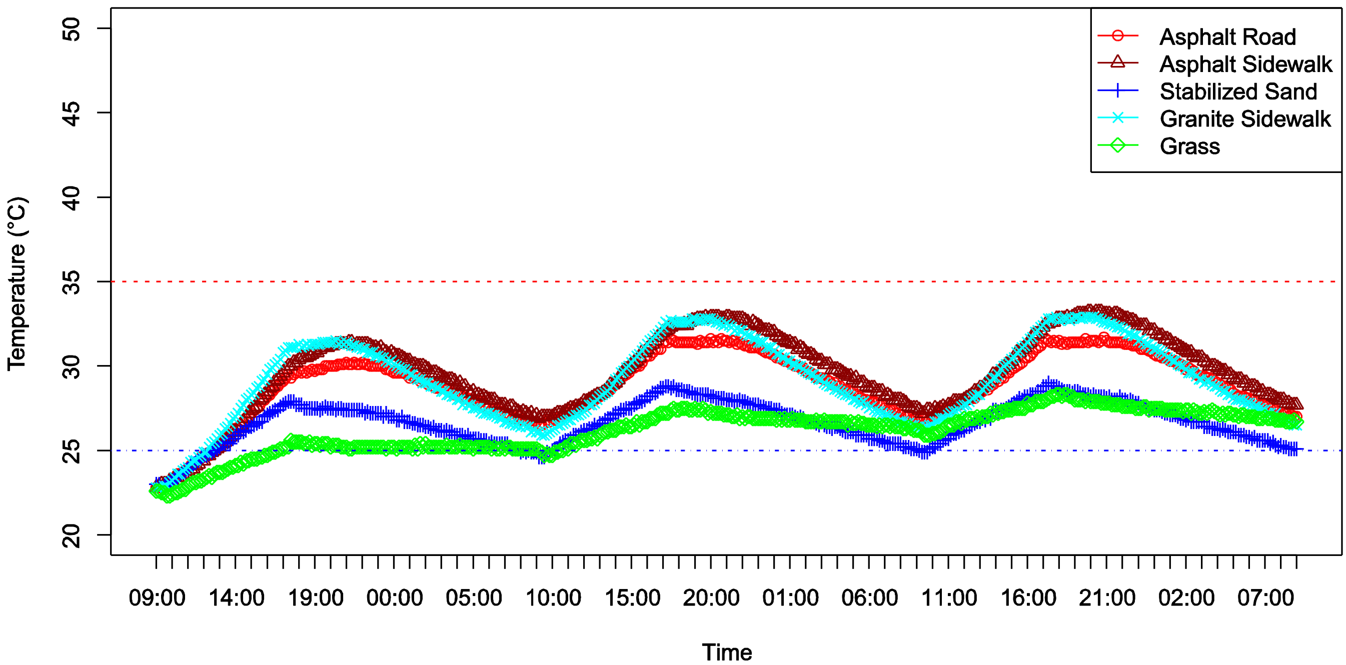

Fig. 6: Temperature measured 32 cm deep. The dotted red and blue lines respectively indicate the day and night setpoint temperatures inside the climate chamber.

Unlike at other depths, temperature spikes are visible. These coincide with the beginning of the night phase and are due to a faulty seal which allowed an air leak inside the insulating casing. This seal has since been corrected. At this depth, the grass sample is the coolest structure on the first day, but is warmer on average than the stabilized sand structure on the last day. Otherwise, temperature trends are similar to those 25 cm deep. Once again, intertial trends are clearly visible and greatest for the grass and asphalt sidewalk structures (+2;7°C and +3°C, resp.).

3.2. Discussion

While temperature observations 6 cm deep may not be identical, they agree well with field observations 5 cm deep made in a similar asphalt road in Paris, France over the summer of 2013 (Hendel & Royon, 2015). Differences between observations can be explained by the climate signal created in the la, which has longer and stronger insolation. Despite this, the overall trend obtained is deemed satisfactory.

Generally-speaking, these temperature observations agree well with the behavior expected of each sample given their surface albedo, with the notable exception of the granite sidewalk structure. Indeed, temperatures similar to those of the stabilized sand would be expected for this structure given its similar albedo. As previous work has revealed (Hendel, Grados, et al., 2015a), this is linked to the granite's high thermal conductivity. Heat is not only reflected away, it is also transmitted into the deeper layers of the structure, thus explaining the higher-than-expected temperatures 6 cm deep.

Overall, the data set provides a global view of how these structures react to a given climate signal. Indeed, the grass and stabilized sand structures are clearly the coolest, while the road and sidewalk structures have similar behavior at the considered depths.

In addition, inertial phenomena are clearly visible in varying intensity at the different depths considered. Table 3 summarizes the average increase in daily maximum temperature for each structure between the first and third day. By this metric, the grass and asphalt sidewalk structures have the highest inertia among the considered structures, while the stabilized sand has the lowest.

Table 3: Average daily maximum temperature increase from D to D+2.

Asphalt road	*Asphalt sidewalk*	*Stabilized sand*	*Granite sidewalk*	*Grass*
+1.3°C	+2.4°C	+0.88°C	+1.5°C	+2.6°C

While cooler material temperatures will have positive consequences such as lower atmospheric heating in cities, higher inertia will slow temperature increases when a heat spike arises. Ideally, urban materials should therefore combine both properties via high albedo for example. The urban materials used in Paris that have been considered here present either one property or the other, except for the grass structure.

4. Conclusion

A lab experiment was used to characterize the relative behavior of five Parisian street structures. 32 cm tall cylindrical samples were constructed and instrumented in the lab. Temperature measured 6 cm, 14 cm, 25 cm and 32 cm deep was used for this purpose. It was found that the stabilized sand and grass structures were the coolest, while the road and sidewalk structures were significantly warmer. Via these observations, it was found that the underlying layers of the asphalt sidewalk and grass structures have the highest inertia.

While low temperatures will result in lower atmospheric cooling in cities, high thermal inertia helps slow temperature rises in the case of heat spikes. Among the five structures considered, only the grass structure combines low temperatures with high thermal inertia. The second best option is either the stabilized sand structure which presents the second lowest temperatures, or the asphalt sidewalk which has the second highest temperature increase.

Further research efforts are needed to determine the full extent of the benefits of increasing the inertia of existing urban materials for pavements, but this may be achievable by including thicker layers of concrete or even phase change materials as has been studied previously for roofing materials (Santamouris, Synnefa, & Karlessi, 2011).

In the coming months, another set of tests will focus on the effects of pavement-watering of the considered samples in order to clarify the technique's effectiveness on other structures than asphalt roads.

Acknowledgments

The authors acknowledge the support of the Roads and Traffic and the Waste and Water Divisions of the City of Paris for their expertise and material support. Funding for this experiment was provided by APUR (Parisian urban planning agency).

References

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, *70*(3), 295–310. doi:10.1016/S0038-092X(00)00089-X

Asaeda, T., Ca, V. T., & Wake, A. (1996). Heat storage of pavement and its effect on the lower atmosphere. *Atmospheric Environment*, *30*(3), 413–427. doi:10.1016/1352-2310(94)00140-5

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, *97*(3), 147–155. doi:10.1016/j.landurbplan.2010.05.006

Hendel, M., Colombert, M., Diab, Y., & Royon, L. (2014). Improving a pavement-watering method on the basis of pavement surface temperature measurements. *Urban Climate*, *10*(December), 189–200. doi:10.1016/j.uclim.2014.11.002

Hendel, M., Colombert, M., Diab, Y., & Royon, L. (2015a). An analysis of pavement heat flux to optimize the water efficiency of a pavement-watering method. *Applied Thermal Engineering*, *78*, 658–669. doi:10.1016/j.applthermaleng.2014.11.060

Hendel, M., Colombert, M., Diab, Y., & Royon, L. (2015b). Measurement of the Cooling Efficiency of Pavement-Watering as an Urban Heat Island Mitigation Technique. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *3*(1), 1–11. doi:10.13044/j.sdewes.2015.03.0001

Hendel, M., Grados, A., Colombert, M., Diab, Y., & Royon, L. (2015a). Comparaison des matériaux de l'espace public parisien : caractérisation de la contribution aux îlots de chaleur urbains. In *CIFQ* (p. (Under Review, In French)). 8-10 Juin 2015, Sherbrooke, QC, Canada.

Hendel, M., Grados, A., Colombert, M., Diab, Y., & Royon, L. (2015b). Quel est le meilleur revêtement pour limiter la formation des îlots de chaleur urbains ? In *Congrès Français de Thermique 2015 : La Thermique de l'Habitat et de la Ville* (p. (under review) (in French)). 26-29 mai 2015, La Rochelle, France.

Hendel, M., & Royon, L. (2015). The effect of pavement-watering on subsurface pavement temperatures. *Urban Climate*, (submitted).

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. *Renewable and Sustainable Energy Reviews*, *26*, 224–240. doi:10.1016/j.rser.2013.05.047

Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*, *85*(12), 3085–3102. doi:10.1016/j.solener.2010.12.023