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The Effect of Urban Heat Islands and Traffic Wheel Pressure on the Performance of Asphalt Pavements

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Abstract

This paper propose two main software to establish a simulation model, and analysis of how solar radiation affects asphalt pavement performance under the influence of traffic loading. The objectives of the project are to indicate how solar radiation and traffic loading affect asphalt pavement. The step-by-step objectives are quantifying the effect of urban heat islands on the performance of asphalt pavements, analyzing stresses of asphalt pavements imposed by wheel pressure, and studying the properties of asphalt pavements affected by both urban heat islands and wheel pressure. Daily solar radiation data was collected and calculated by Autodesk Project Vasari. The graph of Autodesk Project Vasari showed the geometric solar radiation which a specific location received in the whole day. Solidworks was used to determine how asphalt temperature causes fatigue under traffic loading. After field data collection and observation, the relationship of asphalt performance and geometric location with traffic loading was approved. Introduction/Problem Statement: Conventional asphalt pavements are impervious, which can reach peak summertime surface temperatures of 120–150°F (48–67°C). These surfaces receive heat energy from solar radiations and transfer heat downward to be stored within the pavement layers (pavement layer, subbase, and subgrade), where the heat stored is remitted back to the air at night. These effects known as urban heat islands have been seen as part of factors that have affected the performance of asphalt pavements. Although mechanical responses of traffic loading on pavement properties have been widely researched, however, relevant work in the effect of urban heat islands on the asphalt's behavior have not yet well studied. In combination with wheel pressures, this project is being implemented to study the relation between the properties of asphalt pavements and the combined wheel pressure/urban heat islands. Research Objectives/Hypothesis/Key Questions: The objectives of the project are to (1) quantify the effect of urban heat islands on the performance of asphalt pavements, and (2) analyze stresses of asphalt pavements imposed by wheel pressure, and (3) study the properties of asphalt pavements affected by both urban heat islands and wheel pressure. Specifically, the project will discuss (1) the impact of landscaping and vegetation of roadways on the increase of life cycle of asphalt pavements, and (2) conditions that engineers can take into consideration for roadway design and landscaping planning

Keywords: Solar Radiation, Wheel Pressure, Simulation

1. Introduction

Asphalt pavement on streets and parking lots occupy about 30% of the land in cities and can be characterized as miniature heat islands.[7] Conventional asphalt pavements are good solar absorbers and poor thermal conductors, which can reach peak summertime surface temperatures of 120–150°F (48–67°C) [1]. As a solid materials experiences an increase in temperature, the volume of this material will increase, which is also called thermal expansion. Within an asphalt pavement, each small solid spices are close to each other. Increasing of volume of all small spices would lead to compaction inside the pavement, which is a major source of thermal stress. As pavement temperature rise, volatilization of the asphalt binder and oxidation lead to a progressive hardening of the pavement, which result in increased fatigue cracking and reduced durability.[5] So that higher surface temperatures make the pavement more prone to rutting.[6] Surfaces receive heat energy from solar radiations and transfer heat downward to be stored within the pavement layers (pavement layer, basement, and subgrade), where the heat stored is remitted back to the air at night. These effects known as urban heat islands have been seen as part of factors that have affected the performance of asphalt pavements.

Solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: 5 percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn; 43 percent of solar energy is visible light, in colors ranging from violet to red; and the remaining 52 percent of solar energy is infrared, felt as heat. Energy in all of these wavelengths contributes to urban heat island [1].

Although mechanical responses of traffic loading on pavement properties have been widely researched, relevant work in the effect of urban heat islands on the asphalt's behavior have not yet well studied. In combination with wheel pressures, this project is implemented to study the relation between the properties of asphalt pavements and the combined wheel pressure/urban heat islands. A series of numerical simulations and analyses were conducted to quantify the effect of heat island effect on the performance of asphalt pavements. Using computer software is a symbol of 21st century, so there are two software packages used in this study: Autodesk Project Vasari and Solidworks. In this research, Autodesk Project Vasari was used to determine the distribution of solar radiation on the pavements of Flagstaff downtown. In addition, Solidworks is employed to build 3D models of asphalt pavements according to its real physical properties and perform heat transfer analyses and compute stresses imposed by traffic loading and temperature changes.

1.1. Problem Statement and Hypothesis

Heat island effect has been well known for its significant impact on the sustainability of buildings and energy absorption. However, only a handful of studies have been focused on the relationship between road orientations/geometry and pavement performance. This study is to add the knowledge of how heat island effect impacts the properties and performance of asphalt pavements.

The hypothesis of the study is the geometric location of roads along with wheel pressure can influence the performance of asphalt pavements. Numerical analysis associated with field observations and temperature measurements has been made in this research.

1.2. Literature Review

A paper conducted by Ho and Romero [2] proposes three mathematical models using solar radiation theory, transient heat transfer theory, and the finite element method to compute daily solar radiation, determine a thermal-penetration depth as a boundary condition, and eventually estimate pavement temperatures. The paper provided some important information to this research. First, the boundary condition equation from their paper was used into this research to calculate the bottom temperature of one piece of pavement after knowing the surface temperature and depth of the pavement. In addition, material properties were also cited from their paper.

Ferguson and Fisher [1] provides information of cool pavement technology and some basic idea of asphalt pavement especially solar energy part. Cool pavement technologies tend to store less heat and may have lower surface temperatures compared with conventional products. In the other words, cool pavement is a kind of technology which try to lower the surface temperature of pavement, and lower the solar energy absorption. The basic idea of solar energy and asphalt properties contribute to this research.

2. Software for Simulation

Two main software packages were used in this research.

Autodesk Project Vasari is an easy-to-use, expressive design tool for creating building concepts as well as providing integrated analysis for energy and carbon dioxide estimation [3]. This project provided a function called solar radiation to gather solar radiation data from one specific location on the earth at a specific time. Accumulated solar radiation could be calculated and showed on a graph automatically.

SOLIDWORKS is widely-used software in mechanical area. This is not only software to build a 3D model; the simulation in this software is also used in stress & strain analysis and thermal analysis. SOLIDWORKS is a solid modeler, and utilizes a parametric feature-based approach to create models and assemblies, and perform engineering analyses.

3. **Solar Radiation Analysis**

3.1.Simulation Model Establishment

In this analysis, a Vasari model was built in accordance with existing geometric locations and layouts of buildings located in Flagstaff, Arizona (Figure 1). Getting a screen shot of the area where the research would happen from google map, and input the map as the background. Like Autodesk Revit, a mass model could be built according to its real layout. The height of buildings could be calculated by getting the height-shadow ratio.

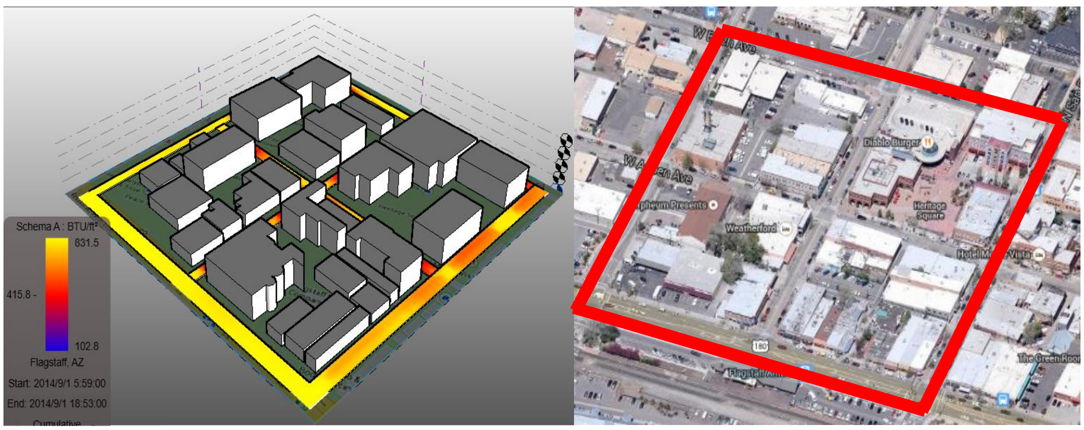


Figure 1. Solar Radiation Modeling (Left: graphic model. Right: Flagstaff Downtown Imagery)

3.2.Simulation Result

Vasari graphs show the solar radiation incident on the pavement each two hour.

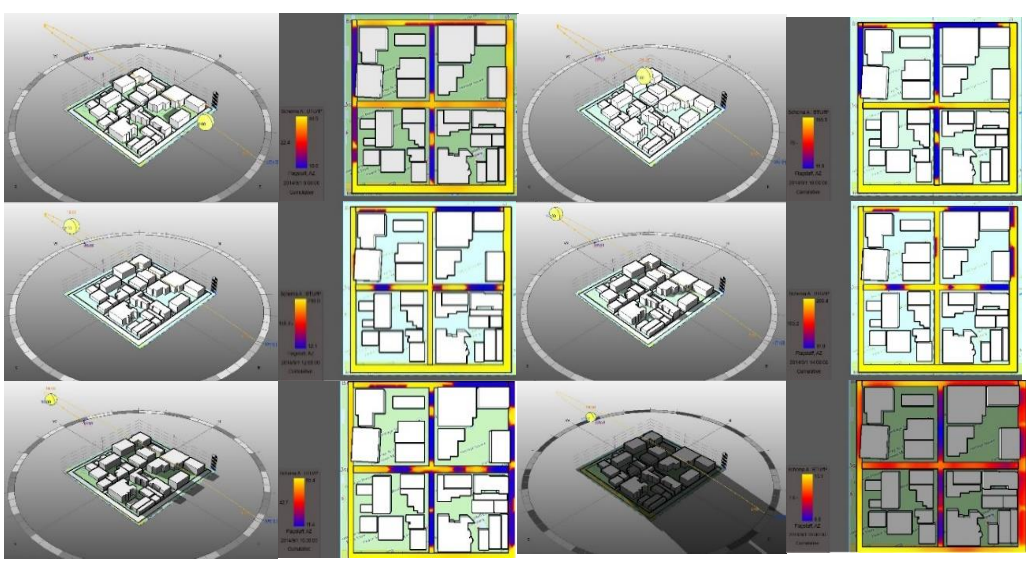


Figure 2. Sun Path and Solar Radiation Gathering at 8:00, 10:00, 12:00, 14:00, 16:00, 18:00. Sep 1st, 2014.

The reason of different solar radiation is shadow of buildings. The pavement, which is covered by shadow received little solar radiation than the area under sun shine. The legend of different color was shown in the graph, which measures the solar radiation received in BTU/ft^2.

Autodesk Project Vasari has a function of sun path, which is same as Autodesk Revit. By turning on the sun path and shadow functions, we received graphs including sun path and shadow to determine where the shadows were located at the specific time. (Figure 2) There is also a simulation function called wind tunnel, which shows the wind variation of a specific area.

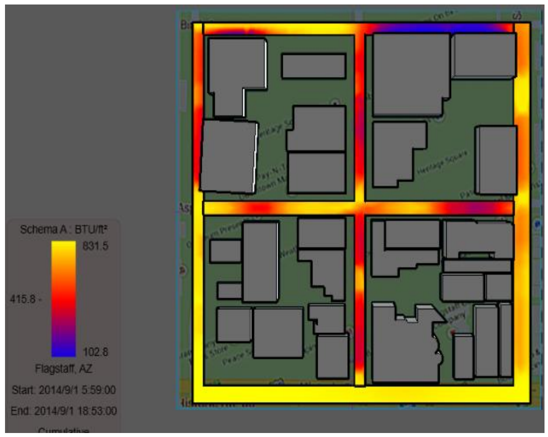


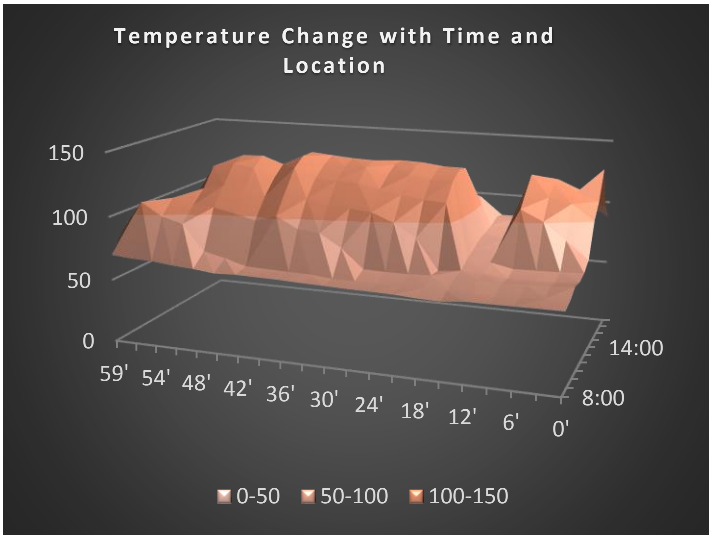
Figure 3. Accumulate Solar Radiation on September 1st, 2014

There is also a graph, which shows accumulated solar radiation which the pavement received in the whole day. (Figure 3) At the time we took pictures on the same location on the crossing, the thermal cracking showed on the picture match the solar radiation simulation from Autodesk Project Vasari.

4. Field Data Collection

To further validate the numerical simulation in the lab, a field temperature measurement collected at N. Leroux St. to Aspen Ave. in Flagstaff, AZ, was performed on 09/01/2014 from 8am to 6pm.

The pavement was divided into twenty parts per three feet, and the temperature of each three feet was collected per hour using thermal gun. (Figure 4) Based on results, the highest surface temperature was measured at 1pm with 139.6 °F. The data was input in excel and labeled with different colors to determine the variation of temperature of pavement surface. (Table 1) A 3D graph was built to show how temperature variation with time and location. (Graph 1) There was a directly drop down area, because of a vehicle parked, and the shadow made the surface temperature lower than the others parts.



Graph 1. Temperature Change with Time and Location

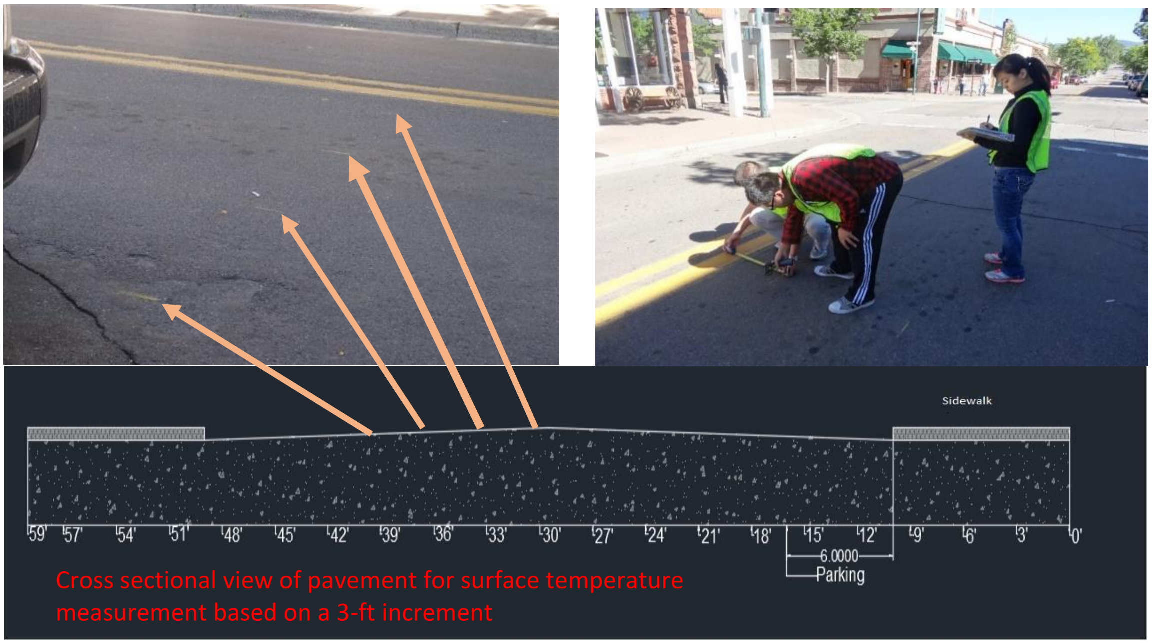


Figure 4. Pavement cross section and real location on the pavement.

Different location on the pavement was shown on the AutoCAD drawing.

Table 1. Table of Surface Temperature on Pavement Vary with Time and Location

Time	59' shadow	57'	54'	51'	48'	45' tree	42'	39'	36'	33'	30'	27'	24'	21'	18'	15' tree	12'	9'	6'	3'	0'
8:00	69.8	68.4	68	66.2	65.1	63.3	64	63.7	63.5	62.8	62.4	61.9	61.7	61.3	60.3	59.7	61.5	61.5	61.7	61.9	61.9
9:00	86.2	109.2	99	94.5	74.5	70.7	65.8	65.3	64.8	64.6	62.8	62.6	62.4	62.6	63	62.6	62.8	62.2	62.6	63.9	63.9
10:00	83.3	102.9	110.1	105.6	105.1	101.7	97.3	102.2	93.6	91.8	81.9	67.1	66.6	66.7	67.5	66.3	66.9	66.6	67.3	67.6	69.4
11:00	81.5	102.3	92.8	115.3	118.8	116.2	112.3	117.9	113.4	109.8	108.3	106.7	100	90	66	67.8	66.9	65.1	65.5	65.7	67.5
12:00	81.7	90.7	90.5	130.1	132.8	130.6	123.6	133	125.8	125.1	124.2	120.6	117.9	115.2	113.9	72.4	71.2	67.6	68	68.4	69.3
13:00	81	90.9	87.4	109.4	136.9	137.5	131.7	139.6	133.4	132.8	133.3	128.1	129.4	127.2	127.6	75.6	74.8	109.4	101.1	88.2	74.7
14:00	79.3	84.4	84.9	100.4	107.2	113.5	118.2	139.5	138	136.6	136	133.5	134.2	132.3	132.8	79.2	79	120	116.1	112.3	100.4
15:00	80.4	81	83.3	93.9	99.3	101.8	102.9	104.9	108.5	111.4	115.3	133.9	133.3	131.2	131	80.4	79.7	129.2	122.9	117.7	111.9
16:00	78.8	79.3	79.3	88.9	93.4	93.9	94.1	93.6	96.3	95.4	90.9	100.8	106.2	110.3	110.3	81.7	81.3	112.3	123.3	113	133.5
17:00	84.2	84.4	86	92.3	94.3	95.5	95.4	95.5	95.9	96.1	95.7	101.7	102.7	103.5	102.6	84.9	85.8	107.4	113.7	111	101.1
18:00	82.8	82.4	81.5	87.8	90.9	90	90	90.1	90.3	91	92.3	93.2	93.9	93.2	96.5	82.8	82.8	96.4	96.9	96.4	87.8
	West															parking	parking				East

Lowest Value	(blue)
Midpoint (50 Percentile)	(red)
Highest Value	(yellow)

This table showed that the peak temperature was collected at center of the pavement at noon, because there wasn't any shadow at the center of pavement at that time. The solar radiation was also accumulated. In the afternoon, the solar energy was hard to lose because the pavement already stored much energy inside to keep the pavement warm.

5. **Solidworks Analysis**

5.1 Wheel Path

Wheel path of pavement needed to be considered because the pavement receives plenty of pressure from traffic and this is the dominant effect causing fatigue of pavement. AutoCAD is useful software to draw 2D graph, so that a wheel pressure graph is established in AutoCAD to show the wheel pressure to pavement. (Figure 5)

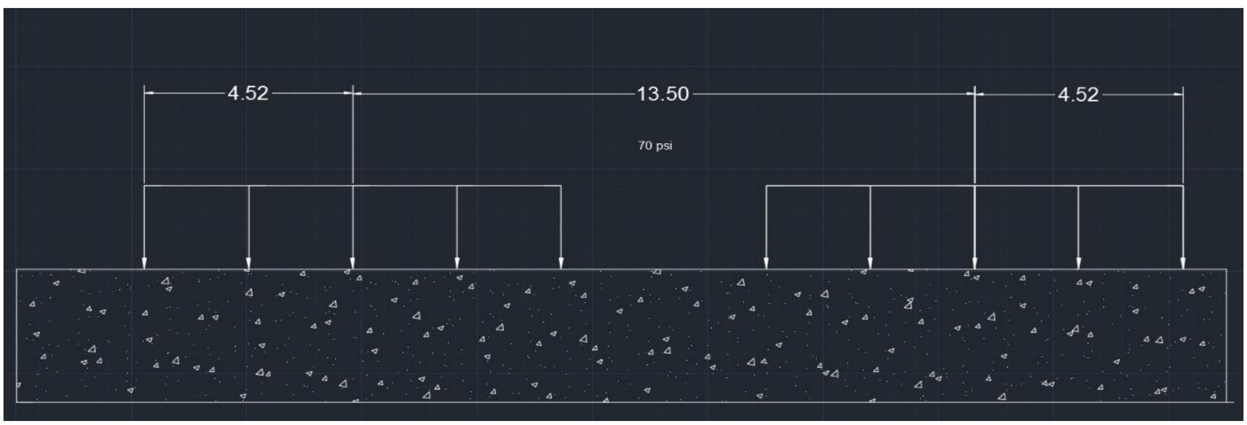


Figure 5. Wheel Pressure with Dimension on Pavement

The figure was drawn using Autodesk CAD, and the data was collected from real dimension.

5.2 Study Condition

One pair of data gathered from Field Data Collection was used in Solidworks analysis which made the stress analysis realistic.

Temperature under Shadow: 80°F
Temperature under Sun: 130°F
Temperature at Bottom of Pavement: 95°F
Gravity: 9.8m/s^2
Wheel Pressure: 70psi
The equation we used to calculate the temperature of bottom of pavement is [2]:

$$T_{Pav} \times 0.859 + (0.002 - 0.0007 \times T_{air}) \times D + 0.17 \quad (1)$$

T_{pav} = pavement temperature at calculated depth (°C)
T_{air} = low air temperature (°C)
D = depth (mm)

5.3 Static Analysis

When an overlay is placed on an existing pavement, physical tearing of the overlay often takes place as a result of movement at the joints and cracks in the underlying pavement layer [4]. Solidworks was used to show how traffic loading and solar radiation leads to asphalt cracking.

A model of a single part of pavement was built and conditions which might affect the stress and strain of the material was added to do some simulations. (Figure 6) The stress differences are shown in the legend, which vary with different color. Conditions are added including gravity, pavement surface temperature (under shadow and under sun shine), pavement bottom temperature (according to equation (1)), and wheel pressure. (Figure 7)

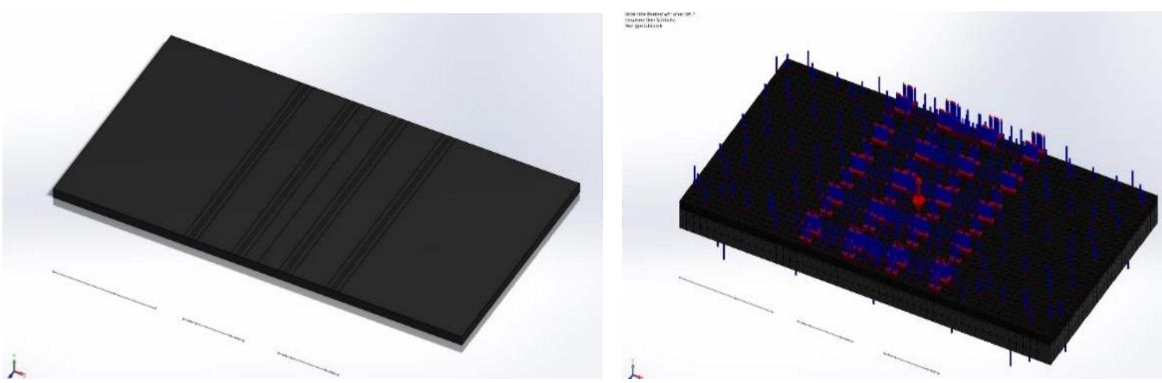


Figure 6. Solidworks Pavement Model with Wheel Path and Shadow Line

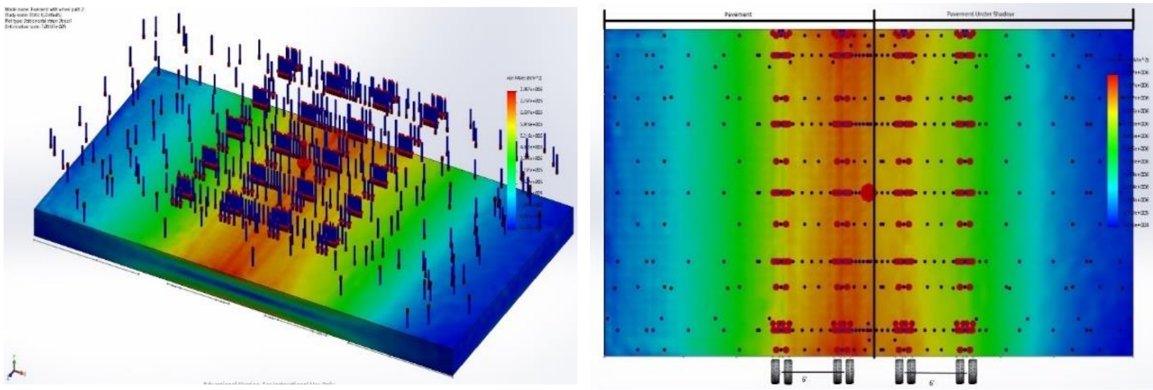


Figure 7. Solidworks Static Simulation (Stress) Result

As shown in Figure 7, the left boundary had a surface temperature of 130°F and the right boundary of pavement had a surface temperature as 80°F. Legend showed that red area had larger stress than the others color. The result indicated that under same wheel pressure, asphalt pavement received larger stress under sunshine than under shadow. This analysis combined thermal cracking (temperature) and fatigue (traffic loading), which are two major reasons caused pavement cracking, to explain how these two factors affect asphalt pavement using straight-forward graph.

5.4 Thermal Analysis

Heat transfer analysis and thermal stress calculation were performed in the lab to evaluate the temperature distribution and thermal induced stress within the pavement. (Figure 8)

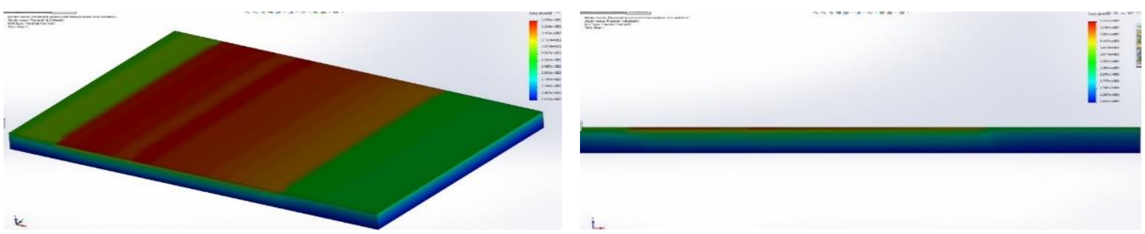


Figure 8. Thermal Analysis

6. Comparison with Field Observation

After comparing to the pavement performance in the different area of the specific research crossing, a significant difference was shown. (Figure 9)

Left top picture was taken on the east part of the crossing, and left bottom picture was taken on the south part of the crossing. This figure showed that the piece of pavement which received higher solar radiation had more cracking than the piece of pavement which received lower solar radiation.

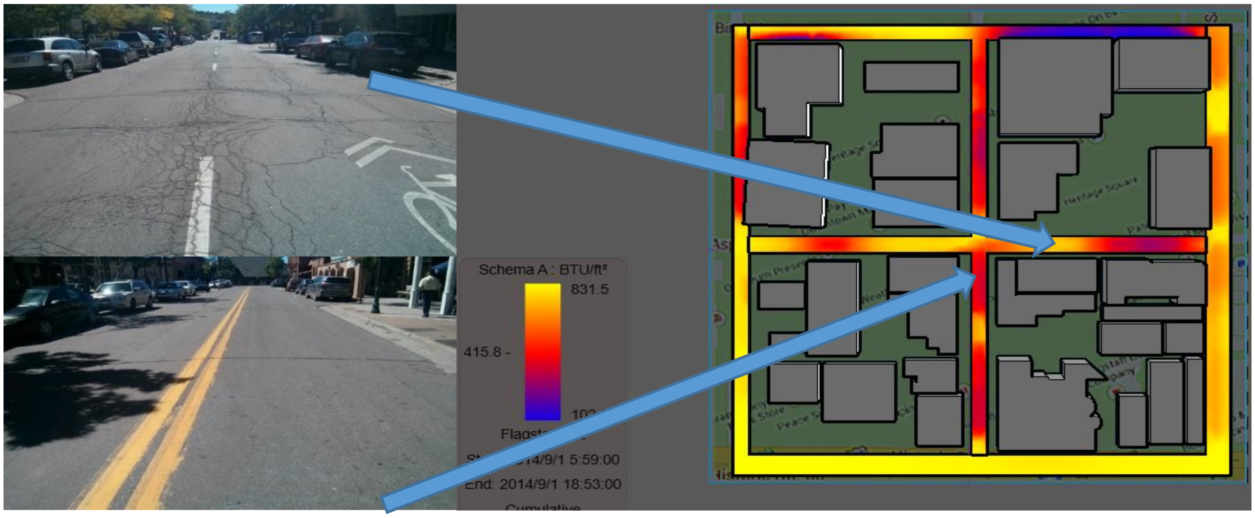


Figure 9. Field Observation and Location

The field observation matched the solar radiation graph, which mean the hypothesis was approved by field observation.

7. Conclusion

In this paper, software was the most important tools used to prove two basic concepts.

Autodesk Vasari was used to gather solar radiation data online and make a simulation of a real building model. After comparing with the field observation, the result approved that shadowed and unshadowed pavements caused by the geometric location of roads could have a significant impact on the heat energy absorption and thermal stress calculation.

At the same time, Solidworks was used to build a model of pavement with its real physics properties. With a controlled trail, the result showed that pavement stresses are obviously influenced by solar radiations, surface temperature changes, and wheel pressures. Under the same solar radiation and surface temperature condition, adding traffic loading led to larger stress. Under the same traffic loading, higher surface temperature led to larger stress. This conclusion matched two major reason of pavement cracking: thermal cracking and fatigue.

These results could be used in civil engineering area to make a simulation of solar radiation and traffic loading stress. Urban planning and design could use these results to design the city properly to control asphalt pavement cracking.

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