Evaluation of Geothermal Pavements and Other Energy Harvesting Systems in Roadways

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Background, Problem Statement, and Justification

More than half of the world's population lives in urban environments. This number is expected to increase to 70 percent by 2050 as a result of increased migration from rural to urban and suburban areas (Population Reference Bureau 2013). Knowing that the built environment absorbs and stores solar energy, the temperature in cities can be several degrees higher than in adjacent rural areas (Chen et al. 2008). This is known as the urban heat island (UHI) effect. Replacing natural surfaces (e.g., vegetation) with built impervious surfaces such as a road or a concrete building contributes to the UHI effect (Wang and Xue 2013). The UHI effect, in turn, contributes significantly to the increased demand for energy to cool urban and suburban areas, particularly in countries with moderate and warm climates (Carnielo and Zinzi 2013). This increased demand, coupled with increased greenhouse gas concentrations, contribute to the increase in the Earth's average temperature.

Realizing the negative impact of this phenomenon, environmental agencies, governments, and researchers have been looking for sustainable and eco-friendly solutions to alleviate the problem of UHI. According to the United States Environmental Protection Agency: "Many communities are taking action to reduce urban heat islands using four main strategies: increasing tree and vegetative cover, installing green roofs (also called "eco-roofs"), installing cool—mainly reflective—roofs, and using cool pavements" (US EPA 2012).

Pavements typically comprise 30 to 45 percent of the land area in major cities and, therefore, contribute significantly to the UHI effect, through low reflection of solar radiation and high levels of thermal storage (TRB 2007). Hence any effort invested in decreasing the pavement's temperature will lead to a decrease in UHI that indirectly helps in reducing energy consumption, decreasing greenhouse gas emissions, and extending the service life of a pavement structure.

These facts are encouraging researchers and practitioners alike to investigate ways to reduce the temperature of pavements and, generally, roads in moderate and warm climates. Several studies (e.g., Chen et al. 2008, Rockett 2008, Seo et al. 2011, Carnielo and Zinzi 2013) provide evidence that it is possible to lower the surface temperature of asphalt pavements by flowing water underneath the pavement. This technique, which is often referred to as geothermal pavement system, offers advantages that go beyond combating the UHI effect. A geothermal pavement also offers, in colder climates, an environmentally friendly procedure for snow melting. By replacing chemical deicing agents such as calcium and sodium chlorides, a geothermal pavement reduces the chances of soil and water contaminations as well as corrosion of paved roads (Seo et al. 2011).

The basics behind geothermal pavements concepts are the fundamental heat transfer phenomena that allow for heat transfer from one medium (asphalt) to another (water) and vice versa. A geothermal pavement is a pavement structure with pipes embedded in its layers. A circulating fluid (e.g., water) offers a chance to harvest energy from the hot pavement during summer times. The heat transfer allows for heating water which can be used for various domestic applications and cooling the pavement structure and thereby decreasing its rutting potential. The reverse phenomenon takes place in cold seasons where the embedded pipes can be used to melt ice formations on asphalt pavement surfaces. This is ultimately beneficial for the pavement structure by reducing its thermal cracking potential. From a material characterization perspective, having asphalt bitumen as a binding agent, asphalt mixtures have a viscoelastic behavior. Temperature has a considerable influence on the physical properties of a pavement structure (Yang 2012). One of the main performance criteria of pavements is the dynamic modulus (Anochie-Boateng et al. 2010). With increasing temperatures, the dynamic modulus of the asphalt pavement decreases leading to a structure vulnerable to different types of distresses. Hence, any invested effort in the process of decreasing a pavement's temperature will ultimately return an expanded life cycle of the structure itself.

This research study aims at enhancing the current state of knowledge on geothermal pavement systems and, generally speaking, the field of energy harvesting from roadways. In addition to geothermal pavements, other energy harvesting mechanisms such as photovoltaic membranes and thermoelectric systems will be examined for applicability in the context of roads in the Middle East. Design variables (e.g. pipe diameter and thickness layout network) affecting the performance, effectiveness, and durability of geothermal pavements will be studied through a set of theoretical and experimental tests. The proposed research project will ultimately provide its users with the capability of assessing the efficiency of using roadways for solar energy harvesting under different environmental setups. Harvesting energy from the roads will not only provide an environmentally friendly source of heat for water, but will also reduce the temperature of the pavement and the near surface air which will, in turn, result in savings in energy consumption of adjacent buildings and reduction of the UHI effect.