Relationship between Asphalt Composition and Thermal Behaviour for Solar Energy Collection

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***Abstract*—Using asphalt to harvest solar energy is an ideal and sustainable solution to the problems involved with increasing energy demand and using fossil fuels. Asphalt has the most heat absorbent colour and is already covering large surfaces in and between urban areas. Asphalt solar collection systems have not been implemented on a large scale worldwide. This is because the current energy/heat collection efficiency does not outweigh the costs involved in constructing on road level and under/within adjacent buildings which can use the energy. This paper is based on testing and evaluation of variations in asphalt composition which can provide a greater quantity of energy/heat in a given time, to increase effectiveness of energy collection to make this system more feasible. Also there is a discussion of other research on asphalt thermal properties, characteristics and factors other than asphalt involved in energy collection. The potential application of this research is also discussed in this paper. The results showed that an increase of 1% in bitumen can increase the maximum temperature of asphalt by almost 14%. In addition, decreasing void ratio, using other aggregates and larger aggregate sizes can increase the maximum temperature and thermal conductivity.**

***Index Terms*—solar, thermal, energy, asphalt, road.**

I. INTRODUCTION

Asphalt roads and surfaces have the potential to efficiently collect solar energy from the sun. Energy is simply not being used and stored for later use in most cases. With the increase in population, there is an ever-growing demand for energy. Fossil fuels are becoming rarer and more expensive and they cause environmental issues. Therefore, there is a need for more research and implementation of sustainable energy production. Australia has an abundance of sunlight with the highest average solar radiation per square metre of any continent in the world [1]. Therefore, there is an unmatched, and largely untapped potential for harvesting the sun's energy in this country.

Periodically, asphalt roads and other asphalt surfaces are demolished and repaved, so a solar collection system can hypothetically be installed and implemented without an overly significant strain on construction time and cost. However, low efficiency of solar energy absorption is a hurdle which needs to be overcome for asphalt solar collection to compensate for the installation and maintenance costs. The testing and research discussed in this paper are to assist in making this system more efficient and therefore more feasible to implement on a large scale to provide alternative and fully sustainable energy.

This paper is structured as follows. The following section explains the relevant existing research. The methodology used in this research is explained afterwards. Then, the outcomes are presented and discussed. The final section summarizes the results of this paper and provides directions for future research.

II. RELEVANT EXISTING RESEARCH

A. Factors for Thermal Performance in Asphalt

Properties of the finished asphalt are the most important factors in this type of solar collection. The whole process begins with the asphalt surface being heated by the sun, so that if the asphalt has unfavourable properties leading to slow heating rate, low maximum temperatures and bad heat storage, there will be very little energy to gain.

1) Thermal conductivity

The transfer of heat through asphalt plays a significant role in the operation of the heat transfer system. Regardless of the high temperature at the surface, if we are unable to reach the asphalt at the depth of the collection pipes then energy cannot be collected. According to Gui *et al*. [2, 3], when the asphalt has a high thermal conductivity, heat obtained from solar radiation can be transferred quickly away from the surface and consequently absorbed deeper into the ground. The positive effect of increased conductivity is also supported by Shaopeng *et al*. [4] who claimed that using aggregates with high conductivity could benefit heat capture efficiency according to their small-scale tests.

However, Gui *et al*. [2] added that the average maximum temperature decreases as thermal conductivity increases. This means that while high conductivity can be beneficial to heat collection, a careful balance needs to be found because the obtained energy largely depends on good maximum temperatures and not only high quantities of low temperatures collected.

2) Volumetric heat capacity

Volumetric heat capacity is simply the ability of something to store energy as the temperature changes, and this plays an obvious and important role in a heat collection system. As this attribute grows, there is an increase in energy storage and thermal mass, slowing the rate at which the temperature in the asphalt increases [2].

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For the purpose of energy collection volumetric heat capacity of the asphalt should be controlled, so there are no lengthy delays between the asphalt gaining high temperature/energy and collection of the energy.

3) Thermal diffusivity

This attribute is the ratio of the thermal conductivity to volumetric heat capacity, which is used to determine the rate at which heat travels or spreads through the substance (asphalt in this case). Gui *et al*. [2] found that maximum surface temperature decreases as diffusivity increases. Since this is a ratio, we can either increase thermal conductivity or decrease volumetric heat capacity (or a combination of both) to increase temperatures and thus energy gained.

4) Albedo

Albedo is the reflectivity of the road surface, measuring the ratio of reflected radiation energy from the surface to the incoming solar radiation. Since this solar radiation is the source of heat of asphalt, it has an important effect on the heat/energy collection system. Gui *et al*. [2] explain that higher albedo values mean more energy is reflected from the surface which means that less energy is absorbed into the roads. This is due to less energy being absorbed which means less heat. Therefore, a solar-based heat collection system would need the surface of the road to have low albedo/reflectivity for it to be effective (the use of spray on, non-reflective finishes may be quite useful and worthwhile in some cases).

5) Emissivity

The emissivity of a surface is the ratio of radiation emitted to the radiation emitted by a blackbody while both are at the same temperature. It is found that surface temperatures (consequently temperatures at depth) tended to decrease as emissivity increased [2], [3]. This is due to the fact that if the asphalt is releasing the energy, less heat is being retained. However, Shaopeng *et al*. [4] argue that solar collection from asphalt would involve a balance between emissivity and conduction heat transfer from the surface downwards. This means a higher or lower emissivity may not be a necessarily good or bad indicator, depending on the amount of heat transfer.

Hermansson [5] found that an emissivity 0.85 and 0.90 has high performance. Therefore, a more effective heat collection system would be more effective if the asphalt surface had low emissivity. However, the importance of emissivity can change depending on heat transfer and perhaps other factors.

From the sources investigated, only considered all of the previously mentioned properties and factors related to heat collection and retention. According to Gui *et al*. [2], in maximum temperature, the most significant effect on asphalt was albedo.

B. Other Factors

The properties of asphalt are not the only significant attributes to consider when using asphalt surfaces to collect heat. There are other factors which could play quite an important role in the system's efficiency and effectiveness. Those factors include: wind speed and water velocity in the collection pipes.

1) Wind

In regards to the effects of wind it is important to consider how much does a windy day affect temperatures and energy collection. It may worth having the system installed in places with regular high winds. However, it is better to reduce wind in smaller easily manageable areas such as partially enclosed car parks, and so on.

According to Gui *et al*. [2], cooling of asphalt is mainly due to the convection heat transfer that happens at the surface because of wind velocity. In support of the importance of wind, Hermansson [5], states that maximum surface temperature is mainly dependant on wind velocity (Fig. 1).

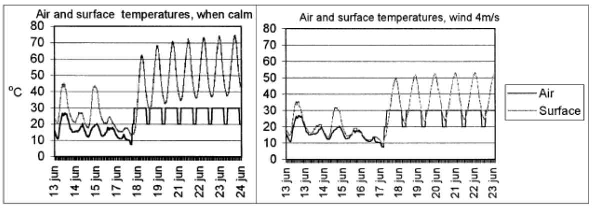

Figure 1. Simulation model for calculating pavement temperatures including maximum temperature [5].

The views of the above sources and the test data displayed above shows that the velocity of wind is a significant factor in the success of the solar collection system, where unsurprisingly more wind means lower temperatures of the asphalt.

2) Water velocity

Water velocity in the heat collection pipes could have an effect on the overall system. For instance, water with slow velocity, can waste a potential for more energy gain from hot asphalt. Meanwhile, water with high velocity is more expensive to operate and high flow might keep the asphalt too cold for energy collection.

According to Hasebe *et al*. [6] and Shaopeng *et al*. [4], velocity of the fluid was found not to have a high significance on the energy collection. This shows that a lower velocity which is cheaper and takes less energy to run could still result in good heat collection. However, Shaopeng *et al*. [4] mentioned that the time that water starts running is of importance. Where the asphalt is at a higher temperature, better energy can be gained. This is an interesting view which could be significant in finding the optimum times/temperatures to have the water flow and collect the heat energy.

III. Methodology

As previously stated, the purpose of this research is to quantitatively determine the changes in thermal behavior (e.g. rate of heating, maximum temperature, transferral of heat through the sample) between different asphalt samples, and identify the causes of those changes. To most clearly demonstrate this and determine the cause of changes in thermal behavior, each sample is only changed in one attribute where possible, tested and then results are compared to the standard/control sample. The samples are as follows:

- Control 1 (a standard mix, granite coarse aggregate, sand, dust, lime, 14 mm maximum aggregate size, 5% bitumen, 5% voids),
- Control 2 (same as above, made to ensure that results and conclusions made are more valid, also to indicate how much error may be expected in the results),
- Higher Bitumen (6%),
- Lower Bitumen (4%),
- Higher Voids (8%),
- Lower Voids (2%),
- Different coarse aggregates (Basalt coarse aggregate, aggregate makes up the majority of asphalt, different rocks have different thermal properties),
- 10 mm Sample (maximum aggregate size),
- 7 mm Sample (maximum aggregate size).

To make each of the above mentioned nine asphalt samples the following steps are used.

Step 1: Create mix design (determine ingredients and necessary proportions of each),

Step 2: Carefully weigh the different aggregates and heated bitumen and place into mixing bowl,

Step 3: Mix for two minutes in the mechanical combiner,

Step 4: Place into the oven at 180 degrees for at least twenty minutes or until mixture is workable,

Step 5: Place desired weight of mixture into the cylindrical formwork,

Step 6: Place into the compaction machine and compact until the desired compaction is achieved (displayed on the monitor),

Step 7: Remove sample from formwork and leave to cool,

Step 8: When cool, label sample with crayon/chalk,

Step 9: Before testing, drill holes from the side of the sample to the centre, at depths of 25 mm and 50 mm,

Step 10: Measure and cut polystyrene insulation to fit sample, with only top surface exposed, drill holes for thermocouple wires to align with holes in samples, cover outer surface of insulation with aluminium foil.

After making the samples, they should be tested for their ability in heat absorption. Sample testing is done by the following steps.

Step 1: Turn on lamp at a safe distance away from sample, for the heat source to stabilize,

Step 2: Place the sample into the insulation so that only the top surface is exposed,

Step 3: Insert one end of the thermocouples (insulated wires) near the surface on 25 mm of insulation, at the surface of the asphalt, at 25 mm depth and at 50 mm depth,

Step 4: Secure the thermocouples with duct tape and close off any remaining gaps in insulation with duct tape to prevent air flow,

Step 5: Make sure the other ends of the thermocouples are in one of the thermocouple ports for electronic thermometer which is then connected to the thermal data taking equipment, which in turn connects to the computer,

Step 6: Open and set up the data recording program on the computer and set parameters – in this case, record temperatures every minute,

Step 7: Set up lamp and allow it to heat up until a constant temperature is reached and determine the distance of the lamp heat source from the sample's surface at which the air temperature is 45℃ (the temperature will vary by approximately ± 2℃ from 45 degrees during the test, which is acceptable.) In this case the distance for this temperature is 108 mm from the sample, using a 72 Watt Halogen bulb,

Step 8: Measure and record the temperatures of the thermocouples in contact with the sample as well as a thermocouple for air temperature above sample. This is to keep a check on the consistency of the heat source as well determine if there is a significant change in ambient temperature/wind. This thermocouple is on 25 mm of polystyrene insulation placed on the sample, so heat coming off the sample has minimal effect on the readings,

Step 9: Surround the sample with cardboard walls or a similar solid material to reduce effects of indoor drafts/wind which may affect temperature,

Step 10: Make sure the lamp is at the correct height so the heat source would be at a distance of 108 mm, and that the heat has more or less stabilised at the correct temperature of 40℃,

Step 11: Start the temperature recording program to record the temperature of the sample and air before heat is applied, then put heat source above the sample,

Step 12: Continue the test for 180 minutes, with the program recording temperatures every minute,

Step 13: After the time has elapsed stop and switch off all equipment,

Step 14: Transfer data collected into excel and tabulate/graph results.

IV. Results and Discussion

Sample 1 was the first control sample, with normal grading, 14 mm mix (maximum aggregate size 14 mm), 5% bitumen content and 5% voids. This will be treated as the 'normal or standard' mix produced in Melbourne, to compare the other results and samples to. The maximum temperature reached was at the full testing time of 180 minutes, and was 52.88℃ at Depth 1 (25 mm) and 51.17℃ at Depth 2 (50 mm). This gives an indication of maximum heat/energy available in the asphalt at the given temperature (Fig. 2).

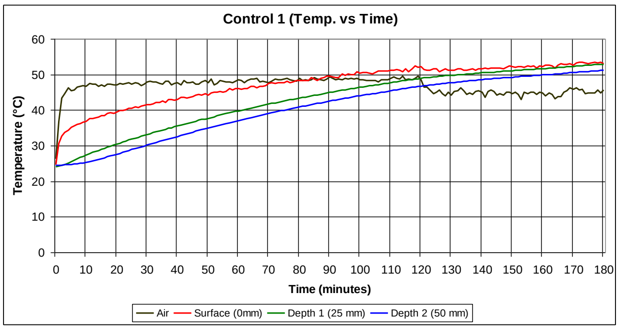

Figure 2. (Sample 1 – Control 1, testing duration of 180 minutes).

Next, at D1 the final 10 minute period in which the temperature changed at least one degree was between 117 minutes and 127 minutes, and for D2 was at 119 and 129. The maximum temperatures at these points were 49.61 ℃ and 47.60 ℃ respectively. This demonstrates a potentially effective time to allow the asphalt to collect solar energy before energy collection begins, at depths of 25 mm and 50 mm. Whether the energy collecting process begins at this point, or at a particular temperature or regular automatic time would depend on the energy needs and capabilities of the area for which it is being used. It can also be seen that the air and surface temperature constantly fluctuate slightly, while the gradients for the temperature increase within the asphalt is steadier. Furthermore the thermocouple measuring air temperature appeared to start experiencing cooling most likely due to wind from a nearby fan, however the sample itself was more protected from wind so results are still valid.

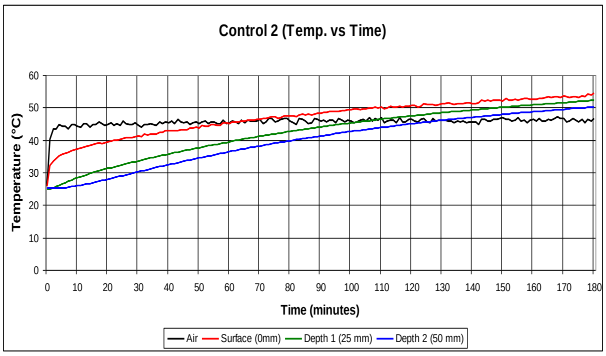

Figure 3. (Sample 2 – Control 2, testing duration of 180 minutes).

Sample 2 was the second control sample, again with normal grading, 5% bitumen content and 5% voids. The maximum temperature reached was at the full testing time of 180 minutes, and was 52.16 ℃ at Depth 1 (25 mm) and 50.13 ℃ at Depth 2 (50 mm). These results are quite close to Control 1, but since the air temperature was more consistent here, these results will be used for numerical comparison with other samples (Fig. 3).

At Depth 1 the final 10 minute period in which the temperature changed at least one degree was between 113 minutes and 123 minutes, and for Depth 2 was at 124 and 134 (again quite similar to Control 1). At this time, for D1 the temperature reached 47.73 ℃, and for D2 it reached 46.43 ℃.

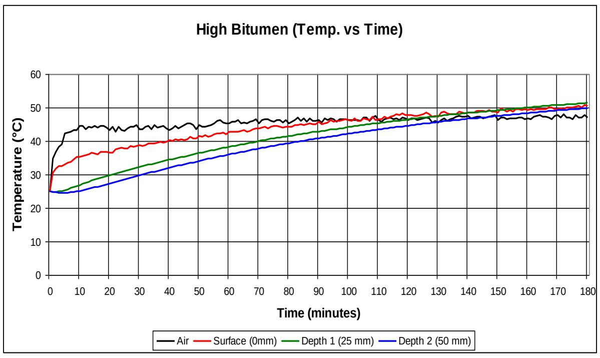

Figure 4. (Sample 3 - High Bitumen Content, testing duration of 180 minutes).

Sample 3 was the same as the control samples, but with 6% bitumen rather than 5%. Bitumen content is potentially the most significant aspect involved in temperature difference of asphalt, as it is black (and this highly heat absorbent) and covers and fills the aggregates. There is still normal grading and 5% voids. The maximum temperature reached was at the full testing time of 180 minutes, and was 51.39 ℃ at Depth 1 (25 mm) and 49.80 ℃ at Depth 2 (50 mm). Then, at D1 the final 10 minute period in which the temperature changed at least one degree was between 128 minutes and 138 minutes reaching a temperature of 47.24 ℃, and for D2 was between 130 and 140 reaching 45.68 ℃ (Fig. 4).

Sample 4 varies from the control samples by having lower bitumen content, with 4% bitumen rather than 5%. There is still normal grading and 5% voids. The maximum temperature reached was at the full testing time of 180 minutes, and was 49.89 ℃ at Depth 1 (25 mm) and 48.53 ℃ at Depth 2 (50 mm).

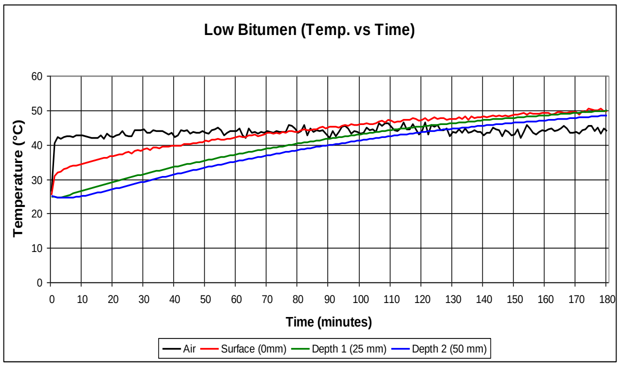

Figure 5. (Sample 4 – Low Bitumen Content, testing duration of 180 minutes).

Then, at D1 the final 10 minute period in which the temperature changed at least one degree was between 115 minutes and 125 minutes with a maximum temperature reached being 44.78 ℃, and for D2 was between 118 and 128 with temperature 43.40 ℃ (Fig. 5).

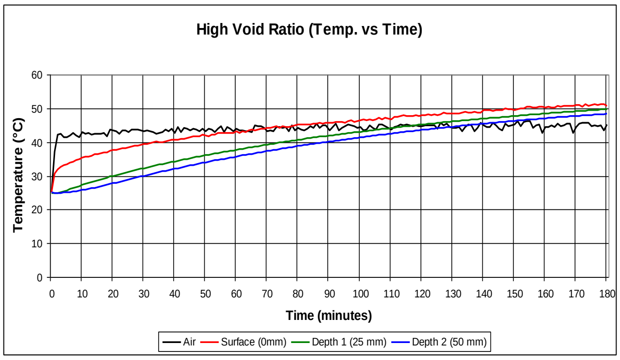

Figure 6. (Sample 5 – High Void Ratio, testing duration of 180 minutes).

Sample 5 differs to the control samples with its high void ratio with 8% voids rather than 5% of previous samples. Void ratio is defined as the volume of voids divided by the volume of solids (then multiplied by 100 to display voids as a percentage for easier comparison.) This is significant because it determines how much space there is between the aggregates and generally how much air voids are in the sample compared to solids and air is a poor conductor of heat especially compared to asphalt (Fig. 6). The maximum temperature reached was at the full testing time of 180 minutes, and was 49.71 ℃ at Depth 1 (25 mm) and 48.36 ℃ at Depth 2 (50 mm).

Also, at D1 the final 10 minute period in which the temperature changed at least one degree was between 113 minutes and 123 minutes with a peak temperature of 44.47 ℃, and for D2 was between 116 and 126 with peak temperature of 43.17 ℃.

Sample 6 has a lower void ratio, with 2% voids rather than 5% voids of the control and standard mixes. This could mean that heat is more effectively absorbed and have an increased thermal conductivity due to less air in the sample. The maximum temperature reached was at the full testing time of 180 minutes, and was 54.63 ℃ at Depth 1 (25 mm) and 53.22 ℃ at Depth 2 (50 mm).

Then, at D1 the final 10 minute period in which the temperature changed at least one degree was between 118 minutes and 128 minutes with a peak temperature of 49.68 ℃, and for D2 was between 123 and 133 with a peak temperature of 48.39 ℃ (Fig. 7).

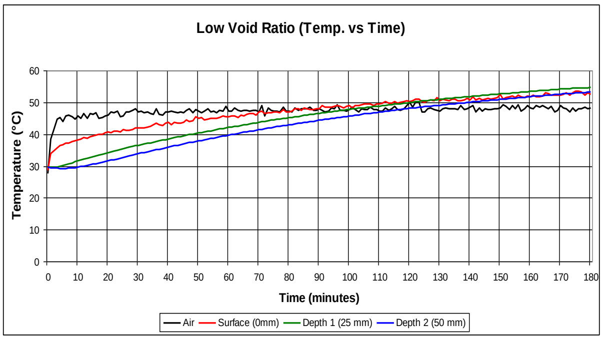

Figure 7. (Sample 6 – Low Void Ratio, testing duration of 180 minutes).

Sample 7 contains Basalt coarse aggregate rather than the Granite used in the control, and indeed every other sample. Different rocks have different thermal properties, and coarse aggregate makes up a large portion of asphalt, so this could have a significant effect on the thermal performance of the finished asphalt. The maximum temperature reached was at the full testing time of 180 minutes, and was 54.10 ℃ at Depth 1 (25 mm) and 51.93 ℃ at Depth 2 (50 mm).

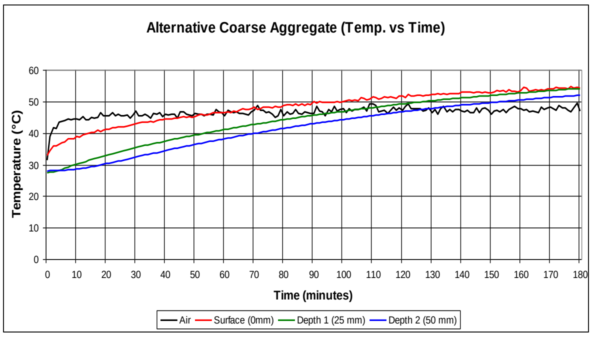

Figure 8. (Sample 7 – Alternative Coarse Aggregate, testing duration of 180 minutes).

Then, at D1 the final 10 minute period in which the temperature changed at least one degree was between 124 minutes and 134 minutes with a peak temperature of 49.59 ℃, and for D2 was between 130 and 140 with a peak temperature of 47.82 ℃. In contrast, the control sample (Fig. 8).

Sample 8 has a smaller maximum size of aggregate, and a resulting smaller size of all other coarse aggregates used. This will help show the relation between amount and size of rocks (coarse aggregate) in asphalt and thermal performance of finished asphalt. The maximum temperature reached was at the full testing time of 180 minutes, and was 53.00 ℃ at Depth 1 (25 mm) and 51.65 ℃ at Depth 2 (50 mm).

Then, at D1 the final 10 minute period in which the temperature changed at least one degree was between 149 minutes and 159 minutes with a peak temperature of 50.16 ℃, and for D2 was between 152 and 162 with a peak temperature of 48.97 ℃. In contrast, the control sample (Fig. 9).

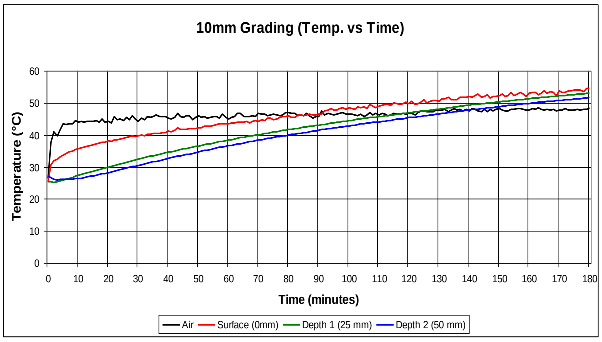

Figure 9. (Sample 8 – 10 mm Mix: Alternative Aggregate Sizing, testing duration of 180 minutes).

Sample 9 has an even smaller maximum size of aggregate, and a resulting smaller size of all other coarse aggregates used. This will further show the relation between amount and size of rocks (coarse aggregate) in asphalt and thermal performance of finished asphalt. The maximum temperature reached was at the full testing time of 180 minutes, and was 54.88 ℃ at Depth 1 (25 mm) and 53.16 ℃ at Depth 2 (50 mm). Compared to the control sample,

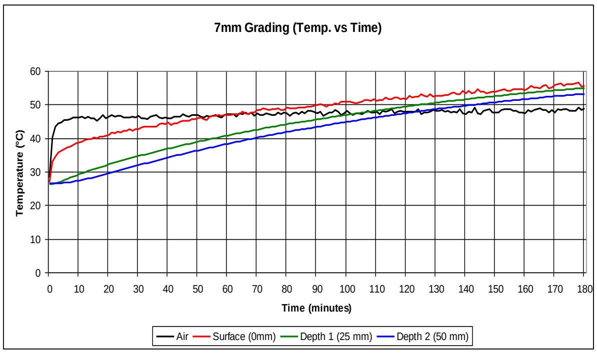

Figure 10. (Sample 9 – 7 mm Mix: Alternative Aggregate Sizing, testing duration of 180 minutes).

Also, at D1 the final 10 minute period in which the temperature changed at least one degree was between 135 minutes and 145 minutes with a peak temperature of 51.04 ℃, and for D2 was between 144 and 154 with a peak temperature of 50.06 ℃. In contrast, the control sample (Fig. 10).

TABLE I. MAXIMUM TEMPERATURES AT DEPTH 1 AND DEPTH 2.

	Maximum Temperature Recorded (℃)								
Sample Number	1	2	3	4	5	6	7	8	9
Depth 1 (25 mm)	52.9	52.2	51.4	49.9	49.7	54.6	54.1	53.0	54.9
Depth 2 (50 mm)	51.2	50.1	49.8	48.5	48.4	53.2	51.9	51.6	53.2

According to the results, the maximum temperature at Depth 1 of 25 mm was found in Sample 9 with a temperature of 54.88 degrees Celsius, closely followed by Sample 6 with a temperature of 54.63 Degrees Celsius. For Depth 2 of 50 mm the maximum was found in samples 6 with 53.22 degrees Celsius, closely followed by sample 9 with a temperature of 53.16 degrees Celsius (Table I). This demonstrates that sample 9 with 7 mm maximum grading and sample 6 with lower void percentage of 2% would be more suitable for heat collection. Sample 6 appears to have slightly better thermal conductivity than sample 9 which could suggest that it may be less suitable in areas with a tendency of high or frequent winds. Furthermore, sample 7 with a basalt coarse aggregate instead of granite, makes the next most significant difference in increased maximum temperature.

Both higher and lower bitumen content samples performed worse than the controls, meaning either an error in testing or fabrication, or a delicate balance in heat transfer at a bitumen content of 5%. That said, the higher bitumen content sample performed better than the lower bitumen sample, and assuming a linear relationship between bitumen content and maximum temperature, the high bitumen content sample would theoretically have had an approximate temperature of 55 degrees, proving to be the most significant factor.

V. CONCLUSIONS

For this system to have a chance to become common and to be widely used in the near future, more engineering companies should be made aware of what the system is capable of achieving. More interest in the system means more engineers can be given the time and funding for research and development to make the system and benefits even more worthwhile.

This system collects heat energy from asphalt and cooling pavements in turn cools surrounding areas and reduces energy and water consumption used for cooling. Electrical energy use was found to increase by two to four percent for every one degree (Celsius) rise in daily maximum temperature above fifteen to twenty degrees Celsius. Hotter air also leads to an increased rate of smog ozone production which has been found to have some serious effects on the environment and even health of people.

In conclusion, there are numerous factors involved in the success of the system including asphalt properties as well as other factors with albedo and wind speed being the most significant respectively. Furthermore, it has been observed that there are additional benefits involved in the use of this system, most notably the cooling of busy cities, and the numerous monetary. Lastly, testing conducted for this paper and the results have demonstrated the slight change of a single value or property in the mix design and finished asphalt can have significant effect on thermal properties/behavior. The results of the testing conducted showed that the most significant increase in maximum temperature would result from (in order): potentially increasing bitumen content, reducing grading/aggregate sizes, lowering void ratio and using Basalt instead of Granite which are both common coarse aggregates used locally.

Repeating this research and testing the samples in other cities with different weather conditions will be a future research direction. Furthermore, using different sample sizes/shapes and with more variety of asphalt attributes can be the future direction of this research.

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