ACHIEVING SUSTAINABILITY WITHOUT COMPROMISING LONG-TERM PAVEMENT PERFORMANCE FOR ROAD INFRASTRUCTURE ASSETS

Waheed Uddin *
Professor and Director, Center for Advanced Infrastructure Technology, The University of Mississippi, USA
* Carrier 203B, The University of Mississippi, University, MS 38677-1848, USA cvuddin@gmail.com

Zul Fahmi Mohamed Jaafar
PhD Student, CAIT, University of Mississippi; Formerly, USM Engineering Campus, Penang, Malaysia

ABSTRACT: This paper reviews current aspirations to achieve sustainability goals in asphalt pavement technology by reducing consumption of energy and natural resources. Recycled asphalt pavement is required in 10-20% for asphalt paving by many US state highway agencies. Warm mix asphalt is being promoted worldwide in the quest of reduced energy consumption. Many such paving technologies claim environment friendly and high sustainability ratings, sometimes without analyzing long-term effects on performance and useful life of these asphalt pavements. Questions arise if top-down cracking and rutting distresses are caused by reduced asphalt binder content in the top layer, faster binder aging, and/or the use of recycled asphalt pavements. In practice there are high uncertainties in traffic predictions and high spatial and seasonal variability in subgrade soil properties, which are shown to affect thickness design as well. This paper discusses several sustainable highway practices that can reduce “heat-island” effects and emissions.

KEYWORDS: Sustainability, asphalt, pavement, road, top-down cracking, life cycle analysis

1. INTRODUCTION

Efficient and safe transportation infrastructure assets are imperative for public mobility, commuting for work and school, freight transport, and emergency management during disasters. About 80% of the population living in industrialized nations and more than 50% living in developing countries now live in cities and urban areas. In the United States, 65% of goods originate or terminate in cities. It is estimated that nearly 10% of the nation’s gross domestic product (GDP) are related to freight logistics at an annual expenditure of a trillion dollars by the US companies collectively [1]. Paved road density per million of population is an indicator of mobility with the US leading most industrialized countries. Intercity traffic flow performance depends upon the capacity of connecting highway networks. The US interstate and other primary highway density is 0.023 km per km², just 17.4% more than the federal and primary highway density in Mexico. If pavement condition is in fair to poor condition, then economic costs will be significantly higher. These costs include vehicle operating costs, congestion cost due to delays and fuel wastage, and environmental costs due to greenhouse gas (GHG) and other harmful emissions [2]. Because of these concerns, construction of asphalt and concrete roads for sustaining long-term pavement performance is imperative for safe and efficient transportation flow. Additionally, evaluation of infrastructure construction, maintenance, and usage with respect to environmental impacts are equally as important considering public awareness of environmental sustainability issues.

1.1 Objective and Scope
The primary objective of this paper is to discuss environmentally sustainable road construction and maintenance strategies which may be competing with long-term pavement performance attributes of surface distresses (cracking and rutting), roughness, structural capacity, skid resistance, and noise. The scope of study is limited to asphalt pavement technologies and reuse of waste glass for pavement marking applications.

Many states in the US and other countries in tropical and temperate climates are reporting top-down cracking as a common distress in asphalt pavements, in addition to rutting. Are these distresses caused by environmental degradation of asphalt binder content in the top layer and faster binder aging? Is the use of recycled asphalt pavement (RAP) leading to accelerated deterioration of asphalt pavements on heavily trafficked roads as it uses aged binder in the mix? These questions need to be addressed by pavement researchers. Warm mix asphalt...
WMA has shown to reduce short-term energy needs, but only limited performance data compared to traditional hot mix asphalt (HMA) and no data was found related to long-term impacts on GHG emissions [3,4].

1.2 Research Methodology
The following key steps were taken to understand the best strategy for achieving environmental sustainability in selecting pavement construction and maintenance treatments while still contemplating long term pavement performance goals:

- Think “outside the box” to find opportunities for pavement related conservation of natural resources to accomplish broad sustainability goals.
- Evaluate effects of spatial variability of pavement layer modulus on thickness design.
- Analyze effects of seasonal variability of pavement layer modulus on thickness design.
- Examine effects of spatial variability in asphalt pavement layer thickness on pavement design.
- Investigate effects of RAP and WMA paving technologies on sustainability impacts and long term pavement performance.
- Study innovative strategies to construct sustainable pavements and reduce heat-island effects of GHG emissions and energy consumption.

2. “OUTSIDE THE BOX” THINKING TO ACHIEVE SUSTAINABILITY
Sustainability is associated with a construction and maintenance method that can be implemented without excess demand on natural resources and exogenous impacts on GHG emissions. A sustainable preservation and development measure meets the needs of the present generation without compromising the ability of future generations to meet their own needs [2,5].

2.1 Opportunities for Conservation of Natural Resources
Environmental preservation and sustainability goals with respect to transport infrastructure can be established by adapting the following conservation policies: reclaim, recycle, reuse, and reduce (4R).

- Reclaim: Examples are milling of asphalt pavement and rubblization of concrete pavement
- Recycle: Recycling of milled reclaimed asphalt pavement material, such as 10% RAP in HMA
- Reuse: Reusing reclaimed concrete from rubblized pavement and demolished buildings; waste tire
- Reduce: Reducing consumption of raw materials (recycling aggregate) and energy such as WMA

These aspects of the environment protection and sustainability are important to plan and implement mitigation strategies and international efforts on reducing GHG emission [6]. Key examples of successful uses of sustainable paving technologies are RAP and WMA for asphalt paving, reusing reclaimed concrete and waste tire rubber in asphalt, and industry waste products (such as flyash, cement kiln dust, and steel slag). Table 1 data shows the annual amount of road related new and recycled construction materials used in the United States. Eventually any success of a candidate 4R technology depends upon the research support and adaptation of associated public policies by highway and public works agencies.

The Washington State Department of Ecology collects data on tire recycling and reuse [7]. The reported recycling, reuse, and disposal data for 2002 to 2011 shows that: “The total estimated number of waste tires generated in 2011 is over 5 million tires. An estimated total 87,974 tons of waste tires was generated in 2011. The total reported tire disposal, recycling, and reuse in Washington for 2011 includes: 7,813 tons retreaded (12%), 30,374 tons recycled (48%), 10,450 tons used for fuel (23%), and 14,156 tons landfilled (17%). (One ton of tires is about 100 passenger car tires).” The countrywide efficient collection and disposal of waste tires have been possible due to the public policy associated with “reducing waste” by auto service and maintenance businesses. The policy has been adopted and enforced by the Environmental Protection Agency (EPA) in the United States.

Use of Waste Tire Rubber: One of the successful examples of incorporating waste products in the road industry is the use of waste rubber tires to modify asphalt binders. It is estimated that around 300 million waste tires are produced annually in the US [8]. Since the 1980s rubber modified asphalt was used extensively in
Arizona. In Mississippi field trials on interstate I-55, rubber-modified asphalt outperformed virgin asphalt and other polymer-modified asphalt sections with respect to rutting [9]. ASTM standards [10] were produced in the 1990s and 2000s with 15 percent recommend rubber content in asphalt binder. By mid-2001, over 210 rubber-asphalt highway projects had been constructed throughout California. It was also used by municipalities and counties for hot mixes and surface treatments with generally good performance. However some of the old problems with product selection, design, and construction continue to arise and some projects reportedly experienced several major rubber asphalt failures [11]. Unit costs for asphalt rubber construction projects were initially high because in the late 2000s both rubber- asphalt and traditional HMA costs were close to $5 per sq. yd. according to Arizona data [8].

### Table 1. Examples of construction materials used in the United States

<table>
<thead>
<tr>
<th>Material</th>
<th>Capacity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waste Materials in United States</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Tire Rubber (Not recycled)</td>
<td>4.87 Million Tons (2009)</td>
<td>RMA [14]</td>
</tr>
<tr>
<td>Used glass</td>
<td>11.5 Million Tons (2010)</td>
<td>EPA [15]</td>
</tr>
<tr>
<td>Concrete</td>
<td>200 Million Tons Annually</td>
<td>EPA [16]</td>
</tr>
<tr>
<td>Sand</td>
<td>6 - 10 Million Tons Annually</td>
<td>FHWA [17]</td>
</tr>
<tr>
<td><strong>Use of New, Recycled, and Waste Materials for Roads</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total RAP Recycled</td>
<td>72 Million Tons (2010)</td>
<td>CC [18]</td>
</tr>
<tr>
<td>Asphalt (Interstate highways only)</td>
<td>35 Million Tons</td>
<td>USGS [19]</td>
</tr>
<tr>
<td>Concrete (Interstate highways only)</td>
<td>48 Metric Tons</td>
<td>USGS [20]</td>
</tr>
<tr>
<td>Aggregate</td>
<td>2 Billion Tons</td>
<td>FHWA [21]</td>
</tr>
<tr>
<td>Steel Slag</td>
<td>7.5 Million Tons</td>
<td>FHWA [22]</td>
</tr>
<tr>
<td>Steel (Interstate highways only)</td>
<td>6 Metric ton</td>
<td>USGS [23]</td>
</tr>
<tr>
<td>WMA</td>
<td>47.6 Million Tons (2010)</td>
<td>NAPA [25]</td>
</tr>
<tr>
<td>Glass beads for road marking</td>
<td>200 Million Gallons</td>
<td>AU [26]</td>
</tr>
<tr>
<td>Thermo plastic materials</td>
<td>60 Tons (Interstate only)</td>
<td>AU [27]</td>
</tr>
<tr>
<td>Waste tire rubber (small fraction used in asphalt pavements)</td>
<td>300 million scrap tires annually (estimate)</td>
<td>RPA [28]</td>
</tr>
</tbody>
</table>

**Waste Roofing Shingle:** As stated in reference [13]: “It is estimated that between 8 million and 12 million tons of roofing shingles are manufactured each year in the United States. Since approximately 65 percent of these shingles are used for re-roofing, between 5 million and 8 million tons of old wasted shingles are produced annually. In addition, between 400,000 and 900,000 tons of waste are produced annually from the manufacturing of roofing shingles.” Several studies have focused on the use of reclaimed roofing shingle waste in HMA as an asphalt highway pavement material. Again, a real life cycle cost and benefit analysis should look into the extra energy involved in blending with HMA and any detrimental effect on pavement performance before making a policy guideline like RAP usage policy implemented by highway agencies.

**Reusing Waste Glass:** Based on Table 1 literature search, here are some interesting facts about waste glass: “Glass makes up approximately 7 percent -- approximately 12 million tons -- of the total weight of US municipal solid waste discarded annually. Approximately 20 percent of this glass is being recycled, primarily for cullet in glass manufacturing. The ability to use glass in highway construction depends on the type of collection methods used, costs, and public factors. In general, the large quantities of waste glass needed for such application are found only in major metropolitan areas. Many agencies have experimented with glass in highway construction. Much of the current research in this area focuses on the use of glass as coarse aggregates in asphalt pavements.”
There is a large amount of waste glass available for recycling and reusing. Pavement technologists’ concerns are the poor bonds with asphalt films around glass aggregates, which may lead to asphalt stripping and degradation of asphalt layers, as well as reduction of skid resistance of pavement surface due to glass slipperiness. But “thinking outside the box” approach can lead to a great opportunity for using waste glass in road markings as glass beads and as partial replacement of fine aggregate (in sand size) for increased reflectivity and other favorable optical and thermal properties. This “outside the box” approach is discussed later because it involves minimal consumption of energy and processing of raw materials and lower GHG emissions, as well as, reducing “heat-island” effects.

2.2 Examples of Sustainability Practices in Pavement Technologies and Long-Term Performance

Use of Reclaimed Asphalt Pavement: Increased environmental awareness and enforcement of stricter emissions regulations have led to intensive research towards warm asphalt. Numerous benefits have been reported on this technology, cold weather paving, compaction aid, longer haul distances, and use of higher percentages of RAP [29]. Since the adaptation of Superpave asphalt material specifications by most US highway agencies in the 1990s, RAP has been implemented in asphalt highway paving projects generally in the amounts of 10-30% of design asphalt content. The intention from sustainability considerations has been good and there is less demand for raw materials. However, possible adverse impacts of mixing of aged binder on long-term pavement performance have not been studied. Are these distresses caused by reduced asphalt binder content in the top layer and faster binder aging? Is the use of RAP leading to accelerated deterioration of asphalt pavements on heavily trafficked roads? These issues are being investigated by the authors.

Use of Warm Mix Asphalt: WMA paving technology, introduced in the US in early 2000s, has been used in over 140 projects in 44 states, using about 20 commercial technologies and shown to reduce short-term energy needs [3,4]. Most reported studies have shown limited performance data from a couple of years, showing rutting performance similar to traditional HMA. A recent study revealed that WMA accounted for 20-30% of the total plant mix produced in the US in 2011 [30]. This is due to WMA’s benefits to agencies and contractors including, lower energy costs, reduced emissions, and enhanced workability even during colder months. It was reported that warm mix asphalt tends to reduce production temperature at 20 to 50°C lower than typical hot mix asphalt and provides better working conditions [29]. The authors also stated that this technology reduced energy consumption, which resulted in lower carbon dioxide (CO₂) emissions. The reported reduction in plant emissions were 31.5 percent and 23 percent in Norway and France, respectively. In the Netherlands, the recorded CO₂ reductions were between 15 – 30 percent, while 30 – 40 percent decrease was observed in Italy [31].

Most researchers are unaware that the CO₂ emissions produced during asphalt production are associated with about heating of 5% asphalt binder, 95% aggregate heating, and pugmill mixing. In reality, the bulk of CO₂ emissions come from the basic process of aggregate production (about 95 percent of traditional paving asphalt mix). This includes blasting and crushing at quarries and transportation to asphalt batch plants. Additionally, asphalt mix transportation to a paving site is among the factors contributing to the largest CO₂ emissions irrespective of the WMA or HMA technologies.

Eco-friendly Permeable Pavement Technologies: Porous asphalt (PA) and pervious concrete are permeable pavement technologies and have been supported by the EPA as “cool” pavements to reduce the effect of heat-island and drain stormwater in an eco-friendly manner. PA wearing courses consist of highly interconnected air voids that allow surface water to flow and eliminate ponding water especially on road surfaces that are exposed to rutting and raveling. Porous asphalt provides good vision by reducing splash and spray on roads during heavy rainfall and reduces noise. PAs require frequent maintenance due to accelerated permeability loss caused by clogging of the air voids, high temperature, and traffic densification [32]. Many states experiencing rutting distress are paving stone matrix asphalt (SMA) or thin SMA overlays at higher construction unit costs. We need to assess performance of these relatively new pavement technologies, such as premature cracking due to binder aging from rapid oxidation, because these are not dense asphalt mixes.
Top-Down Cracking in Asphalt Pavement Related to Poor Asphalt Mix Design and Construction:
Economic competitiveness can be adversely affected due to the increased average travel time and safety risks caused by poor pavement performing with respect to surface distresses, roughness, skid resistance, and noise. These pavement performance attributes may be competing with sustainability goals. In recent 25 years, there has been an alarming increase of pavement distress related to top-down cracking (TDC) in longitudinal wheel path of asphalt pavements. It has been a topic of frequent and continuing discussion between researchers worldwide, mostly focused on the role of binder aging in creating this distress. The cracking distress is further accelerated because of wheel loads and contact stresses. However, an understanding and equipment for nondestructive evaluation at highway speed of this distress type have not yet been established. TDC identification in the field and consideration in pavement design methods are problematic compared to fatigue cracking that is assumed to initiate from the bottom of pavement system.

According to Rolt [33] the top-down cracking was discovered in the late 1970s in UK’s Transportation Research Laboratory (TRL) research, as summarized here. Initially, the severity of this phenomenon was ignored by most of the engineers who did not even discuss this type of distress and claimed that it happened in countries with tropical climates only. In 1980s, similar distress types were observed in England and other European countries. With continuous observation of top-down cracking in France and Holland, the countries with more temperate temperature found that there was considerable evidence of top-down cracking occurrences. The TRL engineers had initiated possible solutions to prevent this cracking problem. From 1973 to 1977, the first asphalt performance study was carried out on eight different sites with varying climatic conditions. The early findings showed that the cracks started from the top and propagated downwards. Similar deterioration was also reported in France, the Netherlands and South Africa. In countries with pavement temperatures 8°C lower, the hardening was approximately 33% of the warmer climates [33]. A recent presentation by Rolt [34] reviews the latest progress associated with longer life pavement research.

In the United States, top-down cracking was discovered in the late 1990s [35,36]. During the 2000s, a lot of research closely related to AASHTO pavement design had been carried out in several states including Florida [37], Michigan [38], and Washington [39]. It was also discovered in Malaysia as observed by the authors of this paper. Uhlmeyer et al. [39], in a study for the Washington State Department of Transportation, discovered that thick asphalt concrete was also susceptible to top-down cracking. These authors noted that top-down cracking occurred typically 3 to 8 years following construction for pavement sections that satisfy structural requirements and were designed for acceptable equivalent single-axle loads. Uhlmeyer et al. [39] concluded that top-down cracking would randomly stretch, especially for asphalt layers with thicknesses surpassing 160 to 180 mm. The observed performance years before the TDC occurred varies from 1 to 5 years (Japan), 3 to 5 years (France), 5 to 10 years (Florida) and up to 10 years for the UK.

Top-down cracking has been assumed to start from the top of the surface by most researchers in Europe and the US [33,34,37,39,40]. However, Japanese investigators reported that TDC occurred somewhere from the middle of the asphalt layer [41]. Wang et al. [42] reported similar findings and states that a mix sensitive to rutting will probably also be sensitive to TDC. The following section describes the results of a parametric study of asphalt thickness design as functions of asphalt modulus and traffic volume.

3. ASPHALT PAVEMENT THICKNESS DESIGN STUDY

This section presents the results of a parametric study of pavement thickness calculated using the senior author’s instructional software based on the 1993 AASHTO asphalt pavement design equation for a given set of unbound layer material’s resilient modulus values and thicknesses, two levels of asphalt resilient modulus, and six levels of cumulative traffic (Table 2) over 20 years of design as number of Equivalent Single Axle Load (ESAL) applications. Traffic levels on local roads are typically 500,000 ESALs or lower, while 1,000,000 ESALs refer to arterial or rural roads (major roads). On highways, the traffic level is estimated at 1,000,000 ESALs and higher.
Table 2. Design input values for the asphalt layer thickness parametric study

<table>
<thead>
<tr>
<th>Common Asphalt Pavement Design Data (High Asphalt Modulus and Weak Subgrade)</th>
<th>Thickness, T</th>
<th>Modulus, E</th>
<th>Other Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>Thickness, in. (cm)</td>
<td>Modulus, psi (MPa)</td>
<td>Design Reliability, R = 90.0%</td>
</tr>
<tr>
<td>1. Asphalt, T₁, E₁</td>
<td>8 in. (20.3 cm) (at 5 million ESALs)</td>
<td>500,000 psi (3,447 MPa)</td>
<td>Overall Standard Deviation, SO = 0.45</td>
</tr>
<tr>
<td>2. Base, T₂, E₂</td>
<td>6 in. (15.2 cm)</td>
<td>40,000 psi (276 MPa)</td>
<td>Design Serviceability Loss, Δ PSI = 2.5</td>
</tr>
<tr>
<td>3. Subbase, T₃, E₃</td>
<td>25 in. (63.5 cm)</td>
<td>15,000 psi (103 MPa)</td>
<td>Design period, n = 20 years</td>
</tr>
<tr>
<td>4. Weak Subgrade</td>
<td>---</td>
<td>2,000 psi (14 MPa)</td>
<td>Assume zero traffic growth</td>
</tr>
<tr>
<td>Drainage Factors:</td>
<td>M₂ = 1, M₁ = 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Six Traffic Levels, ESALs, million:</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

3.1 Effects of Design Traffic Levels and Asphalt Modulus Variability on Asphalt Thickness Design

A preliminary study showed that for a strong subgrade (resilient modulus of 8,000 psi) there is no significant effect of traffic volume variations on asphalt pavement thickness. For weaker subgrade (resilient modulus of 2,000 psi as shown in Table 2) with higher traffic volume thicker asphalt layer is required. Figure 1 shows the predicted asphalt layer thicknesses for higher asphalt modulus value. As the design level of cumulative traffic in number of ESAL applications increase, the required asphalt layer thickness also increases in a nonlinear way. For example, at 0.5 million ESALs, asphalt layer thickness is 5 inches (12.7 cm) and at 100 times more traffic at 50 million ESALS, 140% times asphalt thickness is predicted (12 inches or 30.4 cm). Similar effects are observed at lower asphalt modulus. However, at 50% lower asphalt modulus, required layer thickness is even higher, as follows (Table 3).

Table 3. Design asphalt layer thickness calculated for low and high asphalt modulus and range of traffic

<table>
<thead>
<tr>
<th>ESALs, million:</th>
<th>0.5</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>25</th>
<th>50 million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Modulus: 500,000 psi (high)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt Thickness, in:</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>11</td>
<td>12 inch</td>
</tr>
<tr>
<td>(cm):</td>
<td>12.7</td>
<td>15.2</td>
<td>20.3</td>
<td>22.9</td>
<td>27.9</td>
<td>30.5 cm</td>
</tr>
<tr>
<td>Asphalt Modulus: 250,000 psi (low)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt Thickness, in:</td>
<td>7</td>
<td>8</td>
<td>12</td>
<td>13</td>
<td>16</td>
<td>18 inch</td>
</tr>
<tr>
<td>(cm):</td>
<td>17.8</td>
<td>20.3</td>
<td>30.4</td>
<td>33.0</td>
<td>40.6</td>
<td>45.7 cm</td>
</tr>
</tbody>
</table>

Table 3 shows asphalt thickness values based on traffic volumes for both low and high asphalt modulus. Asphalt layer thickness increases at higher traffic levels. For low traffic level, the thickness difference is not much. It can be seen that an asphalt layer with a low modulus requires a thicker layer. As observed in Figure 1, the asphalt thickness differences between thickness calculated for the high asphalt modulus and thickness for the low asphalt modulus were analyzed as percent of thickness based on the lower asphalt modulus values. The findings show that the ranges in asphalt thickness that increase due to 50% lower asphalt modulus are between 33 and 50% for traffic volumes 0.5 to 50 million ESALs. In other words, in summer months when the modulus value decreases 50% or lower than the modulus in reference month, pavement structure requires thicker asphalt layer in order not to rut or have other excessive distresses.
Further analysis was implemented to observe the relationship between increase in asphalt thickness and traffic variations. Increase in traffic, \( T \), was calculated as a multiple of the basic 500,000 ESAL traffic. The increases in thickness were calculated based on the lowest thickness recorded for each low and high asphalt modulus. Figure 2 shows that regardless of the asphalt modulus, the asphalt thickness increases with an increase in traffic ESALs. The increase of asphalt thickness due to traffic increase is higher for weaker asphalt layers except for low volume roads. Nonetheless, the factors show a slight difference for traffic equivalent to 2T.

For traffic levels equal to 20T (10 million ESALs), the thickness values estimated from the graph are only 6.9 and 7.5% higher than the thickness values predicted from initial design input values for low and high asphalt modulus, respectively. The log models, shown in Figure 2, are reliable to predict percent increase in asphalt thickness due to increased traffic level for this set of design inputs. From the model, the asphalt thickness for traffic equivalent to 3 and 5 million ESALs increased by approximately 50% and 100 to 110% for both low and high traffic.
These results clearly demonstrate that it is important to have reliable values of design traffic applications and representative subgrade resilient modulus. In practice both are difficult to ascertain accurately because of high uncertainty in traffic predictions and high spatial variability in subgrade soil properties.

3.2 Effects of Seasonal Variability of Unbound Layers on Design of Asphalt Pavement Thickness

The Pavement Design System for New and Existing Asphalt Pavements (PADAP), mechanistic-empirical pavement thickness design software [4], was used to simulate 12-month cycle of moisture content and resilient modulus changes of unbound layers and subgrade. Figure 3 shows seasonal variations in water contents of unbound layer and subgrade spoil, as well as monthly variations in pavement surface temperatures. Pavement temperature and adjusted asphalt modulus values were predicted using PADAP’s climatic simulation algorithm for each month of the year. Figure 4 shows the environmental/seasonal variability in pavement layer modulus values. The seasonally adjusted modulus values were selected by subtracting one standard deviation from the average modulus value for each layer. This implies that the probability of under-designing will be only 16% based on the normal distribution of this data.

Figure 3. Seasonally adjusted water content of unbound layers and surface temperature data by PADAP

Figure 4. Seasonally adjusted design modulus values of unbound layers by PADAP
Table 4 shows that for the high asphalt modulus value, the required asphalt layer thickness: (a) increases by 1 inch (2.54 cm) for low volume traffic up to 1 million ESALs and (b) increases by 2 inches (5.08 cm) for moderate to high volume traffic (5-50 million ESALs). If a life cycle analysis of costs and benefits are made comparing these results with the thickness calculated for average design modulus values, the analysis will probably be inadequate and pavements will most likely fail early due to the seasonal variations of these layer modulus values. The excess user costs will be higher due to early degradation of pavements and of maintenance treatments will be required more frequently. A full analysis is not done in this paper due to space limitations. However, readers can refer to other papers for such examples [4,43].

Table 4. Asphalt thickness predictions using seasonally adjusted modulus values of pavement layers

<table>
<thead>
<tr>
<th>ESALs</th>
<th>Assumed Average Condition</th>
<th>Seasonally Adjusted Environmental Condition</th>
<th>Thickness Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 Million</td>
<td>5 inch (12.7 cm)</td>
<td>6 inch (15.2 cm)</td>
<td>+ 1 inch (2.54 cm)</td>
</tr>
<tr>
<td>1.0 Million</td>
<td>6 inch (15.2 cm)</td>
<td>7 inch (17.8 cm)</td>
<td>+ 1 inch (2.54 cm)</td>
</tr>
<tr>
<td>5.0 Million</td>
<td>8 inch (20.3 cm)</td>
<td>10 inch (25.4 cm)</td>
<td>+ 2 inch (5.08 cm)</td>
</tr>
<tr>
<td>10 Million</td>
<td>9 inch (22.9 cm)</td>
<td>11 inch (27.9 cm)</td>
<td>+ 2 inch (5.08 cm)</td>
</tr>
<tr>
<td>25 Million</td>
<td>11 inch (27.9 cm)</td>
<td>13 inch (33.0 cm)</td>
<td>+ 2 inch (5.08 cm)</td>
</tr>
<tr>
<td>50 Million</td>
<td>12 inch (30.5 cm)</td>
<td>14 inch (35.6 cm)</td>
<td>+ 2 inch (5.08 cm)</td>
</tr>
</tbody>
</table>

Table 5. Mechanical properties of traditional (T) and sustainable (S) paving materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Paving Materials</th>
<th>Modulus (psi)</th>
<th>Modulus (MPa)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Dense Hot Mix Asphalt</td>
<td>250,000 - 500,000</td>
<td>1,724 - 3,447</td>
<td>NCHRP, 2007 [44]</td>
</tr>
<tr>
<td>S</td>
<td>Warm Mix Asphalt (at 38°C)</td>
<td>435,000</td>
<td>2,999</td>
<td>Michigan DOT, 2011 [45]</td>
</tr>
<tr>
<td>S</td>
<td>Porous Asphalt (at 30°C)</td>
<td>100,000</td>
<td>689</td>
<td>Subagio et al., 2005 [46]</td>
</tr>
<tr>
<td>T</td>
<td>Concrete, Pavement Quality</td>
<td>5 million</td>
<td>34,474</td>
<td>NCHRP, 2007 [44]</td>
</tr>
<tr>
<td>S</td>
<td>Pervious Concrete</td>
<td>1.5 – 2.2 million</td>
<td>10,342 - 15,168</td>
<td>Thomle et al., 2009 [47]</td>
</tr>
<tr>
<td>S</td>
<td>Roller Compacted Concrete</td>
<td>905,035 – 2,422,830</td>
<td>6,240 - 16,705</td>
<td>Vilena et al., 2011 [48]</td>
</tr>
</tbody>
</table>

3.3 Comparison of Mechanical Properties of Sustainable and Traditional Paving Materials

Pavement engineers must ensure that pavement does not fail as a result of rutting, top-down cracking, or any type of environmental or load related distresses. Table 5 compares the resilient modulus values of traditional pavement materials with new sustainable materials. For example, traditional dense graded HMA modulus is compared to the sustainable warm mix asphalt. Porous asphalt paving material is included in this table too because it enhances safety by removing rainwater quickly but it is prone to rapid oxidation and binder aging. Similarly, sustainable alternatives to normal pavement concrete materials are generally characterized by significantly lower Young’s modulus values. A lower design modulus value has implication on a higher surface layer thickness for the same traffic level compared to traditional materials. Perpetual asphalt pavement technology may be the desirable answer for heavily trafficked high quality highways, which is focused upon milling and recycling only the top 2 inches (5.08 cm) of the asphalt layer built upon a strong base. This design will avoid early failures and show superior long-term performance with lower total life cycle costs. Uddin et al. [5] show a comprehensive life cycle assessment methodology considering vehicle operating costs, accident costs, and public health societal costs associated with vehicle emissions.

3.4 Other Sustainable Innovative Pavement Technologies -- Reusing Waste Glass for Road Marking

Another important concept towards sustainability is reuse of non-pavement waste materials after required processing and minimizing the use of raw materials. This “thinking outside the box” conservation concept contributes towards lower energy consumption, CO₂ and other GHG reduction, a greener earth, and better community. For example, recycling and reuse of waste glass (non-asphalt and non-concrete material) is an innovative approach for incorporating sustainability in pavements and enhancing safety of driving public. Potential pavement applications of waste glass include its use as glass beads for pavement marking and as a partial replacement of sand size for asphalt and concrete surfacing.
Some conservation facts about glass include the following [49]: “Recycling one ton of glass saves the equivalent in energy of 10 gallons of oil. Over a ton of resources are saved for every ton of glass recycled: 1,330 pounds of sand, 433 pounds of soda ash, 433 pounds of limestone and 151 pounds of feldspar.” In other words, one ton of recycled glass saves over 200 lbs of CO$_2$ and additional reduction of GHG emissions from not processing over a ton of other raw materials. Glass recycling is limited to a conservative recycling process of waste glass that requires reheating used glass materials at very high temperatures in order to fabricate new useful glass products. The heating process at high temperatures produces wasted heat and more CO$_2$ emissions. Consequently, reuse of waste glass to produce glass beads for road marking and painting will help reduce heat-island effects and CO$_2$ emissions in a unique way. Glass beads, embedded in road markings, are among the most efficient and most economical means to reuse glass and safely guide traffic at night. The contrast between the pavement and the glass pigmentation and increased light reflection provides clear visibility under daylight and even better during night conditions. Painted road lines embedded with glass beads provide night time delineation, especially during blackouts and in rural areas with no road lights [50].

Considering that there is 80 percent of waste glass available for recycling and reusing, it provides unique opportunities to the glass industry for manufacturing sustainable derivative products. An example of such sustainable industrial application of waste glass is production of glass beads for pavement markings. Additionally, paving material suppliers and constructors can use waste glass as crushed glass for partial replacement of coarse-to-fine sand in both asphalt and concrete mixes. Like any other new technology, laboratory research and pilot field trials are necessary to assess optical, thermal, and other physical properties, as well as optimum proportions to ensure quality, durability, and safety.

4. SUSTAINABILITY CHAMPIONS AMONG BIG CITY POLLUTERS

EPA’s heat-island resource web site [51] provides insight into a grave problem of heat-island effects in cities due to large areas of road pavements and parking spaces. Some highlights follow:

- “Analyses in cities such as Chicago, Houston, Sacramento, and Salt Lake City have shown that pavements for both travel and parking can account for 29 to 39 percent of the land surface in an urban area.
- A large portion of this is due to parking; in the Houston, Texas, metropolitan area, the parking facilities account for approximately 60 percent of the transportation land use.
- As with roofing materials, paving materials can reach 150°F (65.6°C) in daytime, radiating away this excess heat during both day and night into the air in the urban canopy layer (as well as heating stormwater that reaches the pavement surface).
- Due to the large area covered by pavements in urban areas, these pavement assets are an important element to consider in the heat-island mitigation.”

Figure 5 shows the results of a heat-island study of Oxford, Mississippi which is a small university town [52]. Again, it shows that the heat-island effect is not limited to big cities and urban areas only. It is essentially present in most cities where green spaces and trees have been replaced by constructed surfaces. The installation of reflective pavement surfaces, the reuse of recycled waste glass as glass beads in road painting and traffic control markings, planting trees, and addition of green spaces are all good sustainability practices. Societal impacts of air quality degradation from energy and transportation sources and GHG emissions are well known concerns. Public awareness of this issue has been prevalent since the beginning of the 21st century. Cities, generating toxic emissions and about 75% of all CO$_2$ emissions [2], are taking notice and some (e.g., New York City) are taking steps to measure annual emission inventory, establish long-term sustainability targets, and implement mitigation strategies [53].
Consequently, all infrastructure asset owners and operators will want to embark upon annual CO₂ emission monitoring and implement innovative construction and operational strategies to reduce their annual carbon footprints. Condition monitoring for network-level pavement management, calculation of life cycle cost and benefits including emission inventory, and use of value engineering for selecting timely appropriate maintenance and rehabilitation strategies are needed for cost-effective and sustainable pavement investment decisions. These sustainability dimensions, mitigation strategies, and international efforts of reducing GHG emissions, as well as providing financial support to developing countries for implementing sustainable infrastructure assets are discussed in detail in the 2012 Climate Change Mitigation Handbook [2].

5. CONCLUSIONS

This paper demonstrates that achieving sustainability by reducing GHG emissions and long-term pavement performance are equally important in terms of surface distresses, roughness, skid resistance, and noise. These pavement performance attributes may be competing with sustainability goals. A parametric study of asphalt thickness design indicated that it is important to have reliable values of design traffic applications and representative subgrade resilient modulus. In practice there is high uncertainty in traffic predictions and large spatial variability in subgrade soil properties. Seasonal variability of resilient modulus of unbound layers and subgrade soils affects thickness design as well. Ignoring these sources of variability often results in poor performance or early deterioration of pavements.

Achieving sustainability without compromising long-term pavement performance for road infrastructure assets should be the ultimate goal of pavement investment decision making. Condition monitoring for network-level pavement asset management and calculation of life cycle costs and benefits, including emission inventory, are needed for cost-effective pavement investment decisions.

This paper reviews several sustainable asphalt highway practices that can reduce energy consumption, heat-island effects, and emissions. An example of “thinking outside the box” approach is presented, which is to recycle waste glass as glass beads for pavement markings and as a partial replacement of sand fraction in aggregates used for constructing both asphalt and concrete pavements. It is recommended to pursue further laboratory and field research to assess their viability. This sustainable practice will enhance safety, reduce processing of large amounts of raw materials, and result in lower life cycle costs. The research for recycling and reusing processes will enhance safety and reduce processing of large amounts of raw materials, energy consumption, and GHG emissions.
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