Project Title

# Market Analysis of Construction Materials with Recommendations for the Future of the Industry

FINAL REPORT

Date: January 14, 2010

By: **Dr. Melissa M. Bilec, Dr. Joe Marriott, Maria Fernanda Padilla, and Dr. Mark Snyder**

University of Pittsburgh

COMMONWEALTH OF PENNSYLVANIA
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<tr><td colspan="6"><b>16. Abstract</b><br>Due to the volatility of current highway construction commodity prices, owners, contractors, and designers are facing serious challenges in both short-term estimating and long-term planning. Among these challenges is significant uncertainty about the prices and availability of critical highway construction materials; steel, for example, increased in price from $600 per ton to over $1400 per ton in just eight years. At the same time, nearly all facets of the infrastructure in the United States require redesign, expansion or repair. Planners need to make decisions which maximize the value of investment dollars while at the same time considering the environmental and human factors associated with that investment. One way to reduce the uncertainty and make better investment decisions is by studying the past, present and future commodity prices and availability. In this research, we focus on commodities for highway construction such as diesel, asphalt, cement, aggregates and steel. Recent economic trends for these commodities show how production, supply and demand affect the US unit prices. Forecasts for the price trends of the commodities are developed. Comparative life cycle assessment (LCA) results are presented.</td></tr>
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University of Pittsburgh
Department of Civil and Environmental Engineering

# Market Analysis of Construction Materials with Recommendations for the Future of the Industry

## Task 3

**January 14, 2010**

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# Preface

This report presents the results of Task 1, 2, and 3 of the project, *Market Analysis of Construction Materials with Recommendations for the Future of the Industry*. Tasks 1, 2, and 3 were performed by the University of Pittsburgh under an intergovernmental agreement, contract 510601-PIT 016, awarded by the Pennsylvania Department of Transportation.

Task 1 involved investigating construction commodities of asphalt/oil, cement, steel, and aggregates. Specifically, we developed a database of construction related commodity prices. In addition, we conducted interviews with trade organizations and heavy and highway contractors. Metrics highlighting major market influences are discussed. Task 1 was completed and delivered November 15, 2008 and is primarily sections 1 through 5.

Task 2 involved conducting a market analysis on the various construction materials identified in Task 1. The analysis included consumption, production, and pricing for the next five (5), ten (10), and twenty (20) years, based on the major market influences. *The primary output was graphical projections.* The graphs included the following:

- Consumption and production: mass functions on the y-axis with time on the x-axis
- Pricing: Dollars/mass function on the y-axis with time on the x-axis
- Environmental: $/mass of carbon on the y-axis with time on the x-axis.

Additionally from a local perspective, the University looked at the regional availability (supply) within Pennsylvania of the aggregates. The University conducted interviews with state-based suppliers to obtain additional data on supply and quality. This portion was completed and delivered in Task 1 in section 5

The University used the predictions from the analyses to discuss what the highway and bridge construction industry might look like in the five (5), ten (10) and twenty (20) year periods. This portion was done by identifying alternative materials or construction techniques that can be used to supplement or replace these materials should it become economically infeasible to continue using that specific resource in the manner currently being utilized. The products and materials listed in this report are only examples; they are not recommendations for use.

For Task 3, the University developed a Final Report, which explored alternative materials and construction techniques. For each alternative, the University provided a description, past uses, implementation strategies, environmental factors, and cost.

The authors acknowledge the contribution of the technical guidance of and information provided by the Department.

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## 1. Objective of the project

The objective of this work was to perform a market analysis and forecast for key commodities used in the highway and bridge construction industries in Pennsylvania. The focus to date centered on oil and its inherent relationship to asphalt, concrete, cement and aggregates, and steel. The study will eventually provide a basis for recommendations on future commodity use, new technologies, environmental issues, and construction practices and/or substitution commodities for PennDOT to consider for future development.

For Task 1, we examined historical price trends of key commodities: oil and asphalt, cement and concrete, aggregates, and steel. In addition, we used face validity to assess the historic trends and report on recent activities within the construction market, along with surveying key trade organizations. We also discussed major market influences.

For Task 2, we conducted an analysis with respect to consumption, production, and pricing for the next five (5), ten (10), and twenty (20) years on the said construction commodities. We discussed alternative materials or construction techniques that can be used to supplement or replace these materials should it become uneconomically feasible to continue using that specific resource in the manner currently being utilized.

Understanding the impacts of these key commodities is crucial to long-term transportation planning and fiscal budgeting purposes. During the preparation of Task 1, the primary concern was cost escalations and the impacts to Pennsylvania projects, as evidenced by recent new article accounting escalating costs for diesel fuel and liquid asphalt. For example, in District 11, increases in costs will require the district to find $9.2 million for existing highway construction contracts, resulting in delaying, changing, or canceling future projects (Grata 2008). These costs are compounded by the losses of redesign and letting costs. It is projected that statewide the cumulative impacts could exceed $100 million. District 11 is only one example of what is occurring throughout the entire state.

During the preparation of Task 2, the economic environment is unstable. Many prices have rapidly declined and the economy is in a recession. In addition, the federal government has infused billions of dollars into the transportation sector.

For Task 3, for each alternative, we performed an environmental and technical feasibility analysis and discuss all associated economic issues, implementation strategies, environmental factors, global risks and cost projections.

## 2. Market influences

There are certain factors which will influence the price and availability of highway construction materials beyond simple supply and demand fluctuations. These factors are discussed in this section. The most important of these factors are listed below:

- Energy prices
- International markets and demand
- Environmental regulations
- Natural disasters

In general, this analysis looks at the impacts of these various factors on commodities, rather than on specific products. Specific products are affected by the requirements of projects and the prices may not be reflective of larger trends.

Energy prices are rising. While petroleum prices, and the corresponding impact on gasoline and diesel prices, receive most of the attention, similar increases in the prices of natural gas, heating oil and coal lead to increases in the cost of direct heating, electricity, as well as transportation fuels. Whether prices continue to rise or begin to fall, there will be an impact throughout the economy, including on commodity material prices. Higher prices will likely be passed on immediately, while there will be a delay in passing on decreases as suppliers buffer against future high prices.

The world's emerging economies, especially Brazil, Russia, India and China (BRIC) demand enormous amounts of resources to drive their growth. This demand is only partially satisfied with internal supply, so these economies look to import needed materials. This drives the price of key commodities up worldwide. In the case of China, they both produce and consume a large portion of many commodities under discussion (ENR 2008), (ENR 2008). While highway construction in Pennsylvania may seem far removed from the construction for the Beijing Olympics, the economics are connected.

The reality of anthropogenic climate change as a result of fossil fuel combustion has lead local, national and international organizations prosing and even implementing carbon regulation. When regulation is imposed on a waste product which used to be emitted for free, there will be economic impacts of that regulation, whether the regulation is a cap and trade permit scheme or an economy-wide carbon tax. This cost will be passed by suppliers to the final customers, raising prices on nearly everything.

With prices of commodities affected by the extraordinary, but predictable, economic growth around the world, there is little buffer for unpredictable events. When large-scale natural disasters such as hurricane Katrina in 2005, the 2004 Asian tsunami and the 2008 Sichuan earthquake strike, they place additional unplanned strain the supply of important construction commodities. It can be expected that there will be future unexpected events which will generally raise prices significantly in the short term and possibly in the long term as well.

In addition to the broad impacts of market influences, it is also important to understand the relationship between the United States' consumption and production and internationals consumption and production of interested commodities.

## 2.1. Current US and other countries production of materials

### 2.1.1. Asphalt and Diesel

In the United States, crude oil production for 2007 was 1.84 billion of barrels. Of the total products from refining crude oil in 2007, 34.6% corresponds to gasoline, 28% corresponds to diesel fuels, and 3.08% corresponds to production of asphalt, see Figure 1. Table 1 shows the tendency (in percentage) of products obtained from crude oil refining processes from January 2008 to February 2009 (EIA 2009).

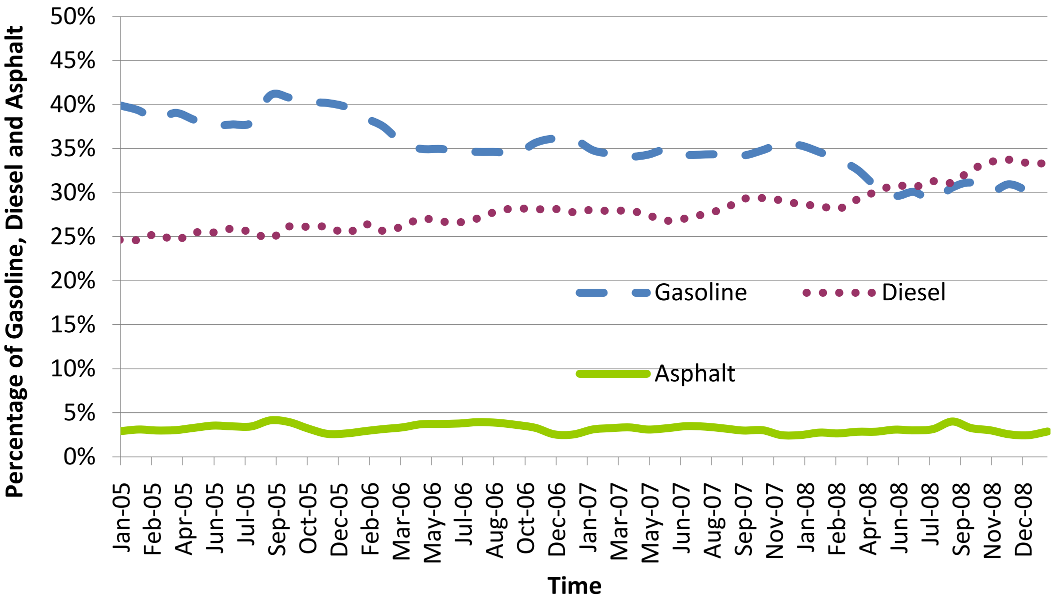

Figure 1: Percentage of Gasoline, Diesel and Asphalt Produced by Volume from the Crude Oil Refining Process in the US (EIA 2009)

Table 1: Overview of 2008 Production of Crude Oil Refined Products (EIA 2009)

| | Production of Diesel | Production of Gasoline | Production of Asphalt |
|---|---|---|---|
| **Jan-2008** | 28.7% | 35.3% | 2.5% |
| **Feb-2008** | 28.5% | 34.6% | 2.7% |
| **Mar-2008** | 28.1% | 33.8% | 2.6% |
| **Apr-2008** | 29.2% | 32.6% | 2.8% |
| **May-2008** | 30.1% | 30.7% | 2.8% |
| **Jun-2008** | 30.8% | 29.6% | 3.1% |
| **Jul-2008** | 30.6% | 30.1% | 3.0% |
| **Aug-2008** | 31.3% | 29.1% | 3.1% |
| **Sept-2008** | 31.1% | 30.6% | 4.0% |
| **Oct-2008** | 32.5% | 31.1% | 3.3% |
| **Nov-2008** | 33.5% | 30.0% | 3.0% |
| **Dec-2008** | 33.7% | 30.9% | 2.5% |
| **Jan-2009** | 33.3% | 30.1% | 2.5% |
| **Feb-2009** | 33.3% | 28.8% | 2.9% |

### 2.1.2. Cement

Cement is a main component of concrete; Portland cement is the material that is mainly used in concrete construction. Table 2 illustrates that the US supplies only 3.7% of world production of cement. The world production of cement has increased 64.8% from 1997 to 2006. With respect to the US, the production and consumption also had an increase of 18.8% and 32.1% respectively for the same timeline (USGS 2008).

Table 2: Cement Production for 2007 and 2008 (USGS 2008; USGS 2009)

| | 2007 | | 2008 | |
|---|---|---|---|---|
| | Thousand metric tons | Percent | Thousand metric tons | Percent |
| **United States** | 9.7E4 | 3.5% | 8.9E4 | 3.1% |
| **Brazil** | 4.6E4 | 1.7% | 4.8E4 | 1.7% |
| **China** | 1.4E6 | 48.7% | 1.4E6 | 50.0% |
| **India** | 170.0E3 | 6.1% | 1.75E5 | 6.0% |
| **Russia** | 60.0E3 | 2.2% | 6.1E4 | 2.1% |
| **Rest of the world** | 104.9E4 | 37.9% | 104.4E4 | 36.0% |
| **Total World** | **2.8E6** | **100.0%** | **2.9E6** | **100.0%** |

### 2.1.3. Aggregates

For sand and gravel production and consumption in the US, there was an incremental change of 39% and 39% respectively from 1997 to 2006 (USGS 2008). For the same time period, crushed stone also shows and increase in production and consumption in the US by 21.9% and 22.4% respectively (USGS 2008). In the US, the sand and gravel produced for construction as aggregates is shown in Table 3, as well as the amount of crushed stone produced in the last year (2007). *The terms "sand and gravel" and "crushed stone" are the terms used by the*

*United States Geological Survey (USGS) and do not denote specific engineering designations in terms of particle size and distributions.*

Table 3: Aggregate Production in the US for 2007 and 2008 (USGS 2008; USGS 2009)

| | 2007 | 2008 |
|---|---|---|
| | **Million metric tons** | **Million metric tons** |
| **Sand and gravel** | 1230 | 1040 |
| **Crushed stone** | 1600 | 1340 |

### 2.1.4. Steel

Comparing 1997 and 2006 data for steel in the US, there was a reduction in the production of steel of 0.3%, and an increase in consumption of 5.26%. For world production, there was an increase of 46.8% for this 9 year period (USGS 2008). Table 4 shows a summary of the production of steel for 2007, having China as the main producer. (USGS 2008)

Table 4: Total Raw Steel Production for 2007 and 2008 (USGS 2008; USGS 2009)

| | 2007 | | 2008 | |
|---|---|---|---|---|
| | **Million metric tons** | **Percent** | **Million metric tons** | **Percent** |
| **United States** | 98 | 7.3% | 94 | 6.9% |
| **Brazil** | 32 | 2.4% | 36 | 2.6% |
| **China** | 489 | 36.5% | 513 | 37.7% |
| **Russia** | 72 | 5.4% | 74 | 5.4% |
| **Rest of the world** | 649 | 48.4% | 643 | 47.3% |
| **Total World** | **1340** | **100.0%** | **1360** | **100.0%** |

# 3. Methods and Data Acquisition

For Task 1, we collected data from several sources, including government agencies, professional organizations, and international organizations. While prices for asphalt and diesel are specific to the state of Pennsylvania, other commodities are on a national basis.

Table 5 summarizes the different sources used for the collected. Most of the sources have a 5-year history. All these data sources have information for the US. There is one data source, MEPS (MEPS 2008), which shows the world price of steel. MEPS is the name of the organization and is not an acronym.

**Table 5: Summary of Data Sources for Material Prices**

| Petroleum Products | | | Steel | Cement | Aggregates | |
|---|---|---|---|---|---|---|
| *Asphalt* | *Diesel* | *Gasoline* | | | *Sand and Gravel* | *Crushed Stone* |
| PennDOT [1] | PennDOT[1] | EIA[3] | PennDOT[1] | USGS[4] | USGS[4] | USGS[4] |
| Other states DOT[2] | EIA[3] | | USGS[4] | | | |
| | | | MEPS[5] | | | |
| | | | MEPS[5] (world prices) | | | |

Some of the data obtained was available up to the year 2006. In order to have a complete sense of what has happened in the recent months, we estimated the prices of the materials using the producer price index (PPI) from the Bureau of Labor Statistics. The approach taken was to use the fluctuations of the PPI and transform that into an increment (or decrement) dollar value for each material (BLS 2008).

In order to obtain the PPI fluctuations, we looked at the yearly average PPI data to obtain the yearly fluctuation. In order to obtain the monthly PPI fluctuations, we looked into the PPI data for every month. Once we identified the years and months of interest, we calculated the fluctuations of the PPI (monthly and yearly). The following formula shows how we obtained the fluctuation:

---

[1] ECMS: http://www.dotdom1.state.pa.us/

[2] California, Wisconsin, New Jersey

[3] Energy Information Administration: http://tonto.eia.doe.gov/dnav/pet/pet_pri_top.asp

[4] United States Geological Survey: http://minerals.usgs.gov/ds/2005/140/index.html

[5] MEPS (International) LTD: http://www.meps.co.uk/world-price.htm

**Equation 1: PPI Fluctuation Calculation**

$$\text{PPI}_{\text{fluctuation year i to year i +1}} = \frac{\text{PPI year}_{\text{i+1}} - \text{PPI}_{\text{year i}}}{\text{PPI}_{\text{year i}}}$$

Once the PPI fluctuation was calculated, we used that data to calculate the price when needed. The following formulas show the arithmetic procedure in order to calculate the price. The prices estimated change accordingly to the fluctuation of the PPI that could be either positive or negative. For the yearly price, we used Equation 2:

**Equation 2: Yearly Price Estimation Using PPI Fluctuation**

$$\text{Price}_{\text{year i+1}} = \text{Price}_{\text{year i}} * (1 + \text{PPI fluctuation}_{\text{year i to year i+1}})$$

In the case of 2008, we used the monthly PPI fluctuations in order to obtain the monthly prices. The reason of using monthly prices for this current year is because of all the economic events and given the sudden changes of the market and economy. For this calculation, we used Equation 3.

**Equation 3: Monthly Price Estimation Using PPI Fluctuation**

$$\text{Price}_{\text{month i +1}} = \text{Price}_{\text{month i}} * (1 + \text{PPI fluctuation}_{\text{month i to month i +1}})$$

Since this project is mainly focused on the highway construction sector, we also conducted interviews with several large-scale heavy and highway contractors who do business throughout the state and around the country and several relevant trade organizations. This action was made for several reasons – validate national data trends, talk with local contractors and trades about their prices and bidding experiences, and develop a general sense of the market/industry responses to recent price volatility. Several entities were contacted (e.g., Brayman Construction, Mascaro Construction, and Trumbull/PJ Dick). For the heavy and highway contractors, the individuals were lead estimators in their associated organization.

## 4. Materials

Note that this section makes a distinction among several similar economic terms, which for the purposes of this analysis are different in important ways.

- *Demand versus consumption:* demand for a commodity is distinct from consumption in that there can be unmet demand, which will generally lead to a price increase. Consumption greater than demand will lead to stockpiling and price decreases.
- *Supply versus production:* In the same way, production is distinct from supply. Overproduction will lead to surplus supply and price drops; underproduction leads to supply shortfalls and price increases.

In other words, the economic market tries to match the supply to the demand at the maximum price the market will bear. The industries try to then match production and consumption to the price signals they are receiving from the market. These prices are also signals for investment in production capacity or infrastructure (transportation or otherwise).

Figure 2 illustrates overall building material trends (Portland Cement Association 2008; Portland Cement Association 2009). This figure was obtained from the Portland Cement Association; therefore, it is not possible to disaggregate the materials (e.g., concrete into cement and aggregates). Figure 2 shows an overview of steel, asphalt, concrete and lumber with sharp increases in both steel and asphalt, and steady increases in concrete. For this report, we are discussing petroleum products, cement, and aggregates.

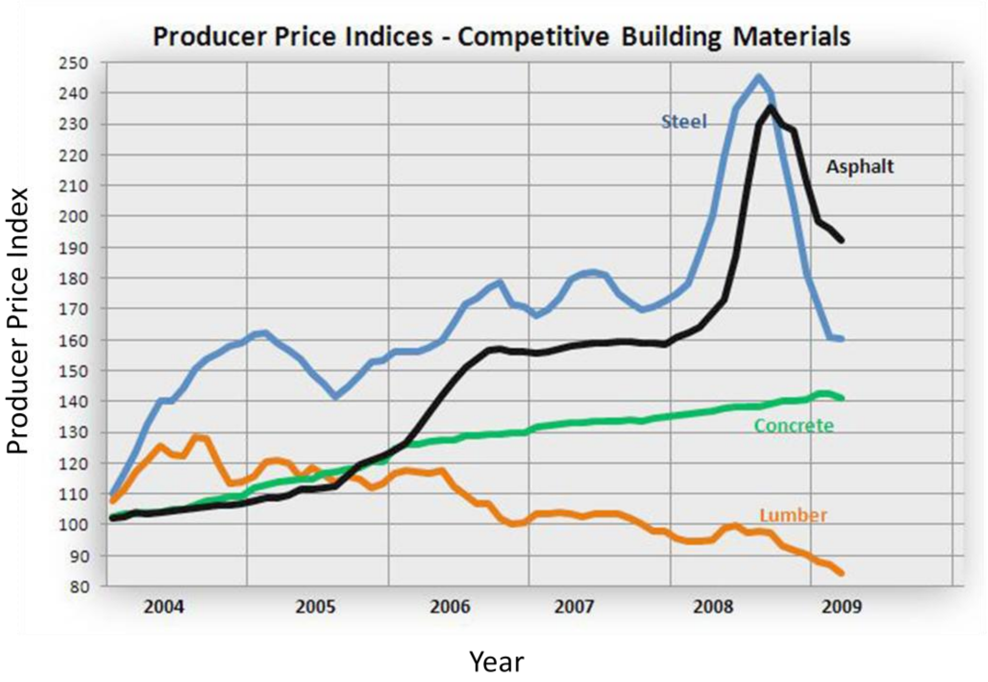

Figure 2: Producer Prices Indices (Portland Cement Association 2008; Portland Cement Association 2009)

## 4.1. Petroleum products

### 4.1.1. Diesel and gasoline

The impacts of diesel prices resonate throughout an entire construction project from transportation of construction materials and equipment, to fuel costs for construction equipment. Diesel prices drive not only direct fuel costs, but also material costs, since material providers use diesel in order to transport the material to the site. The prices of chemicals used in construction will also be impacted by the increase of oil.

As shown in Figure 3, over the past 70 months, the prices per gallon for transportation fuels, especially diesel and gasoline have been rising. In January of 2008 the rate of increase had gone up as well, until June and July of 2008, when prices corrected significantly.

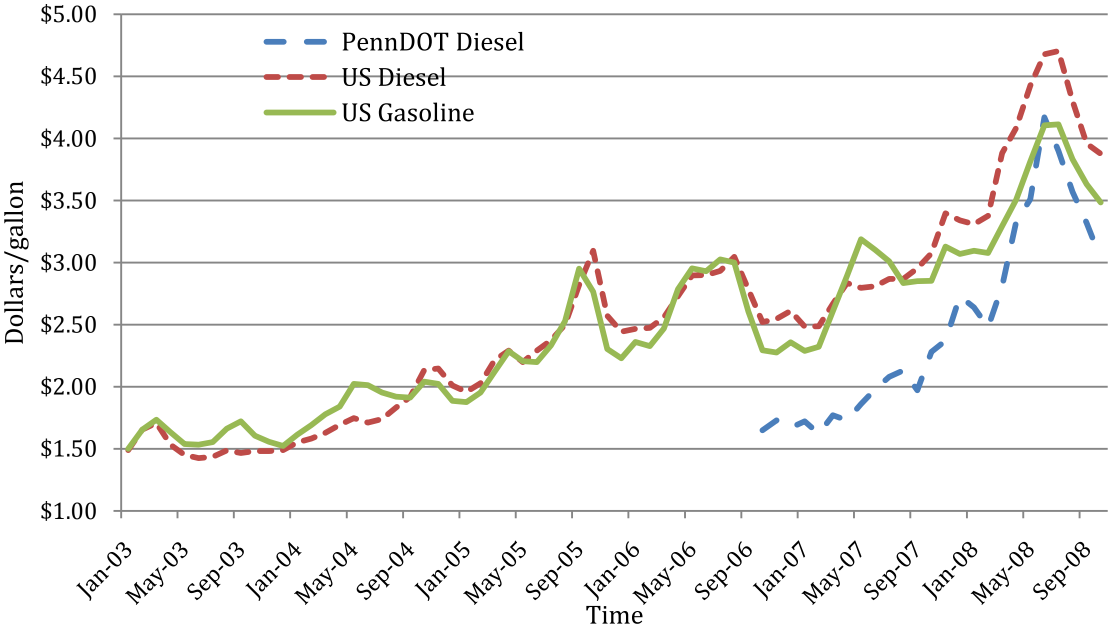

Figure 3: Historical Comparison of Diesel and Gasoline Prices in $/Gallon (EIA 2008) (ECMS 2008)

Table 6 shows fuel prices over the past six months, the peak national average price of diesel fuel was $4.70 per gallon, but two months later, the price was down below $4 per gallon. It should be noted that PennDOT data prior to September of 2006 was not available. Historical projections are not created here since the correlation seen in the last two years cannot be assumed over the prior three years.

Table 6: Recent Diesel Prices (ECMS 2008; EIA 2008)

| | PennDOT Diesel ($/gal) | US Diesel ($/gal) |
|---|---|---|
| **Oct-08** | $3.03 | $3.88 |
| **Sep-08** | $3.32 | $3.96 |
| **Aug-08** | $3.57 | $4.30 |
| **Jul-08** | $3.90 | $4.70 |
| **Jun-08** | $4.17 | $4.68 |
| **May-08** | $3.51 | $4.43 |
| **Apr-08** | $3.33 | $4.08 |

The price PennDOT pays for diesel fuel is highly correlated with the average national price for diesel - correlation coefficient of 98.5%. Figure 3 shows that prices track closely.

On average, PennDOT is paying 27% ($0.83 per gallon) *less* than the national price for diesel fuel; although, this amount varies from as low as 11% ($0.50/gal.) to as high as 40% ($1.10/gal.) since October of 2006. As shown in Figure 4, there is a lot of variation in this difference, although we are seeing a downward trend: PennDOT price is getting closer to the national average. The price of diesel and this differential are actually negatively correlated: as price goes up, the differential goes down. What this means is that we can use national level data to predict when PennDOT's price will go up or down, but we cannot use the magnitude of the change to predict how much.

Given the recent volatility and the magnitude of that change over the last 8 months, each new month of data from both the Department of Energy and PennDOT with regards to price will be important in informing the future direction.

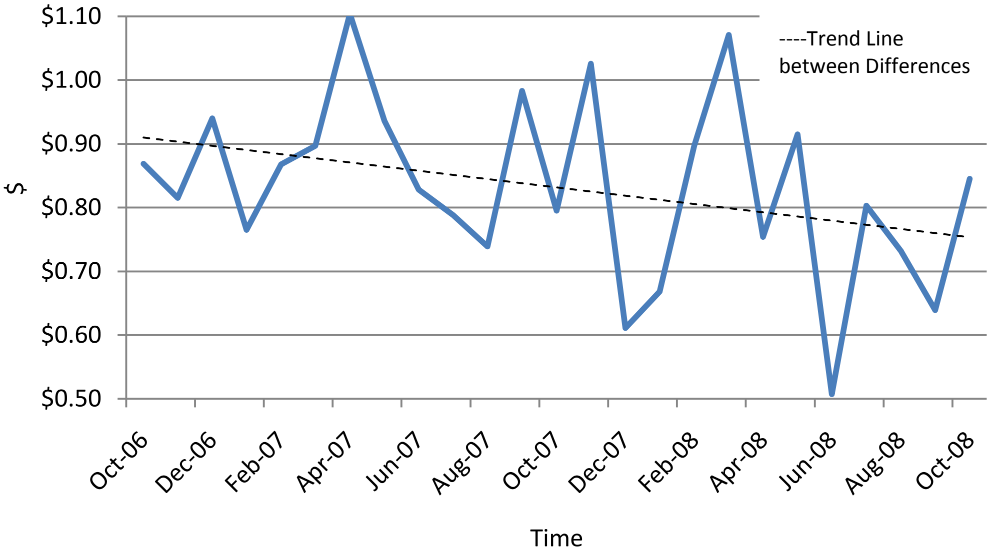

Figure 4: Difference between PennDOT Diesel Fuel Price and National Average Price per Gallon of Diesel Fuel, with Dashed Linear Trend Line (ECMS 2008; EIA 2008)

This figure, combined with the information in Figure 3, will enable a more accurate prediction of PennDOT price: the national trend shows us the direction prices are going, the difference will show us how much less the PennDOT price will be.

### 4.1.2. Asphalt

Asphalt is a by-product of the refinery process of crude oil. The relationship between asphalt with diesel and gasoline lies on the availability of crude oil and the efficiency of the refining process. One of the reasons why asphalt is an important material to study is because there has been seen a decline of production of asphalt (better efficiency of refineries), as well as price increases. As a large number of refineries are installing cokers to increase higher-end products, the supply of asphalt decreases (ENR 2008).

Table 7: Zones for Asphalt Pricing through Pennsylvania

| PennDOT Zone | Districts Encompassed |
|---|---|
| **1** | 3, 4, 5, 6, 8 |
| **2** | 2, 9 |
| **3** | 1, 10, 11, 12 |

PennDOT divides the state in three different geographical areas or zones. Table 7 shows the division of the state into three zones and districts associated with each zone.

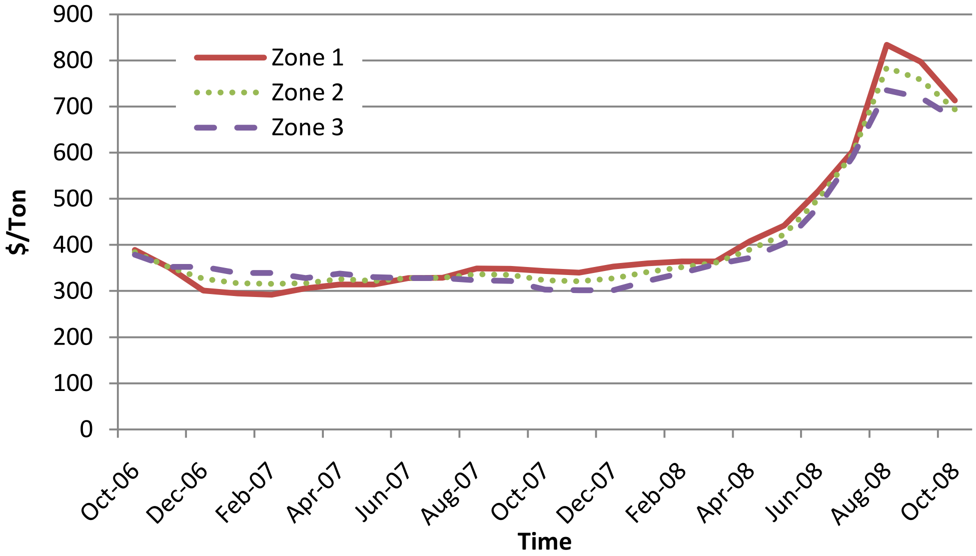

Figure 5: PennDOT Asphalt Cement Price in $/Ton (ECMS 2008)

There is a relatively high correlation between the recent (previous 2 years) price of asphalt and diesel (and petroleum products in general) prices with a coefficient around 70%. While several of the month to month variability is not represented in the asphalt cement price, the overall trend is similar. As such, and as can be seen in Figure 5, there has been rapid escalation in the price of asphalt, followed by recent decline that is very similar to what is occurring with other petroleum products.

While there appears to be some variation in the prices that PennDOT pays in various geographic regions, or Zones, in Figure 5, over the last two years, none of the regions has consistently paid a higher price, and the correlation among the 3 is very high, greater than 98%.

## 4.2. Cement and Aggregates

This section discusses both concrete and aggregates due to the trends discussed below. It should be noted, however, that supply and demand issues of aggregates also impact asphalt paving.

Concrete has many applications in the heavy and highway construction sector. The main components of concrete are Portland cement, aggregates, air and water. “The most important and most costly material in this type of concrete is the cementing agent, Portland cement (Atkins 2003)."

Natural aggregates, which include crushed stone, sand and gravel, are main components as raw materials in different industries (Table 8). One of the main uses of the aggregates is in construction. The correct use of aggregates yields in the concrete or asphalt pavement needed with specific characteristics (USGS 1999). *The terms “sand and gravel” and “crushed stone” are the terms used by the United States Geological Survey (USGS) and do not denote specific engineering designations in terms of particle size and distributions.*

Table 8: Classification of Aggregates as PennDOT’s Publication 408 and Bulletin 14 (PennDOT 2008)

| | Fine aggregates | Coarse aggregates | Antiskid aggregates |
|---|---|---|---|
| **Types** | Type A, Type B #1, #2, and #3, and Type C | Type A, B and C | Type 1 and 1A, Type 2, Type 3, 3A and 3B, Type 4, Type 6S and Type AS1 and AS2 |
| **Gradation Criteria** | Table A | Table C and D | Table E |
| **Other considerations and quality control** | Table A and text within section 1 | Table B and D and text within section 2 | Table E and text within section 4 |
| **Example of materials** | Natural and manufactured sands | Stone, gravel, blast furnace slag, steel slag, granulated slag, lightweight aggregate and recycled concrete | Cinders, coke, boiler slag, crushed stone, crushed gravel, crushed slag, natural and manufactured sand, and burned anthracite coal mine reuse |

In Figure 6, the historic U.S. consumption of two key aggregate categories and cement is shown on a logarithmic scale. Each major horizontal gridline denotes an order of magnitude increase. A logarithmic scale is used here to show two things: 1) the increase over time from millions of tons to billions of tons of consumption and 2) the tight correlation between the aggregates and cement.

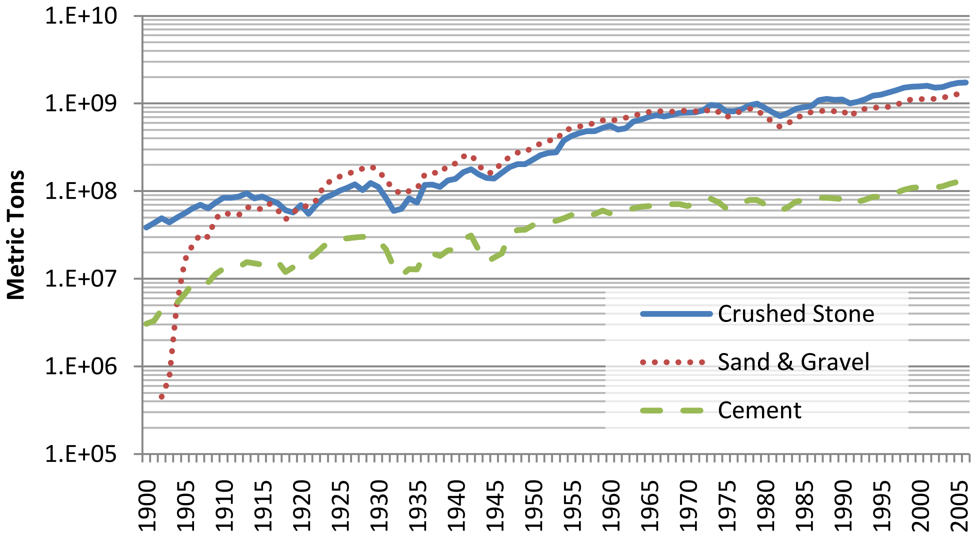

Figure 6: Historic US Aggregate & Cement Consumption in Metric Tons (log scale) (BLS 2008; USGS 2008)

Zooming in on the more recent past, between 1999 and 2005, and moving out of the logarithmic scale, it can be seen that at the national level, the U.S. consumption of these three commodities has maintained overall slow steady growth or remained flat, shown in Figure 7. Certainly, there is no sharp increase in consumption, as will be seen in the steel section.

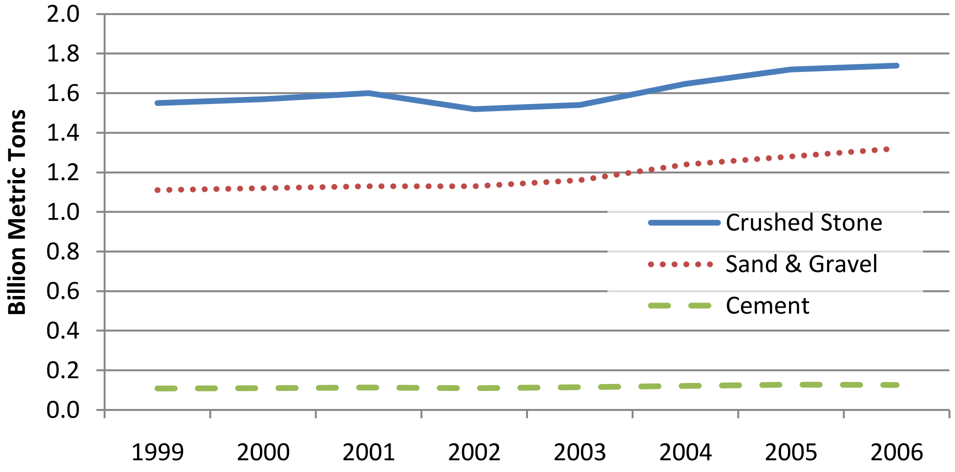

Figure 7: Recent U.S. Aggregate and Cement Consumption in Billion Metric Tons (USGS 2008)

Consumption of aggregates in the United States has remained nearly flat in the recent past. However, a look at the prices and percentage imported for these commodities, shown below in Figure 8, are indicative of a very different trend. Figure 8 shows the prices per ton for the two major categories of aggregates on the left-hand y-axis, and the net imports (imports less exports) of these commodities shown as a percent of total consumption on the right-hand y-axis.

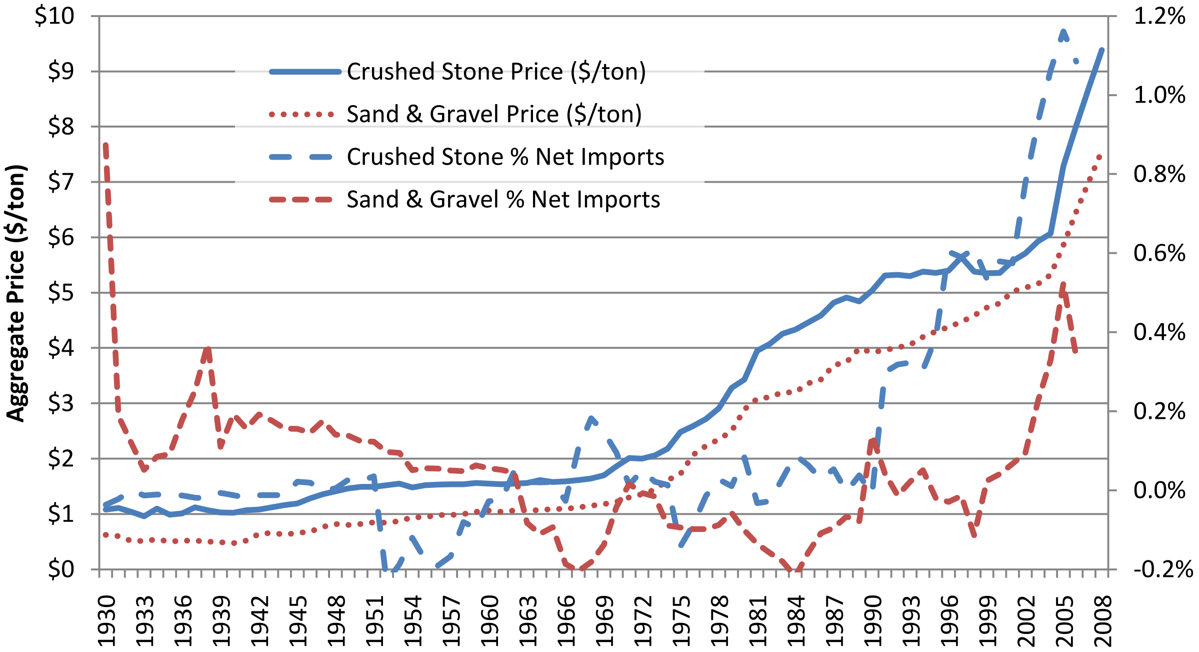

Figure 8: Historic U.S. Aggregate Prices in $/Ton with Net Imports as a Percentage of Total Consumption (USGS 2008), (BLS 2008)

Figure 8 shows recent rapid increase in the price per ton paid for aggregate in the United States. This price has been increasing since the 1960s, but since 2002, there has been a very rapid upward movement of prices. At the same time, the percentage of aggregates net imported into the United States has also increased rapidly. Until the 1990s, there the percent imported was very small, hovering right around 0% imports. Since then, the percent imported has jumped. It is still quite a small percentage, but the magnitude of the increase given the large tonnage consumed is still large.

These three trends: relatively flat consumption, rapid increase in prices, and rapid increase in imports lead to the conclusion that *cheap domestic supply is decreasing*. A more tentative follow-up conclusion is that there is *unmet demand for cheap aggregates* in the United States.

Figure 9 shows a similar trend for price and imports for cement in the United States: demand is flat (Figure 7), price is increasing rapidly and imports are increasing rapidly as well. The percent of imports is also an order of magnitude larger than the aggregates.

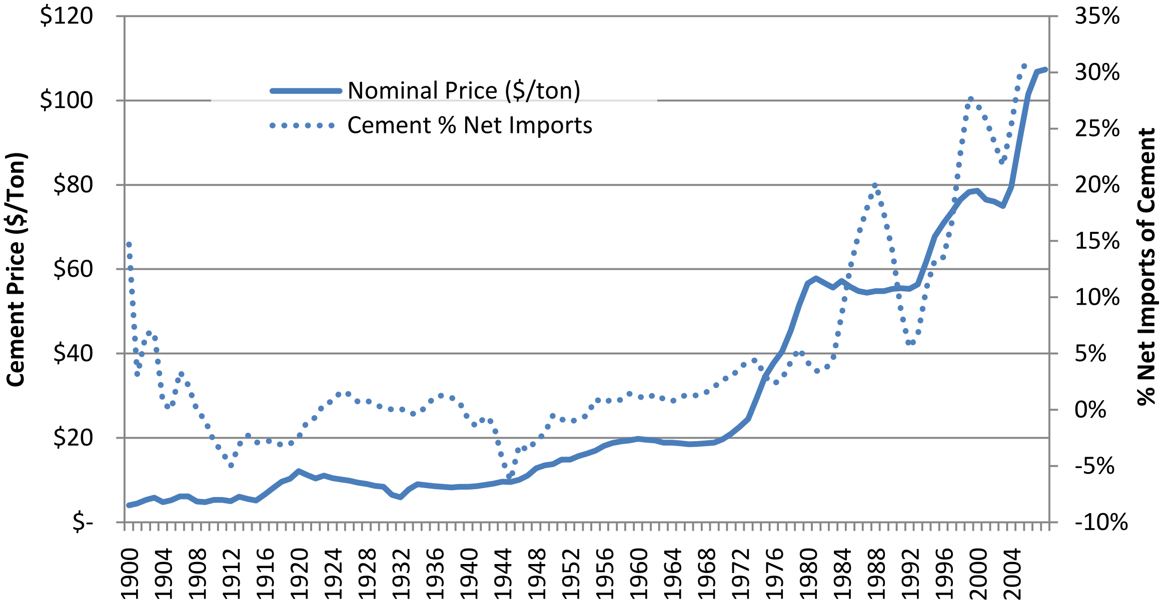

Figure 9: Historic U.S. Cement Price ($/Ton) with Percent Imported on Secondary y-axis (USGS 2008) (BLS 2008)

This trend is borne out by the import and export data for these commodities. Although historically, these are domestically produced resources, as the price goes higher and domestic supply is not increasing (or potentially decreasing given that price continues to rise as demand remains level), consumers turn to imports.

## 4.3. Steel

Steel is a material widely used in the heavy and highway construction sector, including fabricated structural steel, reinforcing bars, piping, etc. (AISI 2008). The world production of steel has been steadily rising since the end of World War 2, with a slight slowdown in the 1980s and 1990s, seen in Figure 10. Since then, there has been a rapid escalation in production as rapid growth in the BRIC countries fuels the creation of additional steelmaking capacity. As production has grown, there has been a corresponding decrease in the percent of the world's steel that the United States supplies, from over 70% during the 1940s to a low point of fewer than 10% in 2006. The high cost of transporting iron ore and raw steel means that production will likely stay in the countries with high growth rates.

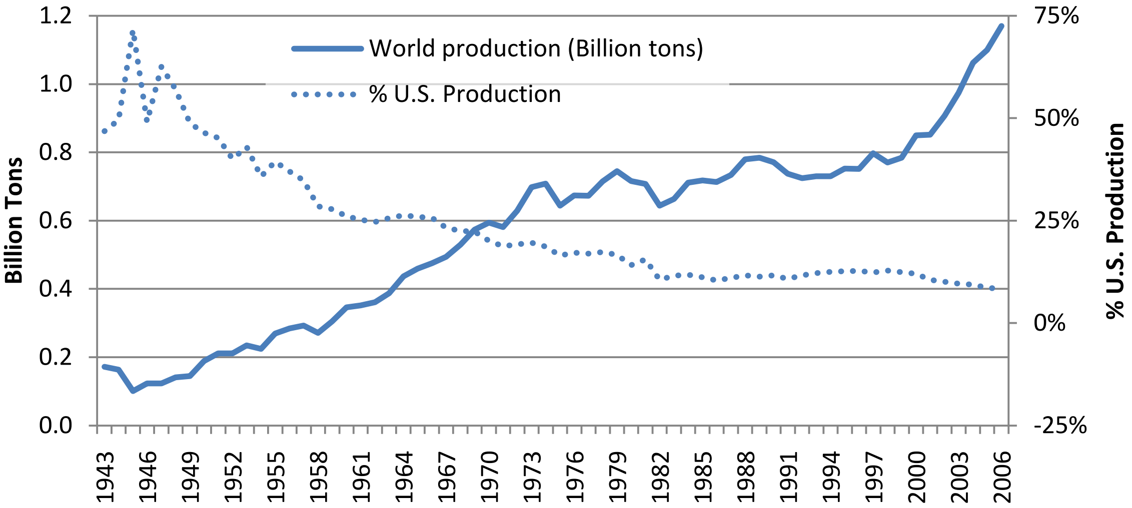

Figure 10: Historical World Steel Production in Billion Tons with U.S. Production as a Percent of World Production (USGS 2008)

Figure 11 illustrates where the U.S. has been in terms of domestic steel production. From a peak of nearly 140 million tons annually in 1970, there was a precipitous drop as production capacity moved oversees in the 1970s and 1980s. Since the end of the decline in the early 1980s, production in the United States has been steadily climbing, although it is only now reaching the levels achieved during World War 2. Another interesting note is that while there is a widely held belief that steel production in the U.S. is gone, there is an overall trend of increase in total production. The increase of consumption of steel around the world has impacted steel prices in the U.S.

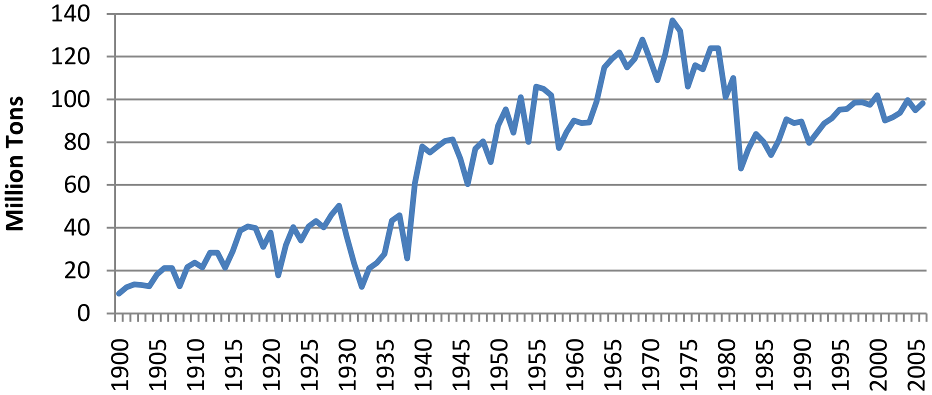

Figure 11: Historical US Production of Steel (USGS 2008)

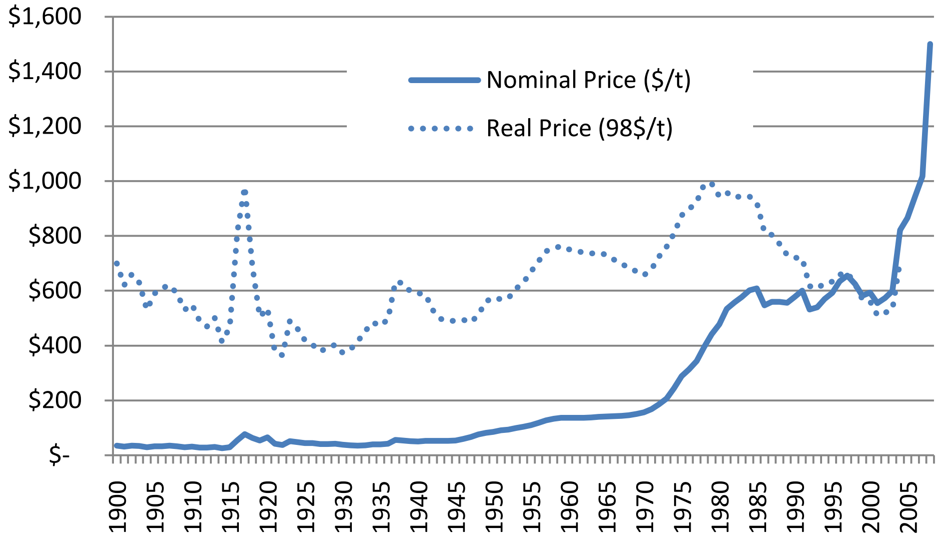

Figure 12: Historical Real and Nominal Price of Steel Per Ton (USGS 2008) (BLS 2008)

In the United States and worldwide, prices per ton of steel are rising, as production capacity strains to keep up with economic growth across the globe. In real dollar terms (adjusting for inflation), prices are showing increases after around 2000, but have seen sharper rises in price (around 1915). In nominal dollar terms (without inflation), the current economic environment is the highest prices have been, along with the sharpest increases, see Figure 12.

For recent U.S. prices, relatively stable prices throughout the 1980's and 1990's, but a sharp increase since then. Recent PennDOT data from February and March of 2008 puts the price at around $770/ton, right around the peak of the price from 2004.

It is important to note that steel companies compete on a world-wide market. Demand in China, for example, impacts prices in Pennsylvania. Buy American requires all federally funded projects to purchase American produces steel, as does PennDOT. While PennDOT has a "Buy American" mandate for steel, they will still be paying the world market prices for steel.

## 5. Industry Pulse

Several large-scale heavy and highway contractors located in western Pennsylvania were contacted for several reasons – validate national data trends, talk with local contractors about their prices and bidding experiences, and develop a general sense of the market/industry responses to recent price volatility. The individuals were lead estimators in their associated organization. The following questions were geared around the commodities and/or products under investigation in this research. These interviews were conducted in the Fall of 2008

*For asphalt and oil, the questions included:*

- Do you see prices for asphalt leveling off or continuing to climb? On a percentage basis, how much has the price of asphalt increased? How much of an impact has the price of oil had on products? Have you had any asphalt supply issues?

Participants indicated that they have seen prices go over 30%. Additionally, the prices are so volatile that prices for suppliers for bids are only valid for 5 days. One company said that they follow the PennDOT asphalt index that hit a high of $735/ton up from $325/ton last year. The diesel index was at $4.17/gallon in June 2008, but decreased to $3.30/gallon in September 2008. Despite the decrease from June 2008 to September 2008, the companies are not necessarily seeing the translation in dropping diesel prices to asphalt prices. One owner also indicated that a project came in $3 million over the estimate, due to asphalt prices. No one interviewed indicated a problem due to asphalt supply.

*For cement/concrete, the questions included:*

- Have you been involved with any projects where concrete paving was selected over asphalt paving, due to the volatility of asphalt prices? What is the general sense for concrete pricing?

Participants indicated that increases in concrete were not as severe or volatile as asphalt. One participant indicated that the increase was only about 5% from 2007 to 2008. The increases are primarily due to increase in the costs of cement and aggregates. The increase in the aggregate prices are due to fuel costs at the quarry and transportation. The increase in the cement prices are also due to energy related costs. One participant indicated that at one point during 2008 asphalt paving prices were comparable to concrete paving prices. In addition on one project, life cycle costing was considered with the results indicating that concrete paving was less expensive. The owner awarded the contract to the company with a design change to concrete paving. In general, the effect of fuel prices is impacting all commodities.

*For steel, the question included:*

- Has the price of steel been relatively consistent?

The response for steel prices varied. One participant indicated that steel prices were steadily rising, but were flat August and September 2008. Other metals were experiencing significant increases, for example, duct work was up 30 to 40% from 2007, and copper prices for piping and electrical wire are climbing considerably. Another participant indicated that fabricated structural steel was extremely volatile in 1st and 2nd quarters of 2008. The volatility is linked to the increase in the cost of scrap steel and subsequent mill surcharges. Prices in January 2008 were between $1.15 to $1.25/pound and are around $1.85 to $2/pound for fabricated structural steel. Black rebar prices were also volatile peaking at almost $1/pound. In 2007, however, the prices were steadily increasing, but were not as volatile. One participant indicated that they are tracking their price against PennDOT's recently published index, which indicated that prices were at about $765/pound in February 2008 and increased to $780/pound in March 2008.

*For aggregates, the question included:*

- Have you experienced a supply issue with respect to aggregates, specifically, aggregates meeting SRL acceptable to PennDOT? Have you experienced price increases for aggregates?

None of the participants indicated that they noticed a problem with supply. All of the participants indicated that the costs of aggregates are increasing due to quarry operations fuel costs and transportation fuels costs. While the contractors have not indicated a problem with supply, PennDOT has discussed the availability of supply in relation to the dredging of the Allegheny River. This issue will be further explored in subsequent tasks.

### General discussion

Due to the increase in conventional materials (during the Fall of 2008), it is possible to introduce new materials. None of the participants noticed an introduction of new materials; however, new projects with materials may be currently under design. One participant indicated that he is participating in a research project involving composites, but he does not believe that the material will be acceptable to PennDOT. Approval process of new materials is perceived to be difficult.

In general, every trade had increased due to fuel prices. Despite the increases, the Owners are awarding some projects, but making adjustments in their programs (e.g., awarding fewer contracts). One participant believes that prices have leveled and the market has calmed.

Trade associations were contacted (at both the national and state levels) to develop additional insight into supply, demand and pricing trends for the construction materials and commodities being considered in this study. Telephone interviews were conducted with representatives from the following organizations:

Portland Cement Association[6]
American Concrete Pavement Association (National Office and Pennsylvania Chapter)[7]
National Asphalt Pavement Association[8]
Pennsylvania Asphalt Pavement Association[9]
National Sand, Stone and Gravel Association[10]
Pennsylvania Aggregate and Concrete Association[11]
Concrete Reinforcing Steel Institute[12]

Some product manufacturers were also contacted for additional information.

The following subsections list the general questions that were asked to lead discussions during the telephone interviews. They also provide summaries of the responses received and any additional information obtained through references that were provided.

*Asphalt (Liquid) and Hotmix (Paving Material) interview questions:*

- What pricing trends do you project or predict for liquid asphalt and hotmix in the next 3-to-5 years?
- What are the main factors that drive these trends?
- Are there any expected or potential considerations or other factors that will mitigate expected pricing trends?
- Please describe any previous, current or expected supply issues and describe how they have been or will be resolved.
- Has the recent volatility of asphalt and hot-mix pricing been a primary reason for agency selections of concrete over asphalt on any construction projects?

Liquid asphalt prices have been highly volatile in recent years, particularly in recent months. In Pennsylvania, prices peaked at about $800/ton in August 2008 and have decreased slightly since that time. These prices have largely driven the cost of hot-mix asphalt paving materials, although other energy costs are also entering the equation, such as the energy required to produce aggregate for the mixtures, and the electricity and diesel fuel required to produce and transport the asphalt and hot-mix.

While some of the increase in price of liquid asphalt is clearly attributable to the increased cost of crude oil used to produce asphalt, it is believed that a significant portion of the increase is due to a desire by asphalt producers to establish a price for the commodity that will make it profitable. It was stated that asphalt production has historically been a money-losing

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[6] http://www.cement.org/
[7] http://www.pavement.com/
[8] http://www.hotmix.org/
[9] http://www.pahotmix.org/
[10] http://www.nssga.org/
[11] http://www.pacaweb.org/
[12] http://www.crsi.org/

proposition for producers. It was predicted that liquid asphalt prices would decrease from their peak levels and would eventually stabilize at a base level around $650 to $700 per ton (above which it could increase in response to increases in crude oil prices and increases in energy and transportation costs).

There have been isolated cases of shortages of liquid asphalt in the past, but these have been due to problems with additive shortages (for polymer-modified asphalts) and temporary supply disruptions, such as when Citgo was taken over by NuStar and when Venezuelan suppliers cut off the flow of pre-processed materials to the U.S. (a political action), which caused some temporary shortages until domestic supply channels were modified. In general, however, there have been no significant long-term shortages of liquid asphalt supplies in the eastern U.S. and none are expected or reasonably foreseen (although it is believed that the Midwest and Far West of the U.S. may have some liquid asphalt shortage and supply problems over the next few years).

It was noted that there are research efforts underway to develop organically-derived substitutes for asphalt (e.g., soybean-based products). These are experimental at this time (although it was reported that there is a short test section of soybean-based sealer in place in PennDOT District 11) and are not expected to be a significant source in the foreseeable future. As with concrete paving, asphalt paving costs are expected to increase only in response to inflationary increases in labor and equipment rates as well as energy and transportation costs (plus material costs, of course).

Asphalt industry staff noted the same US 22 project described by the concrete paving industry as a high-profile job that was switched from asphalt paving to concrete paving by the State after the job was let in response to the rapid escalation (volatility) of asphalt pricing.

*Concrete Interview Questions:*

- What pricing trends do you project or predict for concrete in the next 3-to-5 years?
- What are the main factors that drive these trends?
- Are there any expected or potential considerations or other factors that will mitigate expected pricing trends?
- Please describe any previous, current or expected supply issues and describe how they have been or will be resolved.
- Has the recent volatility of asphalt and hot-mix pricing been a primary reason for agency selections of concrete over asphalt on any construction projects?

Since concrete is comprised mainly of Portland cement and aggregate, and because both of these commodities are projected to be subject to modest upward pricing pressures (mainly due to increases in energy and transportation costs), the price of concrete is also expected to increase proportionately. There does not appear to be any real pressure on concrete paving pricing (i.e., labor and equipment) beyond typical inflationary pressure. Availability is not an issue; pricing is generally dictated by the market.

As mentioned previously, the Pennsylvania residential housing and commercial construction markets are considered soft at present and in the near term, and the concrete paving market is also somewhat depressed (in spite of the relatively low price of concrete paving with respect to asphalt paving) because of problems with the performance of previous concrete pavement designs (now believed to be corrected) and with the current diversion of transportation funding to bridge rehabilitation and construction.

In addition, it is believed that most pavement construction in Pennsylvania (and nationwide) will no longer consist of new full-depth construction, but will be rehabilitation and overlay construction. For concrete paving, this means fewer thick concrete pavements and more thin concrete overlays of asphalt and concrete (whitetopping and unbonded concrete overlays), resulting in less use of concrete per lane-mile than would be used in new construction. Therefore, there is not expected to significant increased demand for concrete paving products (not enough to result in demand-driven price increases) in the near future.

Industry representatives noted that the unit prices for concrete paving on the first few unbonded overlay and whitetopping construction projects in different regions of Pennsylvania may be a little more expensive than expected as the contractors build in some additional margin to cover the uncertainty associated with their lack of experience in constructing these types of pavements. Industry representatives also noted that unit prices tend to vary with the quantity of paving work available in any given region (i.e., adequate work to support local contractors and to encourage competition).

There has been at least one notable project where a construction project was recently changed from asphalt pavement to concrete pavement (US 22 in Indiana County) due to the recent volatility in asphalt pricing. Industry representatives also noted that the last few large projects that were let with an alternate bid option (all on the Mon-Fayette Expressway alignment) all went to Portland cement concrete, presumably due to the rapid recent escalation of asphalt material prices.

Some relief in concrete pricing might be obtained by moving more towards performance (“end-result”) specifications (as some states have done) and avoiding “prescriptive” specifications. This would allow contractors and ready-mixed concrete suppliers to make better use of supplementary cementing materials (i.e., fly ash, slag cement, silica fume, etc.) and chemical admixtures to produce suitable products.

*Cement Interview Questions:*

- What pricing trends do you project or predict for cement in the next 3-to-5 years?
- What are the main factors that drive these trends?

- Are there any expected or potential considerations or other factors that will mitigate expected pricing trends?
- Please describe any previous, current or expected supply issues and describe how they have been or will be resolved.

Nationwide Pricing Trends:

Cement pricing is expected to remain flat or to increase only slightly in the foreseeable future. Downward pressure on cement pricing is expected as cement consumption (nationwide) continues to decrease through 2009 (actual and projected decreases in 2007, 2008 and 2009 are 11%, 12% and 6%) due to mainly to weakness in the housing and commercial construction markets. The total peak-to-trough reduction in consumption is expected to be 30 million metric tons (MMT) per year.

This decrease in consumption is accompanied by large increases in domestic production capacity (3 MMT in 2008, 10 MMT expected in 2009), which is resulting in large market imbalances. Some of these imbalances are being offset by reductions in cement imports (from 36 MMT in 2006 to 11 MMT in 2008), but the ability to offset these imbalances through reduced imports will essentially disappear in 2009.

The production and transport of Portland cement is very energy-intensive. From mining and transport of raw materials, to processing of the materials, to distribution of the finished product, electricity and various fuels are consumed at every step along the way. The steady (and recently rapid) increases in energy prices have offset the negative pressure on prices due to supply and demand imbalances, resulting in overall small increases in cement pricing in recent years.

Pennsylvania Pricing Trends:

Demand for cement is Pennsylvania has decreased in recent years as (similar to the national situation) housing and commercial construction demand is currently flat (or decreasing). In addition, the demand for concrete paving has also decreased somewhat due to problems with the performance of some roads that were built using previous standard concrete pavement designs (with long panels and foundation design issues) and an increased in-state emphasis on pavement ride quality. The concrete paving industry responded with improved pavement designs (featuring shorter panels and stiffer foundations) and improved construction techniques (to result in improved initial ride quality), and the performance (to date) of concrete pavements built in Pennsylvania using these designs and construction techniques has been good. As a result, confidence in concrete pavement design and performance is increasing. Therefore, the demand for cement for concrete paving work might be expected to increase in the near future. However, PennDOT has increased the emphasis on bridge repairs and reconstruction, so the funding available for new pavement construction has not increased significantly (and may have decreased). The bottom line is that demand for cement in Pennsylvania has decreased in recent years.

On the supply side, Pennsylvania is home to at least 7 different cement manufacturers (some with multiple production facilities in the state) and is the 4th largest producer of cement in the nation, exporting (to other states) about 60% of the cement produced here, so potential in-state sources of cement supplies are excellent.

The net view of the supply and demand picture for cement in Pennsylvania is that currently there is excess locally produced supply and relatively weak demand for the commodity. There have been no major changes (decreases) in cement pricing due to this imbalance, however; increases in the costs of energy and transportation are probably mainly responsible for any recent slight increases in cement pricing in Pennsylvania.

Supply Issues:

In 2004, there was a shortfall in cement supply to the U.S. due to lack of adequate domestic production capacity, an interruption in import supplies, and changes in U.S. trucking regulations.

The interruption in import supplies was due mainly to increases in foreign demand for cement (especially in China and India), resulting in the diversion of some foreign cement to these markets. These same markets greatly increased their consumption of steel (both scrap and new material), which required the use of container vessels (that had previously been used for bringing imported cement to the U.S.) to transport the steel.

Changes in U.S. trucking regulations at the same time (i.e., limits on numbers of hours worked by drivers and changes in the way those hours were accumulated on a daily basis) often disrupted the flow of goods and services and commodities (including cement) across the U.S.

As a result of these issues, there were cement shortages and “allocations” of product in 2004. Since that time, U.S. production capacity has increased dramatically (it was never deficient in Pennsylvania to begin with) and the shipping and trucking industries have adjusted to changes in the transportation of the product. No one interviewed thought that there was any significant likelihood of experiencing another cement shortage in the foreseeable future.

*Aggregate Interview Questions:*

- What pricing trends do you project or predict for aggregate in the next 3-to-5 years?
- What are the main factors that drive these trends?
- Are there any expected or potential considerations or other factors that will mitigate expected pricing trends?
- Please describe any previous, current or expected supply issues and describe how they have been or will be resolved.

Aggregate costs have generally increased greatly in recent years and this trend is expected to continue. Much of the increase in costs is due to increases in energy costs required for production and transportation. However, there are also some price increases due to local supply/demand issues for certain types and classes of aggregate. There is also an expectation of additional cost due to increased industry (specifically environmental-related) regulation.

The concrete industry believes that the days of having virtually unlimited supplies of Class A aggregate (for concrete paving mixtures) are behind us. Many of the best sources of this material have been depleted, resulting in local shortages of supply. It has been suggested that these shortages might be alleviated (at least in part) by adopting two-lift concrete pavement construction techniques where Class A aggregate is used in a relatively thin surface lift while marginally acceptable aggregate (e.g., aggregate from the Vanport seam, recycled concrete aggregate or other sources) is used in the thicker lower lift.

The asphalt paving industry notes that supplies of good skid-resistant surface aggregate (Class E) are inadequate in some areas, particularly in the eastern part of Pennsylvania, but also in pockets throughout the state. It was noted that environmental restrictions and local resident resistance ("NIMBY" attitudes) make it almost impossible to open new quarries where good sources are known to exist. The increased costs of aggregate (from \$2 – 3/ton just a few years ago to \$4 – 5/ton now) are responsible for significant portions of the increased cost of hot-mix in recent years.

It is believed that increased recycling of hot-mix asphalt and Portland cement concrete can help to alleviate upward pricing pressures on aggregate throughout Pennsylvania. These techniques are widely used in many states and may be underutilized in Pennsylvania.

Slag aggregate has also been considered a possible alternate to natural virgin aggregate, but there have been questions concerning the durability and aggregate interlock load transfer capacity of this material, so it is not likely a good candidate for widespread use.

There is some ability to bring in high-quality aggregate from Michigan by boat (to Lake Erie ports). Historically, it has also been possible to import aggregate by rail, although rail transportation of "secondary products" like aggregate is becoming more difficult to arrange due to increased demand for rail transport of other products, resulting in lower rail capacity and higher rail transport pricing. Rail and boat imports cannot totally alleviate PA aggregate supply and cost problems because of their limited capacity (including the need for expanded rail infrastructure) and the need to truck supplies from the ports and railheads to the job sites, resulting in added transportation costs.

Aggregate blending has been suggested as another means (utilized in some states) to extend good aggregate sources and increase the use of marginal aggregate sources.

*Steel Interview Questions:*

- What pricing trends do you project or predict for reinforcing steel and dowel bars in the next 3-to-5 years?
- What are the main factors that drive these trends?

- Are there any expected or potential considerations or other factors that will mitigate expected pricing trends?
- Please describe any previous, current or expected supply issues and describe how they have been or will be resolved.

There appears to be no way of accurately predicting short-term pricing trends for most steel construction products. There has been a huge run-up in steel demand and pricing (to about $1000/ton) over the last few years as developing countries (particularly China) developed huge demand for scrap steel. That demand has dissipated greatly in recent months and steel prices have dropped by about $200/ton. Interestingly, this reduction in commodity pricing has been reflected in the pricing of reinforcing steel (rebar), but not so much (to date) in the pricing of structural sections (beams and girders).

The longer-term picture for steel is that pricing is likely to remain high due to the normal mechanics of supply and demand. Worldwide demand for metallics is expected to trend back upward after the current downturn. Markets in countries like BRIC and even the Middle East Region are expected to continue to grow rapidly. Domestic demand predictions for structural steel are also bullish, with one recent study predicting that commercial building space requirements will double (to about 400 billion s.f.) between now and 2030, and that many existing structures will need to be rehabilitated or reconstructure. Meanwhile, global sources and supplies of iron and many other construction metals are expected to remain tight in the context of this increased demand.

In addition, the financial wealth of some areas of the Middle East and Asia will help to maintain steel pricing at higher levels. For example, it has been reported that some developers in these areas have been willing to spend $1250/ton on steel products produced in the U.S., resulting in their diversion from local markets that were only willing to pay $950/ton.

It should also be noted that the lead time required to produce and deliver structural steel elements has increased in recent months (reportedly up to 20 weeks for some projects). Such delays can be attributed, at least in part, to supply issues and uncertainties in pricing, which lead manufacturers to decrease inventories of specific products.

The continued high pricing of structural steel, along with advancements in concrete materials and construction techniques) is expected to lead to an increase in the construction of concrete structures – both bridges and commercial structures – as it already has in many developing countries. Anecdotally, many domestic building construction projects are being (or have been) changed from steel to concrete (including some high profile projects, such as the Trump Towers now being completed in Chicago, Illinois). Further, a June 2008 AASHTO survey of state DOTs revealed that many states are greatly decreasing the number of bridges that they construct using structural steel elements. The decrease in steel demand resulting from these changes of practice are not expected to significantly offset the overall anticipated increases in demand for steel worldwide.

Steel reinforcing is still a key element in reinforced concrete construction, which is also seeing an increase in activity (as described previously). There is increased emphasis on corrosion resistance for steel in marine environments and in areas with exposure to deicing salts and other corrosive agents (e.g., bridge decks, parking structures, etc. in northern states). This emphasis has led to increased consideration (and some use) of noncorroding and corrosion-resistant alternatives to traditional carbon steel and epoxy-coated carbon steel reinforcing steel, including fiber-reinforced polymer/plastic (FRP) reinforcing bars, stainless steel-clad and solid stainless steel bars, through-alloy bars, dual-coated zinc and epoxy rebars and zinc-clad bars. With the exception of the FRP products, all of these alternate products are metallic and are subject to many of the same pricing pressures as traditional steel reinforcing products. Most of the corrosion-resistant metallic products are also priced substantially higher than carbon steel bars. FRP products offer the potential substantial implementation, but have different behavioral characteristics and durability issues than do metallic products and have not been widely adopted.

# 6. Economic Analysis

This section involves the forecasting the aforementioned construction commodities. We have organized this section in the following manner for each commodity:

- Pricing: dollars/mass function on the y-axis with time on the x-axis
- Production: mass functions on the y-axis with time on the x-axis
- Consumption: mass functions on the y-axis with time on the x-axis
- Environmental: dollar/mass of carbon on the y-axis with time on the x-axis.

The next major section reviewed alternative materials and construction techniques.

## 6.1. Review of forecasting methods

Forecasts are needed for the decision-making process to be more effective (Makridakis and Wheelwright 1978). Organizations and companies use forecasting in order to make their decision-making process more rigorous and decrease the dependence on chances or luck (Makridakis and Wheelwright 1978). Some of the areas within a company or organization where forecasting can be implemented include the following:

- Scheduling: staff, resources
- Planning: financial, production, facilities
- Inventory management
- Process control (Makridakis and Wheelwright 1978; Montgomery, Johnson et al. 1990)

In order to perform forecasting for any type of problem a series of steps need to be followed. Figure 13 is a graphical representation of the stages involved in the forecasting process. The boxes in the diagram show the steps in the process. It is a procedural mechanism, where steps should be followed in the sequence presented. The first step is a problem statement; step two is data-gathering. The forecasting model selection takes place in the third step of the process. Implementation and evaluation of the models are steps four and five respectively. The dashed line denotes the iterative process (Armstrong 2001).

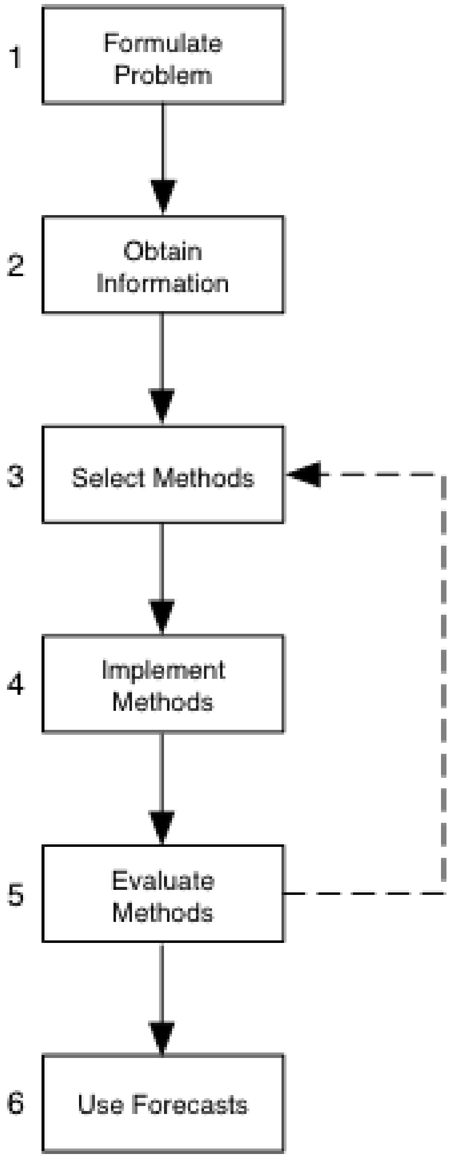

Figure 13: General Process Flow Diagram for developing Forecasting Methods (Armstrong 2001)

There are four main categories of forecasting methods (Makridakis and Wheelwright 1978; Montgomery, Johnson et al. 1990; Wikipedia 2009):

- Time series methods: These methods use previous data in order to estimate the future outcome. Time series analysis is an approach to choose the model that describes the series and then forecast the future events (Jensen 2004).

  Some examples of the series analysis methods are:
  - Moving average
  - Trend estimation
  - Several smoothing techniques
- Causal methods: These methods use models that use factors that might influence the outcome of the forecast, it is usually explained through a cause-effect relationship (Makridakis and Wheelwright 1978).

Some of the models that can be used for forecasting within the causal methods are:

    - Regression analysis
    - ARIMA (autoregressive integrated moving average). Contreras et al (2003) used two ARIMA models to predict the next day price of electricity in Central Spain and in California. Their results show that the models used for the forecast is the adequate one and even though there are differences between both locations (Spain and California) and their errors, the forecast is accurate.
    - Econometrics
        - ARCH/GARCH (autoregressive conditional hetersocedasticity, generalized autoregressive conditional heteroscedasticity). For example, Charles (2008) in her work regarding *Forecasting Volatility with Outliers in GARCH models* (AmÈlie 2008), notes that it seems viable to forecast volatility with GARCH taking into account all available data (including outliers).
- Qualitative methods: Based on experts opinion or experience (Armstrong 2001)
    - Surveys
    - Delphi method
    - Analogy
- Others
    - Artificial neural networks

This research will use causal models, specifically GARCH and regression analysis, because of the type of available data for the commodities.

## 6.2. Forecasting Method

### 6.2.1. Linear method

Using the historical time series information of varying lengths for each commodity, we use basic least squares regression to fit curves to the data. Applying the resulting functional form, we forecast results.

There is a tradeoff between choosing a functional form which maximizes the r-squared value of the regression (a measure of the quality of the fit), and one which minimizes the complexity of the form. As such, for time series regressions, we generally selected linear or 2nd-order polynomials, since they provide reasonable fits without the complexity of a high number of terms. A certain amount of judgment exists when selecting the length of the time series used in the regression. For instance, in Figure 14, results of a regression which use all the data is different from regression which uses last year data. The length of the data that is used to calculate the regression also influences the 2nd-order polynomials.

The green dashed line in Figure 14 is the linear regression when using half of the historic data set of diesel prices. The forecasted data for that regression is the solid orange line. In contrast, the blue dashed line corresponds to the linear regression of the data from the last 6 months; the solid blue line is the forecast of that data set's linear regression. Given the differences in the forecast, choosing the period and length of data is significant.

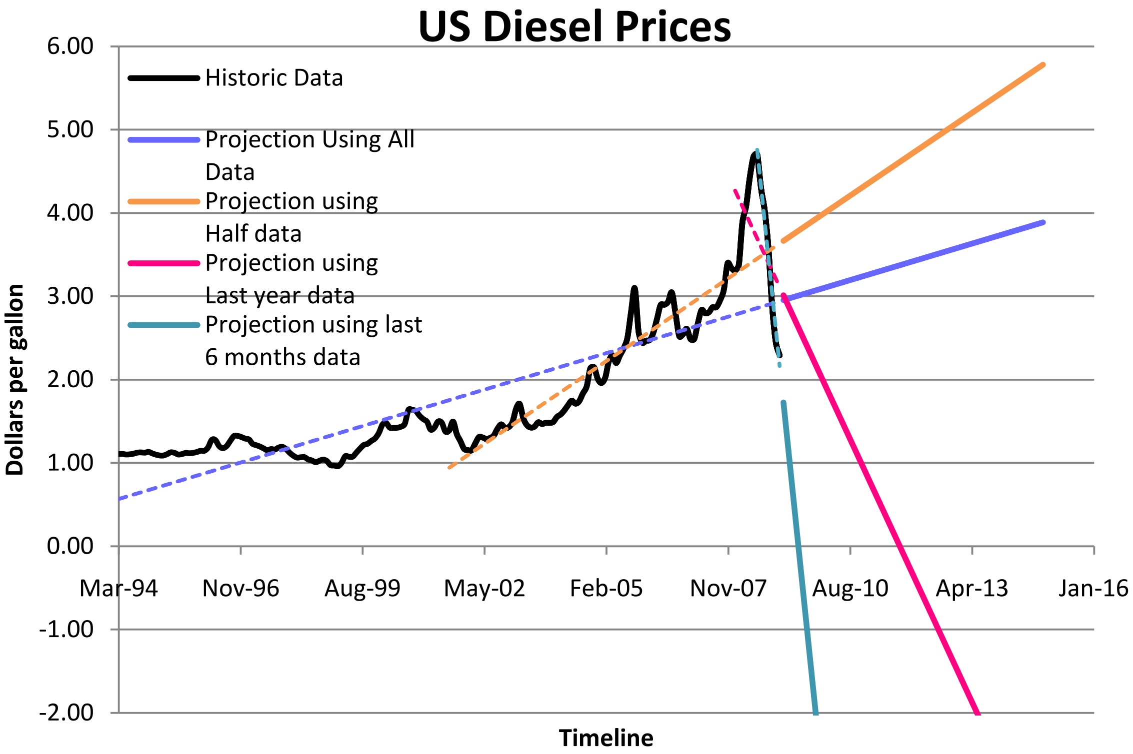

Figure 14: First Order Regression Forecasting Diesel Prices with Different Data Lengths

### 6.2.2. GARCH

GARCH is a non-linear model used traditionally in forecasting financial time series. This function takes into account volatility, variability and the recent past history to predict the future behavior. This particular function uses past occurrences to explain the future ones. The account of volatility and clustering of the data into this model gives a better forecasting result than a linear regression.

In Figure 15 the red dotted line corresponds to the forecasted data using GARCH for diesel prices. Using this function, the forecasted data begins where the historic data ends.

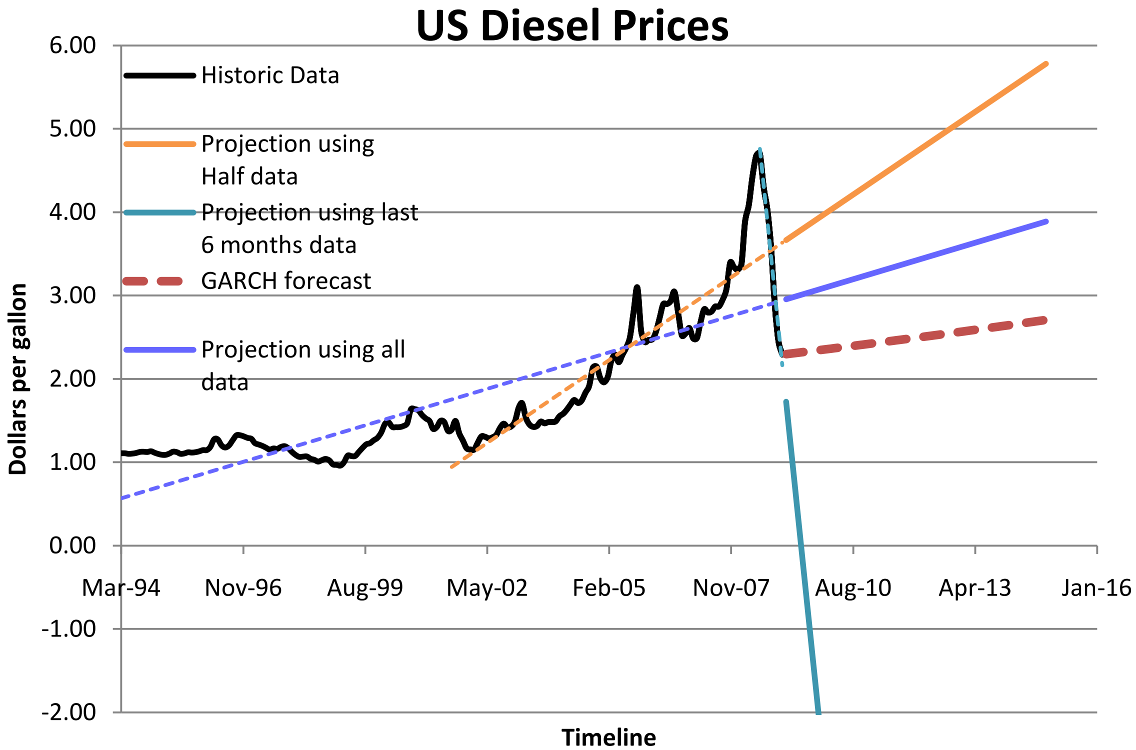

Figure 15: First Order Regression and GARCH Forecasting Prices

### 6.2.3. Validation

In order to validate our method, we used diesel historic prices (from March 1994 until October 2005) and forecasted the prices from November 2005 to January 2020. In our validation, it can be noticed that the lower and upper regression set a boundary for the forecasted prices. The forecasted prices with GARCH fall between the upper and lower regression. See Figure 16 for validating the model used in the forecasting process. The higher and lower regression boundaries give an idea of the general tendency of the prices. Even though there are prices outside the boundaries, the general tendency of the prices is captured with the combination of our projections.

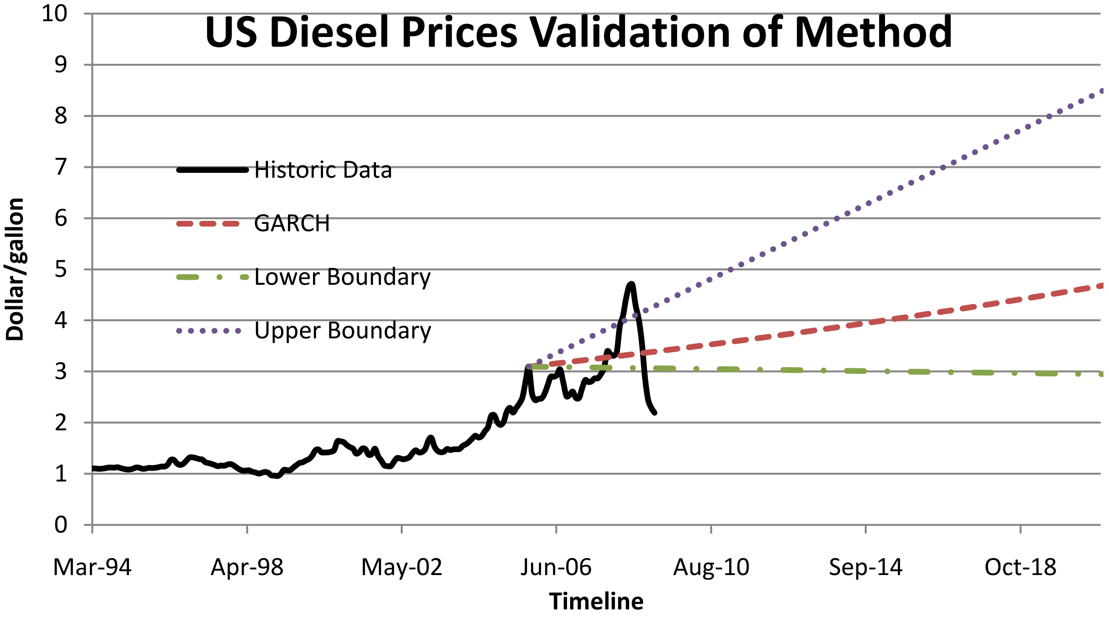

Figure 16: Validation of Model Using Forecasting US Diesel Prices

#### 6.2.4. Combination

In order to have a robust forecasting method, we combined both models described above (first order linear regression and GARCH). The main reason for this approach is that we have the ability to give ranges of prices instead of a single value at a given time - GARCH incorporates volatility; first order regression gives us general tendency. The "result" is a suitable ranges of future prices.

### 6.3. Materials

For each material, we developed the following forecasts:

- Dollar/unit versus time
- Production versus time
- Consumption versus time
- Carbon tax

## 6.3.1. Petroleum products

### *6.3.1.1. Diesel*

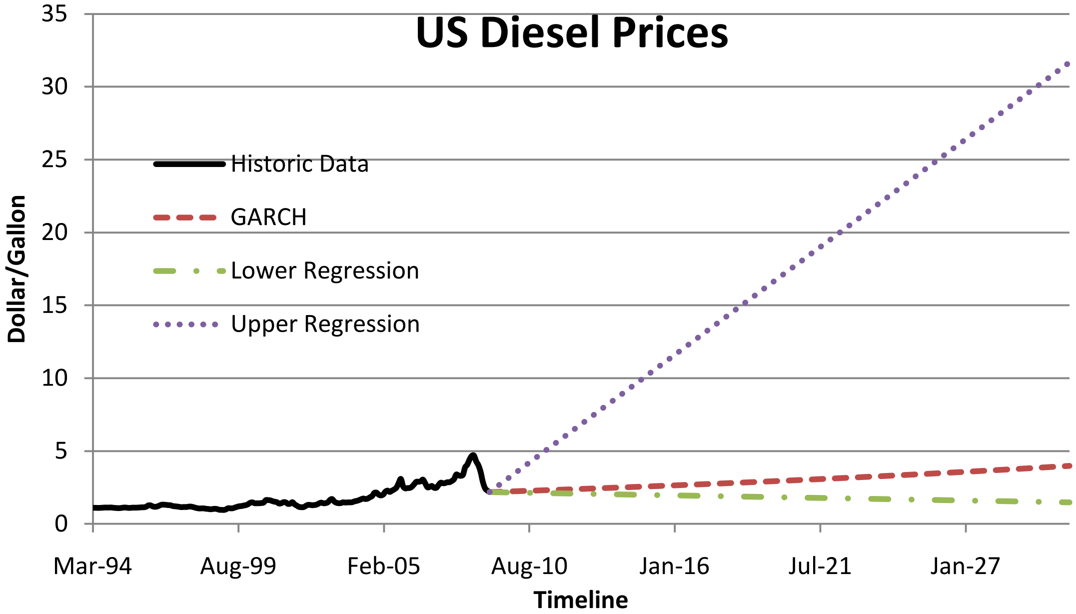

Figure 17: Forecast of US Diesel Prices

Table 9: US Prices of Diesel at Different Time Periods ($/gallon)

| | Lower Regression | GARCH | Upper Regression |
|---|---|---|---|
| January 2010 | 2.16 | 2.25 | 3.43 |
| January 2015 | 1.99 | 2.57 | 10.18 |
| January 2020 | 1.83 | 2.95 | 16.93 |
| January 2030 | 1.47 | 3.87 | 31.68 |

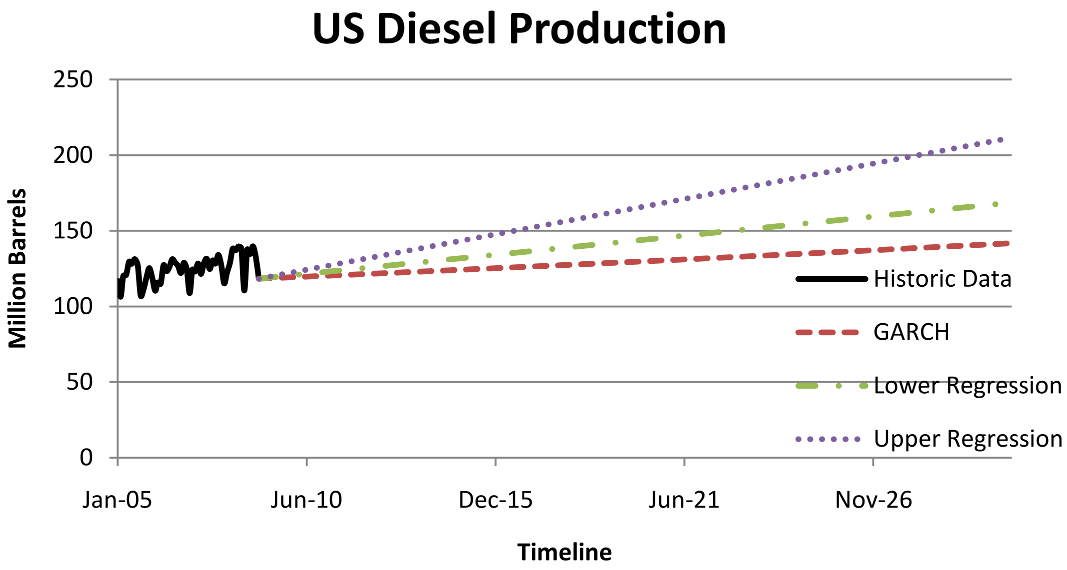

Figure 18: Forecast of Diesel Production

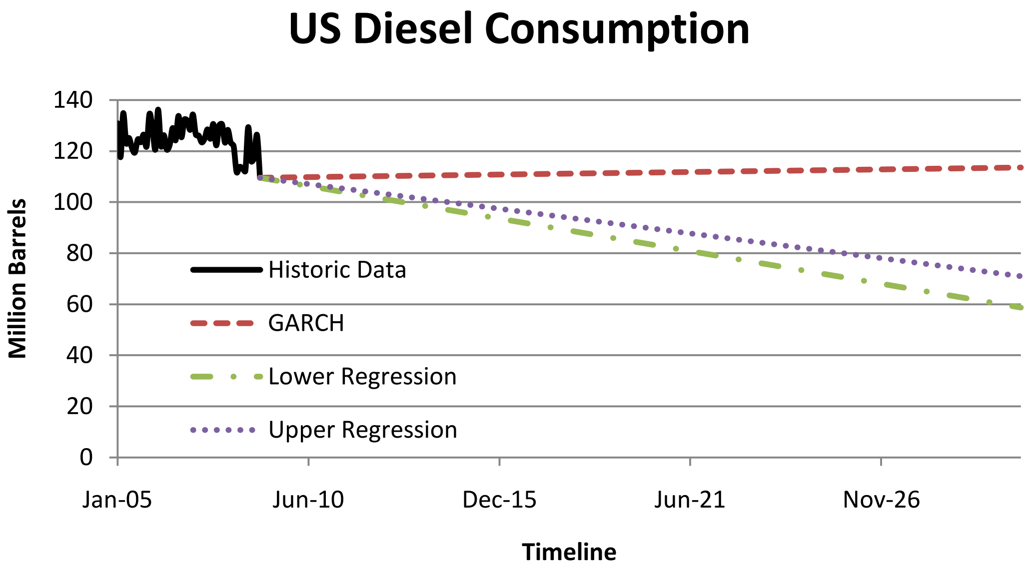

Figure 19: Forecast of Diesel Consumption

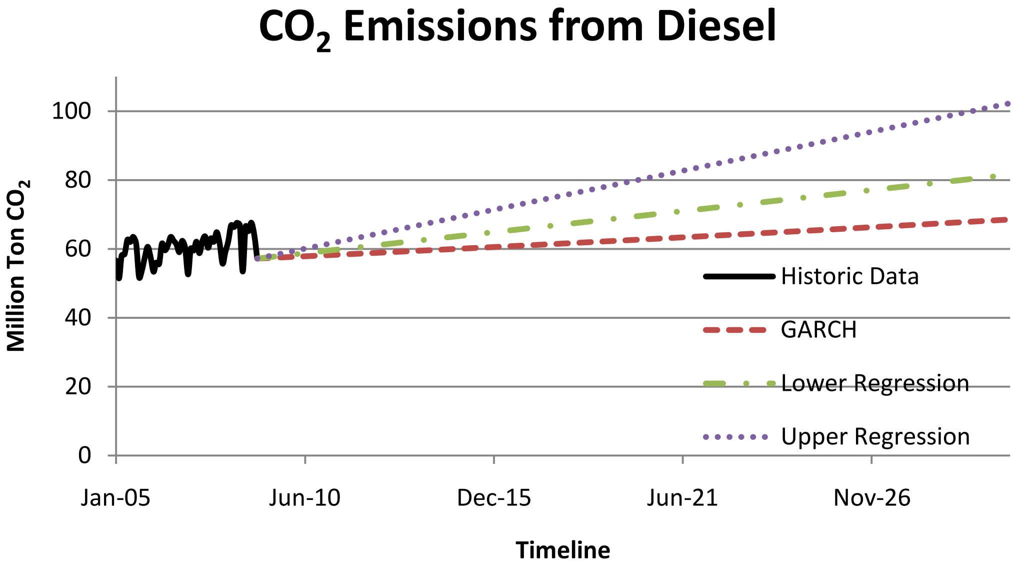

Figure 20: $CO_2$ Emissions from Diesel

Figure 17 through Figure 20 focus on diesel in terms of pricing, production, consumption, and carbon dioxide emissions. With respect to Figure 17, the upper regression shows prices for diesel following the similar increase of energy prices to that seen in the summer of 2008. The upper limit of the forecast is for a prolonged increase of that magnitude. This price will actually plateau at the price of the cheapest alternative, e.g. biodiesel, since no one would be willing to pay $10 or $16 per gallon. The GARCH forecast shows a slow but steadily accelerating price that does not replicate the recent short-term volatility. The decrease in price is not likely without significant demand reductions, which would be the case if a major alternative was mandated.

Production (Figure 18) and consumption (Figure 19) of diesel is currently around 120 million barrels of per year, with production outpacing consumption slightly. These values are obviously related, with each other as well as with the price in the previous forecast. Conclusions must be drawn by taking all three in to consideration rather than dealing with them individually. Production of diesel fuel, for instance, has steadily increased, but recently, high prices, unrelated to a lack of production lead to a drop in a demand. This leads to a surplus and a corresponding drop in prices. A drop in consumption like that seen in the regressions below would be the result of a similar glut in supply, caused, perhaps by the availability of a cheap alternative.

#### *6.3.1.2. Asphalt*

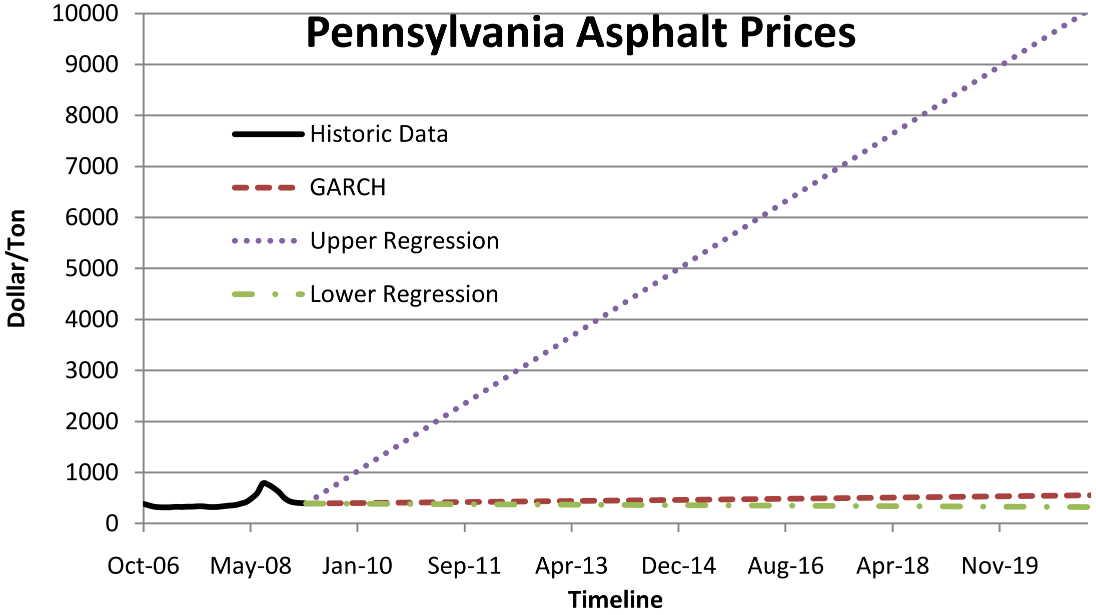

**Figure 21: Forecast of Asphalt Prices in Pennsylvania**

**Table 10: Prices of Asphalt in Pennsylvania at Different Time Periods ($/ton)**

| | Lower Regression | GARCH | Upper Regression |
|---|---|---|---|
| January 2010 | 389.65 | 402.48 | 998.12 |
| January 2015 | 360.68 | 463.91 | 5025.62 |
| January 2020 | 331.71 | 534.71 | 9053.12 |
| January 2030 | 268.46 | 729.13 | 17846.5 |

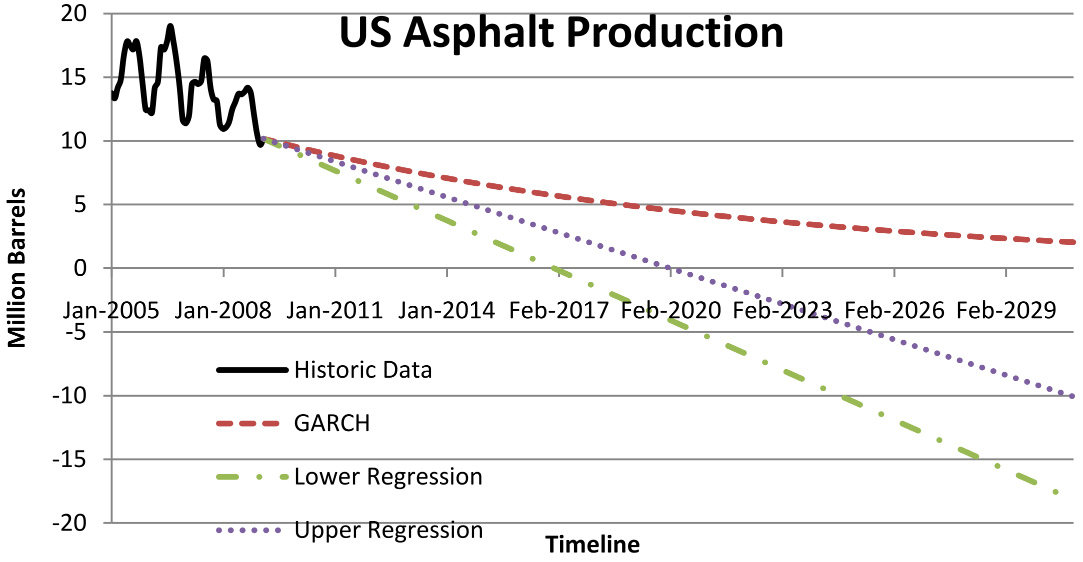

Figure 22: Forecast of Asphalt Production in the US

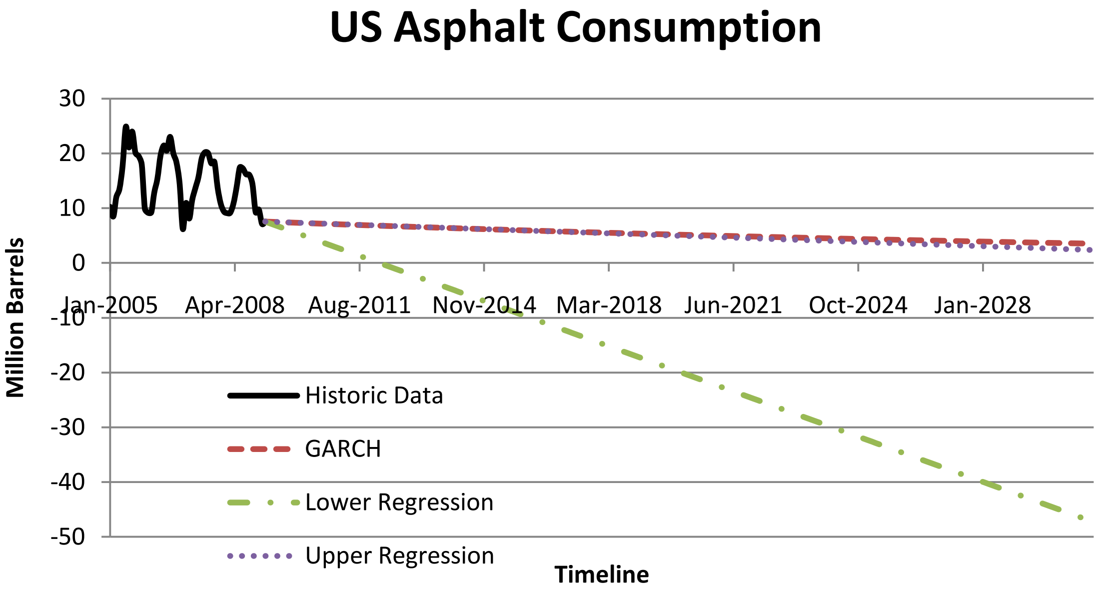

Figure 23: Forecast of Asphalt Consumption in the US

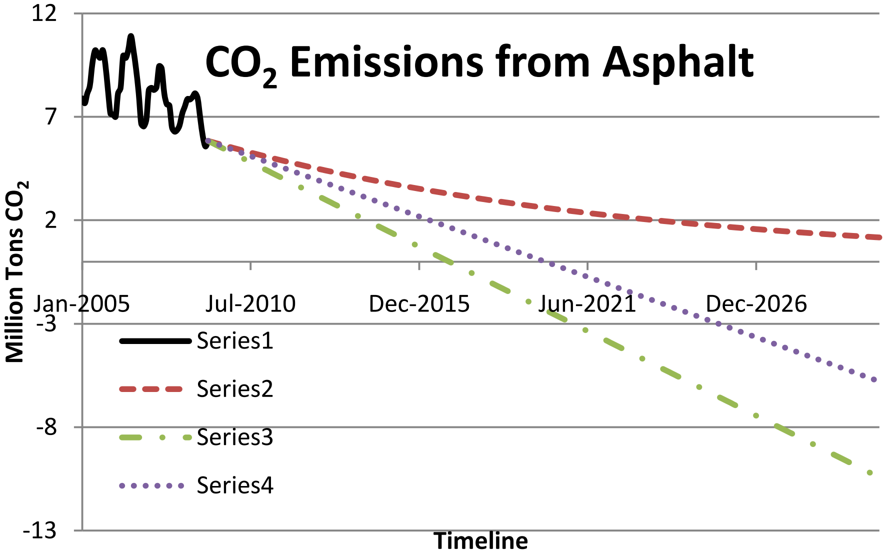

Figure 24: $CO_2$ Emissions from Asphalt

Figure 21 through Figure 24 focus on asphalt in terms of pricing, production, consumption, and carbon dioxide emissions. With respect to Figure 21, the situation for asphalt in many ways reflects that seen in diesel fuel, with the additional complication that the volume of asphalt produced from a given barrel of petroleum is reduced based on the value of the other potential products, such as fuels. The upper regression mirrors the recent price spike. Similarly to diesel fuel, an alternative material would be found in the market place before the price reached $2000 per ton, but if the pace of growth is as rapid, there will be serious challenges to projects using asphalt in the short term.

The production forecast (Figure 22) shows the steady decline in the volume of asphalt being produced, with many scenarios pointing to near-zero production of asphalt. This could mean high priced fuel and corresponding reduction of asphalt as a by-product, increasing the price and movement to an alternative. Consumption (Figure 23), likewise is steadily decreasing, and appears likely to continue in that direction.

## 6.3.2. Cement and Aggregate

### *6.3.2.1. Cement*

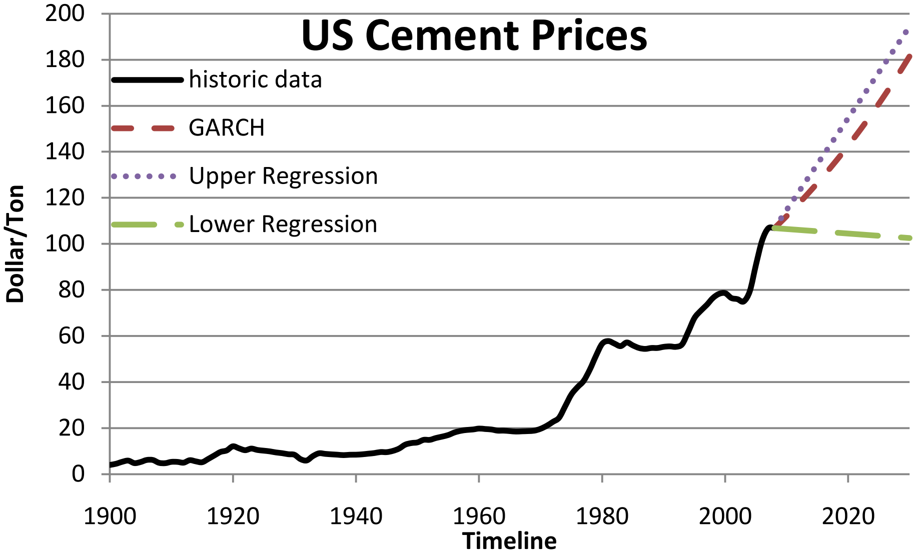

Figure 25: Forecast of Cement Prices in the US

Table 11: Prices of Cement in the US at Different Time Periods ($/ton)

| | Lower Regression | GARCH | Upper Regression |
|---|---|---|---|
| 2010 | 106.40 | 112.077 | 114.76 |
| 2015 | 105.42 | 126.42 | 134.67 |
| 2020 | 104.44 | 142.61 | 154.58 |
| 2030 | 102.48 | 181.48 | 194.4 |

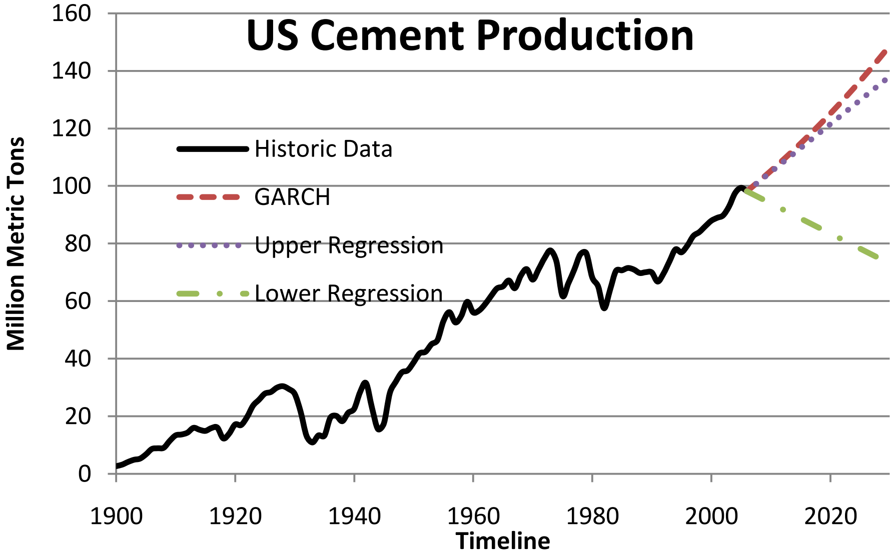

Figure 26: Forecast of Cement Production in the US

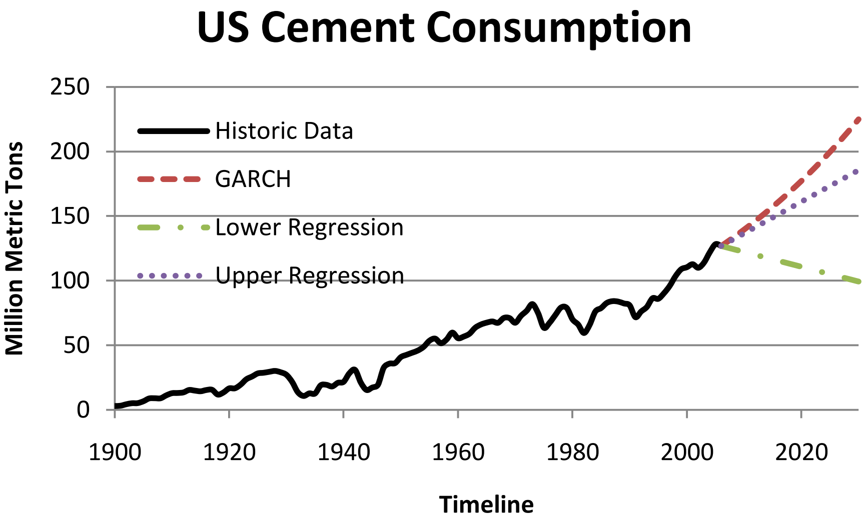

Figure 27: Forecast of Cement Consumption in the US

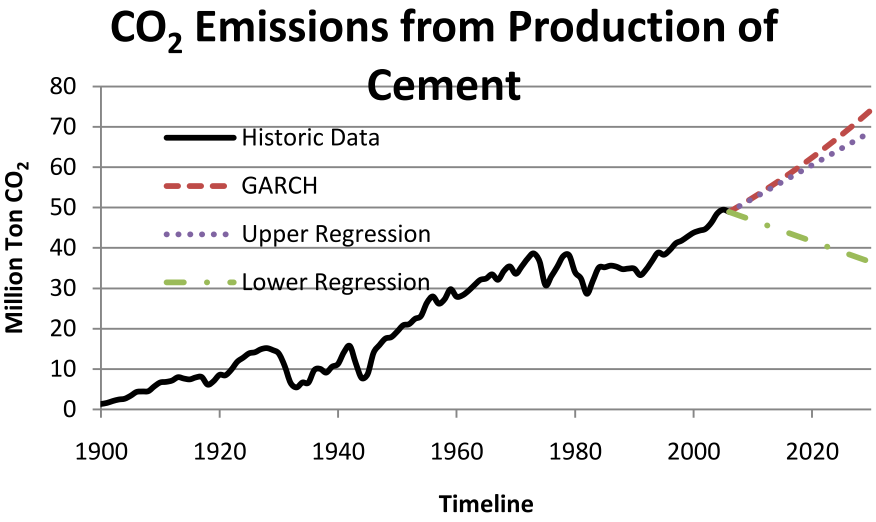

Figure 28: CO2 Emissions from Production of Cement (Emission factor is 0.4985 Ton/CO2 cement produced (IPCC 2009)

Figure 25 through Figure 28 focus on cement in terms of pricing, production, consumption, and carbon dioxide emissions from production of cement. In terms of pricing, the upper regression projections and GARCH projections are relatively closely matched. The upper regression projection represents the highest values, lower regression represents the lower values, and GARCH falls in between the upper and lower regression projections. At the one year interval the price ranges between approximately $112 and $115; at the five year interval the price range increases slightly between $126 and $135; at the ten year interval the range is between

$142 and $154; and the last interval at thirty years is between $181 and $194. The lower regression extends in the negative direction. This information is summarized in Table 11.

Figure 26 (production) and Figure 27 (consumption) continues to represent the relationship of an increases continues to represent the relationship between production and consumption for cement in that production is lower consumption. For example, in 2009, production was approximately 100 million metric tons, and consumption was 125 million metric tons. This relationship is consistent with the price index of concrete as indicated in Figure 2. During the turbulent time period in 2008 to 2009, the concrete price primarily exhibited a slight upward trend in contrast to asphalt and diesel.

### *6.3.2.2. Aggregate*

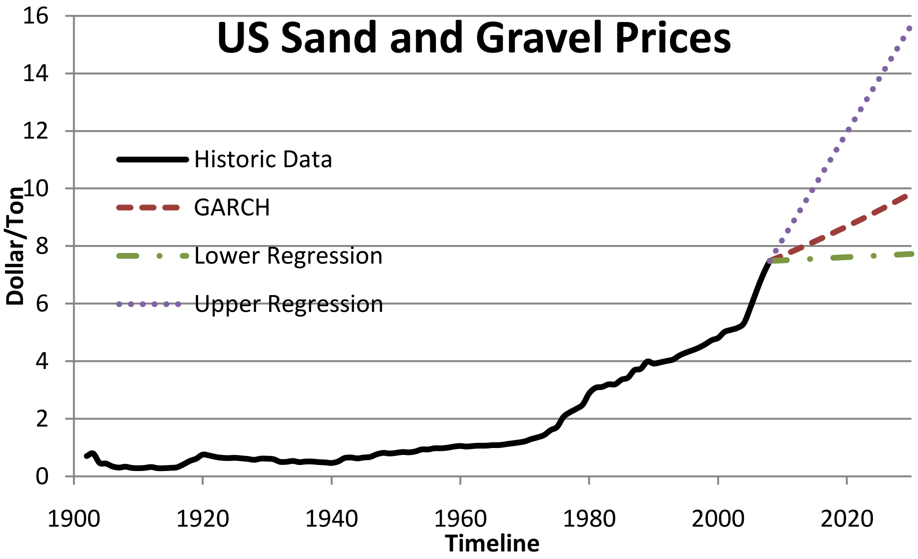

**Figure 29: Forecast of Sand and Gravel Prices in the US**

**Table 12: Prices of Sand and Gravel in the US at Different Time Periods ($/ton)**

| | Lower Regression | GARCH | Upper Regression |
|---|---|---|---|
| 2010 | 7.50 | 7.66 | 8.22 |
| 2015 | 7.55 | 8.16 | 10.08 |
| 2020 | 7.61 | 8.68 | 11.95 |
| 2030 | 7.72 | 9.83 | 15.68 |

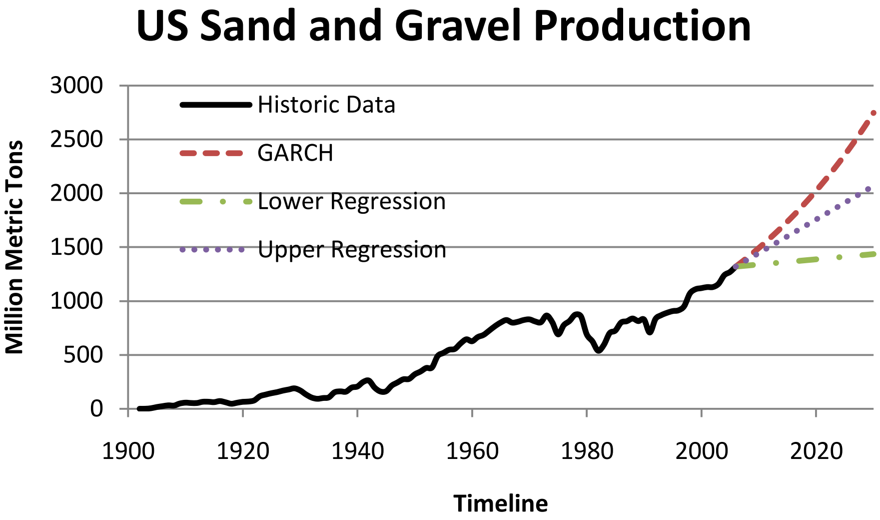

Figure 30: Forecast of Sand and Gravel Production in the US

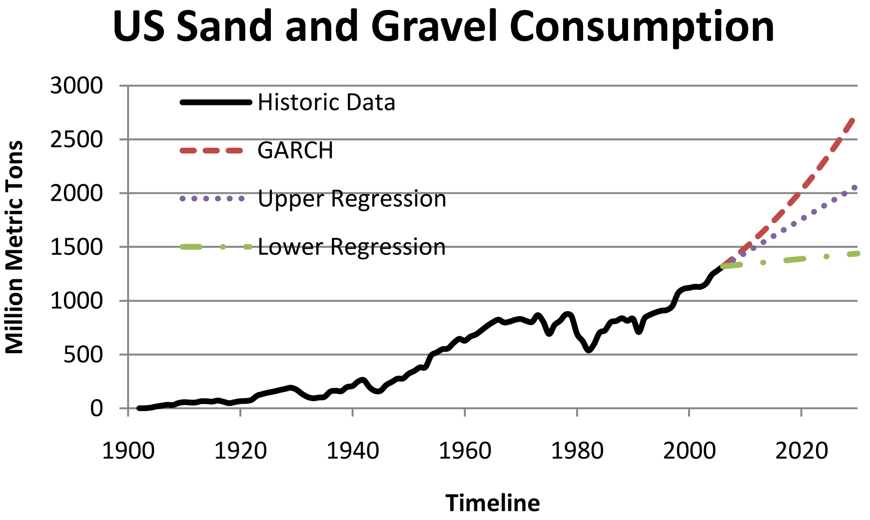

Figure 31: Forecast of Sand and Gravel Consumption in the US

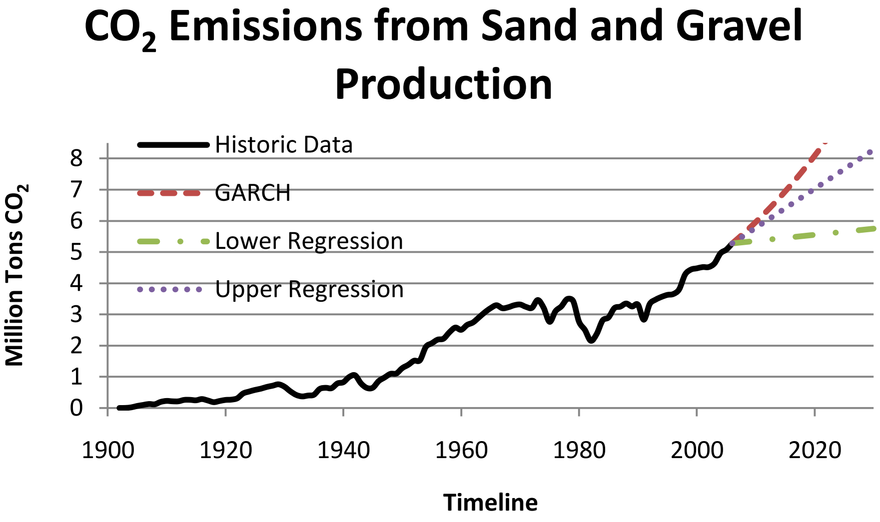

**Figure 32: $CO_2$ Emissions from the Production of Sand and Gravel (Emission Factor: 0.004 ton CO2/Ton aggregate (CMU 2009))**

Figure 29 through Figure 32 focus on sand and aggregate in terms of pricing, production, consumption, and carbon dioxide emissions. In terms of pricing, production, consumption and CO2 emission, the three projections have a fairly large range. For pricing, the upper regression projection represents the highest values, lower regression represents the lower values, and GARCH falls in between the upper and lower regression projections. For production, consumption, and CO2 emission, GARCH represents the highest values, lower regression represents the lower values, and upper regression falls between GARCH and lower regression projections. With respect to pricing, the one year interval price ranges between approximately \$7.50 and \$8; the five year interval price ranges between approximately \$7.55 and \$10; the ten year interval prince ranges between \$7.61 and \$11.95; and the last interval at thirty years is between \$7.72 and \$15.68. This information is summarized in Table 12.

Figure 30 and Figure 31 represent the relationship between production and consumption for sand and gravel. In 2005 and 2007, the consumption and production were fairly well matched with production and consumption both 1.2 million metric tons. While the three forecasts illustrate a consistent trend between consumption and production for each trend, the disparity between any of the three can lead to a significant price differences. For example, higher consumption as projected with GARCH with lower production as projected with the lower regression can lead to higher prices.

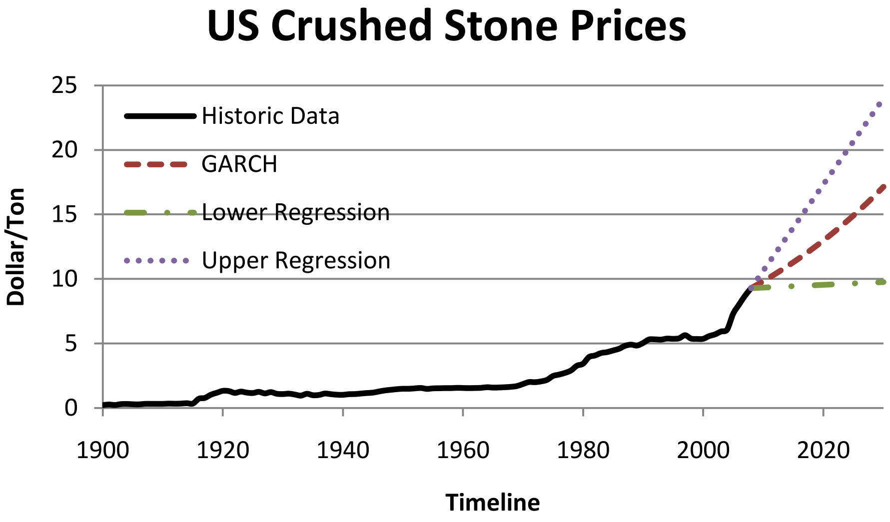

Figure 33: Forecast of Crushed Stone Prices in the US

Table 13: Prices of Crushed Stone in the US at Different Time Periods ($/ton)

| | Lower Regression | GARCH | Upper Regression |
|---|---|---|---|
| 2010 | 9.33 | 9.82 | 10.62 |
| 2015 | 9.43 | 11.28 | 13.97 |
| 2020 | 9.54 | 12.96 | 17.31 |
| 2030 | 9.75 | 17.12 | 24.00 |

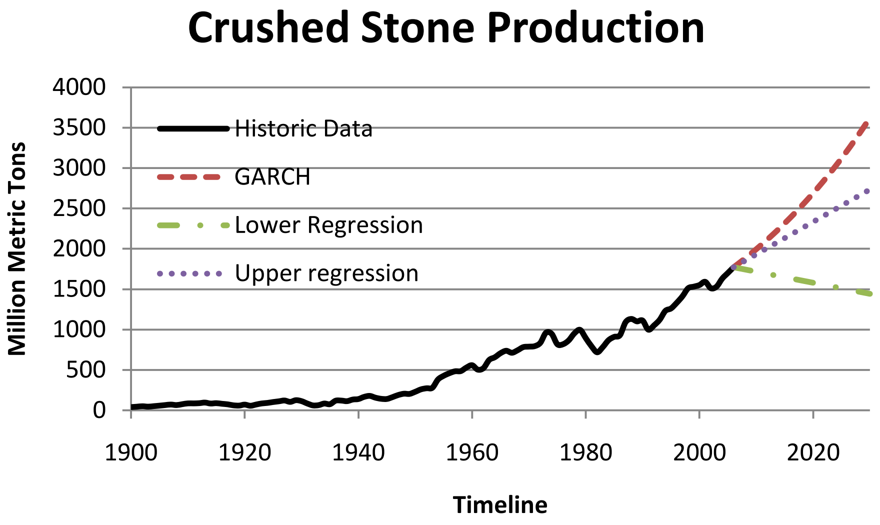

Figure 34: Forecast of Crushed Stone Production

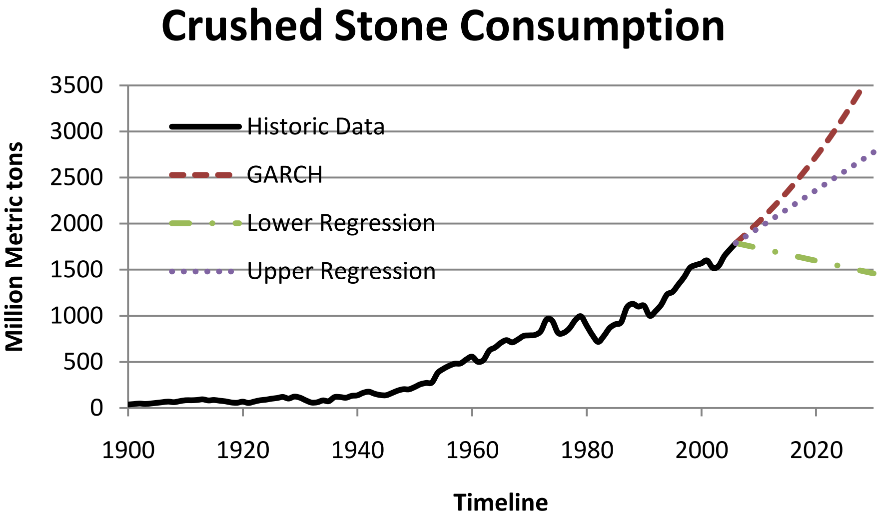

Figure 35: Forecast of Crushed Stone Consumption

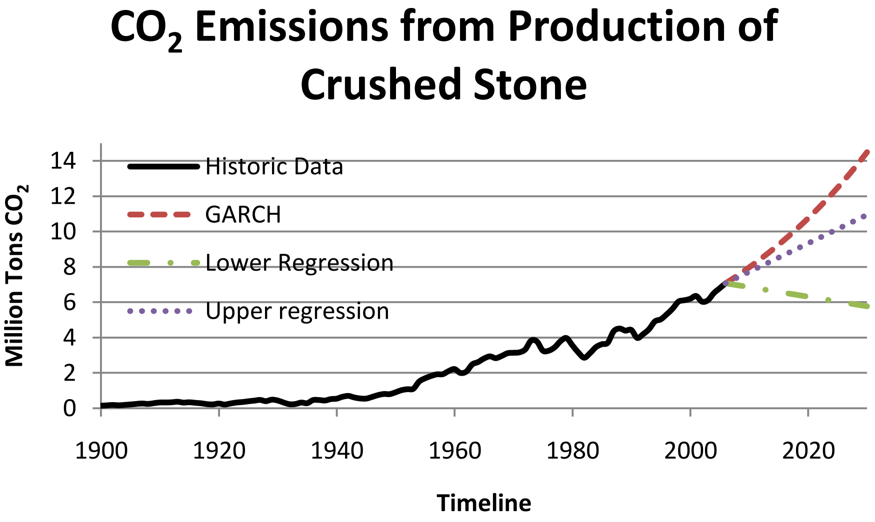

Figure 36: $CO_2$ Emissions from Production of Crushed Stone (Emission factor: 0.004 Ton CO2/Ton aggregate (CMU 2009)

Figure 33 through Figure 36 focus on crushed stone in terms of pricing, production, consumption, and carbon dioxide emissions. In terms of pricing, production, consumption and CO2 emission, the three projections have a fairly large range. For pricing, the upper regression projection represents the highest values, lower regression represents the lower values, and GARCH falls in between the upper and lower regression projections. For production, consumption, and CO2 emission, GARCH represents the highest values, lower regression represents the lower values, and upper regression falls between GARCH and lower regression projections. With respect to pricing, the one year interval price ranges between approximately

$9.33 and $10.62; the five year interval price ranges between approximately $9.42 and $14; the ten year interval prince ranges between $9.54 and $17.31; and the last interval at thirty years is between $9.75 and $24.00.  This information is summarized in Table 13.

Figure 30 and Figure 31 represent the relationship between production and consumption for crushed stone.  In 2005 and 2007, the consumption and production were fairly well matched. While the three forecasts illustrate a consistent trend between consumption and production for each trend, the disparity between any of the three can lead to a significant price differences. For example, higher consumption as projected with GARCH with lower production as projected with the lower regression can lead to higher prices.

### 6.3.3. Steel

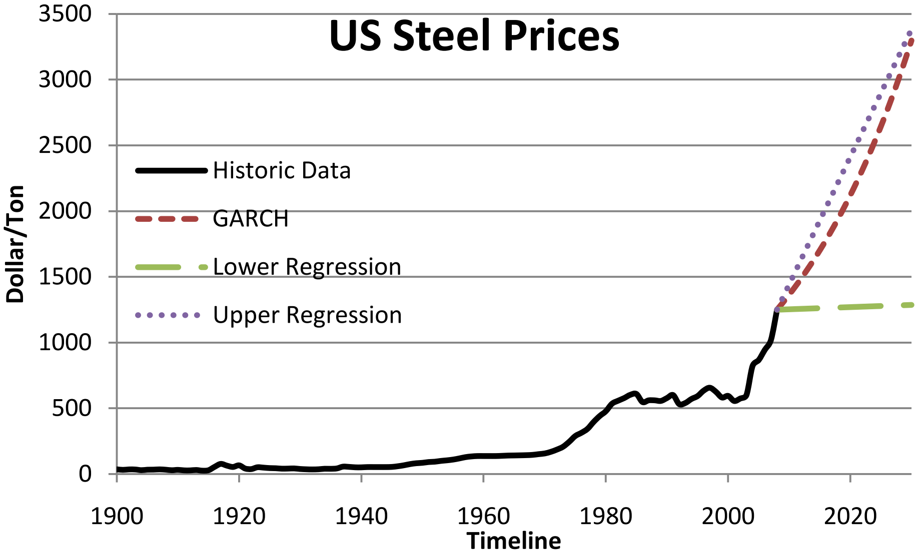

Figure 37:  Forecast of Steel Prices in the US

Table 14: Prices of Steel in the US at Different Time Periods ($/ton)

| | Lower Regression | GARCH | Upper Regression |
|---|---|---|---|
| 2010 | 1252.30 | 1364.10 | 1442.93 |
| 2015 | 1260.83 | 1700.81 | 1928.05 |
| 2020 | 1269.37 | 2120.63 | 2413.17 |
| 2030 | 1286.44 | 3296.73 | 3383.41 |

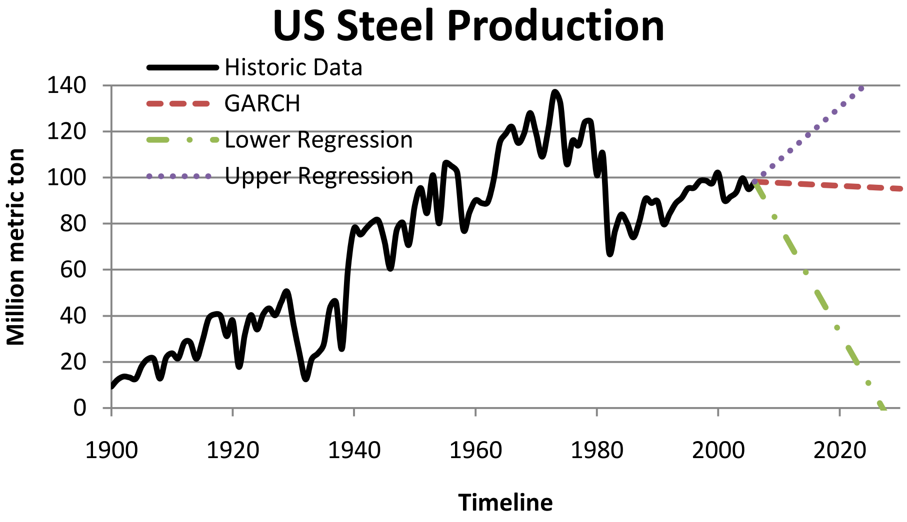

Figure 38:  Forecast of Steel Production in the US

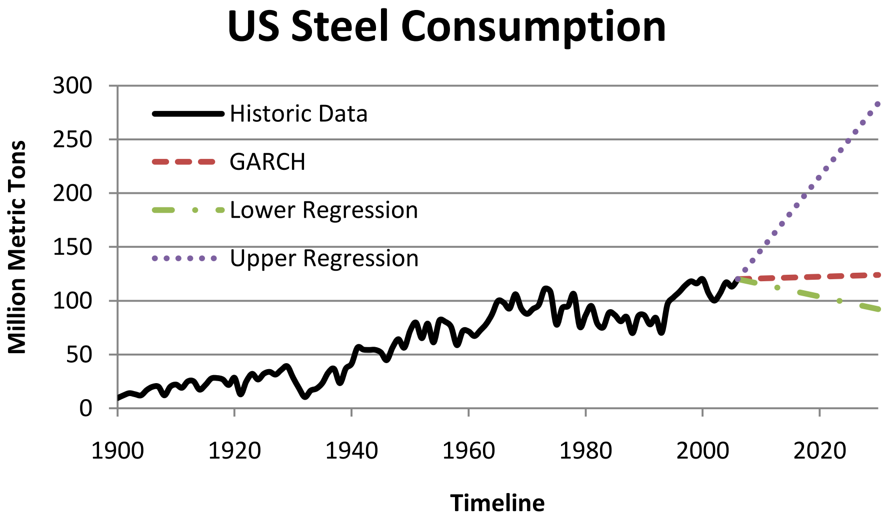

Figure 39: Forecast of Steel Consumption in the US

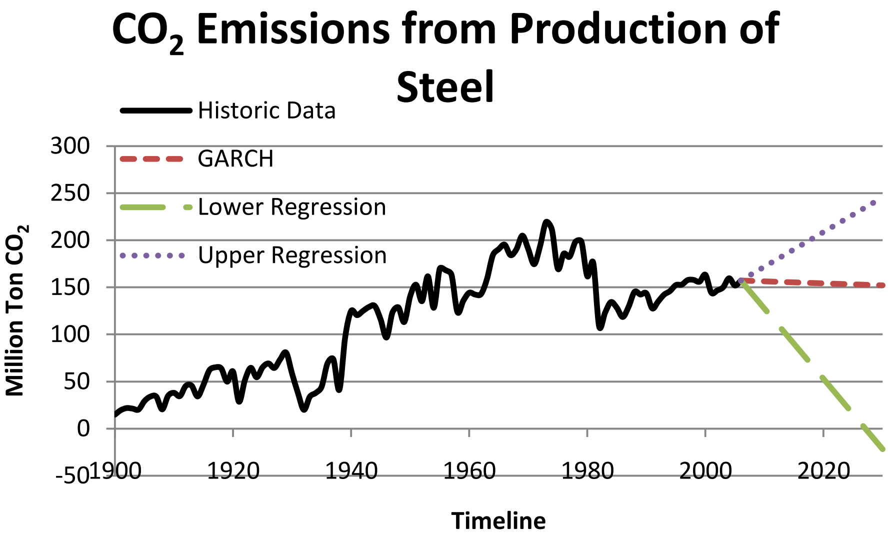

Figure 40: $CO_2$ Emissions from Production of Steel (Emission Factor: 1.6 Ton CO2/Ton Steel (IPCC 2009))

Figure 37 through Figure 40 focus on steel in terms of pricing, production, consumption, and carbon dioxide emissions. In terms of pricing, production, consumption and CO2 emission, the three projections have a fairly large range. For pricing, the upper regression projection represents the highest values, and lower regression represents the lower values. GARCH falls relatively close to the upper regression projection. For production, consumption, and CO2 emission, upper regression represents the highest values, lower regression represents the lower values, and GARCH falls between upper and lower regression projections. A large range of results are represented in this commodity. With respect to pricing, the one year interval price ranges between approximately $1253 and $1443; the five year interval price ranges between approximately $1261 and $1928; the ten year interval prince ranges between $1269 and $2413; and the last interval at thirty years is between $1286 and $3383. This information is summarized in Table 14.

Figure 38 and Figure 39 represent the relationship between production and consumption for steel. Around 2004, consumption was less than production, indicating continued exporting. These trends are consistent with world steel needs with respect to the BRIC nations. The lower regression is showing a trend in the negative direction.

The carbon dioxide ($CO_2$) content of the commodities is shown in Table 15. For asphalt, cement, aggregates and steel, we considered production emission factor. For diesel, we considered both the production and consumption emission factors, on a volume basis.

Table 15: $CO_2$ emission factors from the commodities (CMU 2009; IPCC 2009; IPCC 2009).

| Material | Ton $CO_2$/Ton of product<br>Ton $CO_2$/100 Gal of Diesel |
|---|---|
| Asphalt (production) | 0.0799 |
| Diesel (production) | 0.09 |
| Diesel (consumption) | 1 |
| Steel (production) | 1.6 |
| Cement (production) | 0.4985 |
| Sand and gravel (production) | 0.004 |
| Crushed stone (production) | 0.004 |

To calculate the price of $CO_2$ emissions for each commodity, we used the following formulas:

$$\text{Price of } CO_2 \text{ Emissions} = \text{Emission Factor} * \text{Price of Ca}$$

$$\text{Price of } CO_2 \text{ Emissions} = \frac{\text{Ton } CO_2}{\text{Ton of Product}} * \frac{\$}{\text{Ton } CO_2}$$

Table 16 shows the added price for each commodity with different scenarios of carbon prices. A low carbon price (i.e., $7.50 per ton of $CO_2$) equates to a relatively small increase. Taking steel as an example, if the price of carbon is $7.50 per ton of $CO_2$ the added price to the current steel price is $12 per ton. If the carbon price increases to $200.00 per ton of $CO_2$, then the added price for steel goes up to $320. As of July 14, the Chicago Climate Exchange reported that the price of a ton of $CO_2$ is $0.60 (CCX and Exchange 2009).

Table 16: Price of $CO_2$ emissions per commodity with different Carbon Price scenarios

| | **Carbon Price Scenarios** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Material** | **$7.50/ Ton $CO_2$** | **$15/ Ton $CO_2$** | **$22.50/ Ton $CO_2$** | **$30/ Ton $CO_2$** | **$50 / Ton $CO_2$** | **$100/ Ton $CO_2$** | **$200/ Ton $CO_2$** |
| Asphalt | $0.60 | $1.20 | $1.80 | $2.40 | $4.00 | $7.99 | $15.98 |
| Diesel | $0.08 | $0.16 | $0.25 | $0.33 | $0.55 | $1.10 | $2.20 |
| Steel | $12.00 | $24.00 | $36.00 | $48.00 | $80.00 | $160.00 | $320.00 |
| Cement | $3.74 | $7.48 | $11.22 | $14.96 | $24.93 | $49.85 | $99.70 |
| Sand and Gravel | $0.03 | $0.06 | $0.09 | $0.12 | $0.20 | $0.40 | $0.80 |
| Crushed Stone | $0.03 | $0.06 | $0.09 | $0.12 | $0.20 | $0.40 | $0.80 |

## 6.4. Alternative materials

### 6.4.1. Alternatives to Using Virgin Asphalt Materials

Reclaimed Asphalt Pavement

When asphalt paving materials are removed and/or reprocessed, the resulting pavement materials are called "reclaimed asphalt pavement" or RAP. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement (TFHRC 200X). While most old asphalt pavements are recycled into new hot-mix asphalt concrete mixtures at central processing plants, they may also be pulverized in place and incorporated into granular or stabilized base courses using a self-propelled pulverizing machine.

It is estimated that as much as 45 million tons of RAP may be produced each year in the United States (FHWA 1995). Approximately 80 to 85 percent of the excess asphalt concrete presently generated is reportedly being used either as a portion of recycled hot mix asphalt, in cold mixes, or as aggregate in granular or stabilized base materials (EPA 1993). Some of the RAP that is not recycled or used during the same construction season that it is generated is stockpiled and is eventually reused.

The properties of RAP are largely dependent on the properties of the constituent materials and asphalt concrete type used in the old pavement. Since RAP may be obtained from any number of old pavement sources, quality can vary. Excess granular material, soils and even debris are sometimes introduced into old pavement stockpiles. Quality control is needed to ensure that the processed RAP will be suitable for the prospective application, particularly for in-place pavement recycling (TFHRC 200X).

*Applications*

Milled or crushed RAP can be used in a number of highway construction applications. These include its use as an aggregate substitute and asphalt cement supplement in recycled asphalt paving (hot mix or cold mix), as a granular base or subbase, stabilized base aggregate, or as an embankment or fill material.

Asphalt Concrete Aggregate and Supplemental Asphalt Cement

Recycled asphalt pavement can be used as an alternate source of aggregate material, but in this application it also provides asphalt cement binder, thereby reducing the demand for asphalt cement in new or recycled asphalt mixes containing RAP.

Granular Base Aggregate

To produce a granular base or subbase aggregate, RAP must be crushed, screened, and blended with conventional granular aggregate, or sometimes reclaimed concrete material. It is usually necessary to blending granular RAP with suitable materials to attain the bearing strengths needed for most load-bearing unbound granular applications because RAP alone may exhibit a bearing capacity that is lower than that provided by conventional granular aggregate bases.

### Stabilized Base Aggregate

To produce a stabilized base or subbase aggregate, RAP must also be crushed and screened, then blended with one or more stabilization reagents so that the blended material, when compacted, will gain strength.

### Embankment or Fill

Stockpiled RAP material may also be used as a granular fill or base for embankment or backfill construction, although such an application is not widely used and does not represent the highest or most suitable use for the RAP. This application may, however, be a practical option for material that has been stockpiled for a considerable time period, or may be commingled with materials from several different project sources.

### *Physical and Mechanical Properties of RAP*

The properties of RAP are largely dependent on the properties of the constituent materials and the type of asphalt concrete mix being recycled (i.e., wearing surface, binder course, etc.). There can be substantial differences in aggregate quality, size, and consistency between various asphalt concrete mixtures. For example, since surface or wearing course asphalt concrete must have high resistance to wear and abrasion, aggregates obtained from these layers may be of higher quality than the aggregates in binder course applications, where polishing resistance is not of concern.

The particle size distribution of milled or crushed RAP may vary to some extent, depending on the type of equipment used to produce the RAP, the type of aggregate in the pavement, and whether any underlying base or subbase aggregate has been mixed in with the reclaimed asphalt pavement material during the pavement removal. Milled RAP is generally finer than crushed RAP. Studies of pavements in California, North Carolina, Utah and Virginia have shown that the particle fraction passing a 2.36 mm (No. 8) sieve can be expected to increase from a premilled range of 41 to 69 percent to a postmilled range of 52 to 72 percent, while the fraction passing a 0.075 mm (No. 200) sieve can be expected to increase from approximately 6 to 10 percent to a range of 8 to 12 percent (Kallas 1993). Most RAP will be a well-graded coarse aggregate, comparable to, or perhaps slightly finer and more variable than, crushed natural aggregates.

The unit weight of milled or processed RAP depends on the type of aggregate in the reclaimed pavement and the moisture content of the stockpiled material and has been found to range from 1940 to 2300 kg/m$^3$ (120 to 140 lb/ft$^3$), which is slightly lower than that of natural aggregates.

Information on the moisture content of RAP stockpiles is sparse, but indications are that the moisture content of the RAP will increase while in storage. Crushed or milled RAP can pick up a considerable amount of water if exposed to rain. Moisture contents up to 5 percent or higher have been measured for stored crushed RAP. During periods of extensive precipitation, the moisture content of some RAP stockpiles may be as high as 7 to 8 percent. Lengthy stockpiling of crushed or milled RAP should, therefore, be kept to a minimum.

The asphalt cement content of RAP typically ranges between 3 and 7 percent by weight. The asphalt cement adhering to the aggregate is generally somewhat harder than new asphalt cement, mainly because of oxidation of the old asphalt during use and weathering.  The degree of hardening depends on several factors, including the intrinsic properties of the asphalt cement, the mixing temperature/time (increases with increasing high temperature exposure), the degree of asphalt concrete compaction (increases if not well compacted), asphalt cement/air voids content (increases with lower asphalt/higher air voids content), and age in service (increases with age).

RAP obtained from most wearing surface mixes will usually have an asphalt content in the 4.5 to 6 percent range. The recovered asphalt from RAP usually exhibits low penetration and relatively high viscosity values, depending on the amount of time the original pavement has been in service. Penetration values at 25°C (77°F) are likely to range from 10 to 80 while the absolute viscosity values at 60°C (140°F) may range from as low as 2,000 poises (equivalent to AC-20) up to as high as 50,000 poises or greater, depending on the extent of aging. Viscosity ranges from 4,000 to 25,000 poises can normally be expected from the asphalt cement that is recovered from RAP material. Table 17 provides a summary of the typical ranges of physical properties of RAP, other than gradation.

**Table 17:  Physical and mechanical properties of reclaimed asphalt pavement (RAP)**

| Type of Property | RAP Property | Typical Range of Values |
|---|---|---|
| Physical Properties | Unit Weight | 1940 - 2300 kg/m$^3$<br>(120-140 lb/ft$^{3)}$ |
| | Moisture Content | Normal: up to 5%<br>Maximum: 7-8% |
| | Asphalt Content | Normal: 4.5-6%<br>Maximum Range: 3-7% |
| | Asphalt Penetration | Normal: 10-80 at 25°C (77°F) |
| | Absolute Viscosity or Recovered Asphalt Cement | Normal: 4,000 - 25,000 poises at 60°C (140°F) |
| Mechanical Properties | Compacted Unit Weight | 1600 - 2000 kg/m$^3$<br>(100-125 lb/ft$^3$) |
| | California Bearing Ratio (CBR) | 100% RAP: 20-25%<br>40% RAP and 60% Natural Aggregate: 150% or higher |

*Chemical Properties of RAP*

Mineral aggregates constitute the overwhelming majority (93 to 97 percent by weight) of RAP. Only a minor percentage (3 to 7 percent) of RAP consists of hardened asphalt cement. Consequently, the overall chemical composition of RAP is essentially similar to that of the naturally occurring aggregate that is its principal constituent.

*Mechanical Properties*

The mechanical properties of RAP depend on the original asphalt pavement type, the method(s) utilized to recover the material, and the degree of processing necessary to prepare the RAP for a particular application. Since most RAP is recycled back into pavements, there is a general lack of data pertaining to the mechanical properties for RAP in other possible applications.

The compacted unit weight of RAP will decrease with increasing unit weight, with maximum dry density values reported to range from 1600 kg/m$^3$ (100 lb/ft$^3$) to 2000 kg/m$^3$ (125 lb/ft$^3$).(8) California Bearing Ratio (CBR) values for RAP material containing trap rock aggregate have been reported in the 20 to 25 percent range. However, when RAP is blended with natural aggregates for use in granular base, the asphalt cement in the RAP has a significant strengthening effect over time, such that specimens containing 40 percent RAP have produced CBR values exceeding 150 after 1 week.(9)

Table 17 provides a summary of the mechanical properties of RAP discussed in the preceding paragraphs.

Bitumen can also be made from vacuum tower bottom wastes that are produced in the process of cleaning and recycling used motor oils.

Tar and Coal-Based Products

Tar (also called "coal tar") is a by-product of the carbonization or gasification of coal when making coke or coal gas, respectively. Prior to the widespread distillation of petroleum products to produce asphalt, tars were used widely in bituminous roadway applications, dating back to at least the 8th century. The term "tarmac" is actually a shortening of the term "tar macadam", which was an early form bituminous concrete mixture. Tar is still used in specific applications in some European countries but is rarely used today in the U.S.

Tar offers the advantage of being easily produced from a material that is readily available in great quantities in the US (and particularly in Pennsylvania) – coal. It also is not soluble in petroleum-based products, so pavements constructed using tar binders are not damaged by fuel spills and oil leaks that may cause raveling in asphaltic concrete.

The primary disadvantage to using tar is that it is considered to be toxic and carcinogenic due to the presence polycyclic aromatic hydrocarbons (PAHs), most notably benzene. It is also tends to exhibit much greater sensitivity of viscosity to temperature than does asphalt, and it is more flammable than asphalt. It is unlikely that tar will be considered an acceptable substitute for asphalt in the U.S. until these issues are addressed.

Less toxic versions of tar can be produced from other organic materials (e.g., corn stalks and other vegetation), but such applications are still under development.

### Nonpetroleum-based Products

In a time of concern about pollution, climate change, oil pricing and the possible approach of "peak oil" conditions, nonpetroleum-based alternatives to asphalt, diesel and other fuels are becoming increasingly popular, particularly with regard to being more environmentally friendly and nontoxic. An additional advantage of nonpetroleum-based bituminous binders is that they are often pigmentable, allowing them to be more lightly (and colorfully) colored to reduce roadway surface temperatures, thereby reducing urban heat island effects.

The following sections describe a handful of alternatives to asphalt binder that fall into this category.

#### *Bioasphalt*

Bioasphalt (also called biobitumen) is the generic term for alternative binders that are made from nonpetroleum-based renewable resources, such as soybeans, sugar, rice, corn and potato starches, natural tree and gum resins, natural latex rubber and vegetable oils, cellulose, various vegetable oil wastes, dried sewage effluent, etc.

Commercially available products exists. The authors are not endorsing the materials or products.

- A soybean-based, penetrating asphalt rejuvenator and sealant. Proposed material benefits included restoring asphalt pavement surfaces (countering effects of oxidation) and seals hairline cracks in existing asphalt pavement. Benefits also claimed include a cure time of 15-30 minute, no tracking, and ease of use (with no heat required for application). The United Soybean Board states that this product is currently being used by "several state transportation departments."

  A review of literature produced by BP Bitumen suggests that it is the styrene-butadiene-styrene (SBS) polymer that provides the main benefit in these types of products, from which one can infer that the the soybean-based material is primarily a vehicle for delivering the polymer to the pavement.
  Additional information on this specific product is available at
  http://www.biospantech.com/replay.php# and
  http://www.beyondthebeanonline.org/Article.aspx?id=98

- Shell Oil Company has developed vegetable oil-based binders for flexible pavement structures and has conducted two different trials in Norway using these products. The first trial was an application in Hot Mix Asphalt (HMA) using vegetable oil-based viscosity grade V10000 bitumen. A conventional V10000 bitumen was also used to provide a reference for performance. V-grade binders are very soft bitumen grades and are typically used on low volume roads in Scandinavia where poor and varying bearing capacity often requires flexible asphalt layers.

  A second vegetable-based binder, named BL9000R, was developed for a hot surface dressing application. This binder is a slow-curing cutback and was developed as an alternative for the conventional BL9000R product. Both products were included in the trial for comparison.

Comparative laboratory analyses were performed on the vegetable oil-based binders and reference binders, as well as on the resulting mixtures for both trials. In the comparison of the two V10000 bitumens, the vegetable oil-based binder was found to be less temperature-susceptible, having better low temperature properties than the reference binder. The vegetable oil-based binder met all other specification requirements and was considered to be comparable to the reference binder. The laboratory testing for the surface dressing trial did not reveal any significant differences between the vegetable oil-based and reference materials.

In the two field trials of these materials, fewer emissions were observed for the vegetable oil-based binders.

The details of the laboratory analysis and the data from the field trials are presented and discussed in a paper prepared for the World Roads Congress (PIARC), which can be downloaded at: http://www.shell.com/static/bitumen-en/downloads/wrc/papers/biofluxes_english.pdf

- Screg Company (France) produces a vegetable oil-based surface seal (Compogreen®) that they promote as being energy-efficient and a minimal emitter of noxious fumes. It can also be colored for aesthetic effects as well as reduction of pavement surface temperatures and heat island effects. Additional information (in French) can be downloaded at: http://www.colas.com/fichiers/fckeditor/File/pdf/produit/Brochure_Commerciale_COMPOGREEN_20060901.pdf

There is also work underway to develop more economical bio-based pavement binders than those listed above. A recent feasibility study examined the possibility of using soy soapstock (rather than soilbean oil) as the basis for a bio-based binder. Soy soapstock costs about 1/5 the cost of soybean oil ($0.13 - $0.25/lb vs. $0.56 - $0.69/lb) and about half the cost of asphalt ($0.20 to $0.37/lb) (Haddock 2009). While it appears to be technically feasible to develop this source of feedstock (or similar sources), the cost of the actual binder replacement may be much higher, depending upon the degree of modification required. In addition, current supplies of soybean soapstock (about 0.5 million tons/year) amount to only a few percent of the total asphalt demand in the U.S. (about 34 million tons/year), so it may be useful on a local basis or as a partial replacement for asphalt (Haddock 2009).

### 6.4.2. Alternatives for Aggregate Supplies

#### Manufactured Aggregate

*Recycled Concrete Aggregate (RCA)*

Portland Cement Concrete is 100 percent recyclable and is, in fact, the most recycled material in the US, with more than 140 million tons of concrete being recycled annually (CMRA 2008). The cost of using recycled concrete aggregate varies widely with the application, required process controls, haul distance (vs. on-site production), etc., and is offset by the savings of not using virgin material and not having to remove, haul and dispose of in-place slabs. Bid costs for producing and using RCA on recent paving projects has ranged from $1 - $17 per ton.

Concrete recycling is a relatively simple process. It involves breaking, removing and crushing hardened concrete from an acceptable source to produce "recycled concrete aggregate (RCA)," a granular material that can be produced for use as a substitute for natural aggregate in almost any application (ACPA 2009). Some of the most common and interesting applications (and limitations) of RCA are summarized below.

### *Unstabilized (Granular) Subbase and Backfill*

Unstabilized (granular) subbase applications are the most common use of RCA produced from concrete pavements. Of the 41 states indicating their production of RCA in 2004, 38 stated that they use the material for aggregate subbase applications. In fact, some states believe that RCA outperforms natural aggregate in unstabilized subbase applications (FHWA 2004).

An important benefit to using RCA as unstabilized subbase material is that the presence of contaminants (e.g., asphalt concrete, joint sealant materials, etc.) is of relatively little concern. For example, Minnesota allows up to 3 percent asphalt *cement* by weight of aggregate, and California has no limit on the relative proportions of reclaimed asphalt pavement (RAP) and RCA in their subbase materials. This provides maximum contractor flexibility in production and construction.

### *Free-draining Subbase*

When RCA production yields relatively angular, rough-textured particles, it can be placed to provide a subbase layer that is both permeable and is highly stable. The use of RCA in free-draining subbase layers has been associated with the deposit of crushed concrete dust and leachate (calcium carbonate precipitate or "tufa") in drainage pipes and on filter fabric. The potential for these problems can be greatly reduced by washing the RCA (to remove crusher dust) and by eliminating fine aggregate (passing the #4 [0.2 mm] sieve) from the subbase (Bruinsma 1995). Stabilization with cement or asphalt also effectively eliminates dust and leachate concerns. Drainage systems can also be designed to allow residual crusher dust to settle in a granular filter layer.

### *Dense-graded Subbase*

RCA is an effective and economical material for dense-graded subbase applications. When properly graded, the angular nature of the product provides excellent stability. In addition, fine RCA often experiences a degree of cementitious rehydration, which further strengthens and stiffens the subbase layer.

RCA should not be used in dense-graded subbase layers that will be provide any significant flow or runoff to pavement drainage systems because the contribution of crusher dust and dissolved calcium hydroxide can form deposits in filter fabrics and pipe drains.

*Granular Fill*

Crushed concrete is an economical and highly stable material that is well-suited for granular fill applications. This is a particularly good application for fine RCA products, which may be produced in quantities that are excessive for subbase, concrete mixture and other applications.

*Erosion Control (Rip-rap)*

Most states allow the use of recycled concrete for erosion control ("rip-rap") or slope stabilization (FHWA 2004). In this application, the concrete pavement is broken into pieces that are 6 in [150 mm] or larger. An example RCA rip-rap installation is shown in Figure 41.

**Figure 41: Photo of recycled concrete pavement used as "rip-rap" for erosion control (Photo courtesy of Blessing Construction, Kearney, NE).**

*New Concrete Pavements*

RCA can be incorporated as the primary or sole aggregate source in new concrete pavements. The use of RCA is common in the lower lift of two-lift concrete pavements in Europe (AASHTO 1993) and RCA has been used in concrete mixtures in the U.S. since the 1940s for roadway surfaces, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundations and even structural concrete (NHI 1998) (ECCO 1999). The basic techniques for batching, mixing, delivery, placement and finishing need not be significantly different than those used for concrete mixtures containing natural aggregate.

Two concerns when utilizing RCA in concrete mixtures are increased water demand and premature stiffening of the mixture due to the presence of fine particles and the more absorptive nature of reclaimed mortar. Some agencies address these problems by limiting or eliminating the inclusion of fine RCA in concrete mixture applications. Pre-soaking RCA and maintaining it in a proper moisture state prior to use can also reduce these problems.

It also should be considered that the physical and mechanical properties of concrete products comprising RCA may vary from those containing natural aggregate. For example, the strength and elasticity of RCA concrete may be lower and the coefficient of thermal expansion higher than for concrete prepared using natural aggregate when all other factors remain constant. Differences in strength and other physical properties often can be offset by modifying other aspects of the mixture design (e.g., reducing water-cementitious material ratio and/or including certain mineral admixtures) or the structure (e.g., increased layer thickness). Structural matters, such as load transfer, can usually be addressed with structural design modifications (e.g., required use of dowel bars at transverse joints) (Wade 1997).

There also have been concerns about recycling old concrete with freeze-thaw durability or alkali-silica reactivity problems. However, modifications to traditional crushing and mixture design procedures have proven successful in preventing the reoccurrence of durability and reactivity problems in pavements containing RCA (ACPA 2009).

### *Lean Concrete Subbase and Cement-Stabilized Subbase*

Lean concrete subbase (LCS) and cement-stabilized subbase (CSS) layers can be constructed using RCA. Coating or embedding the RCA in fresh cement paste or mortar prevents the migration of crusher fines and the dissolution and transport of significant amounts of calcium hydroxide, which can otherwise form calcium carbonate precipitate in drain pipes. The physical and mechanical properties of RCA (particularly the absorption characteristics) must be considered in the design and production of LCS and CSS materials, similar to their consideration in concrete production using RCA (ACPA 2009).

### *Asphalt Concrete and Asphalt-Stabilized Subbase*

RCA has been used successfully in new asphalt concrete and asphalt-stabilized subbase applications. Typical RCA particle angularity and rough texture provide excellent potential for stability and surface friction, and the use of asphalt to encapsulate RCA particles effectively eliminates the potential for clogging of drainage structures in subbase applications (ACPA 2009). Unfortunately, the more absorptive nature of typical RCA particles significantly increases asphalt demand, which often increases costs prohibitively.

### *Other Applications*

Numerous other applications for RCA products have been implemented, researched or suggested, including: soil stabilization, pipe bedding, landscape materials, railroad ballast, agricultural soil treatments (similar to soil modification using lime), treatment of acidic lake waters, trickling filters and effluent treatment, components of $SO_2$ scrubbers, ingredients in masonry block production, and formation of artificial reefs for establishing oyster beds (Vandenbossche and Snyder 1993; FHWA 2004; CMRA 2006-2009).

*Recycling Asphalt Pavement*

The recycling of asphalt pavement (RAP) into aggregate for use in asphalt pavement, foundation layers (both stabilized and unbound) and concrete mixtures was described previously and is not repeated here.

*Industrial By-Products*

Slag Aggregate

Slag aggregate (also known as "slag recycling crushed aggregate") is a by-product of the production of steel. These materials are often promoted as good materials for roadway applications in both surface paving materials (i.e., concrete and asphalt) or foundation layers. It is generally acknowledge that they possess rough-textured, angular shape, which promotes stability in unbound applications (but can require offsetting mixture modifications in asphalt and concrete mixture designs to achieve workability and spreadability of the mixtures).

If used in pavement layer construction, the physical, mechanical and chemical properties of slag aggregate must be carefully considered in the structural and material design of the pavement. Slag aggregate typically is very porous and has a much lower specific gravity than traditional construction aggregate. Therefore, it usually must be substituted on a volumetric (rather than weight-based) basis, and appropriate adjustments must be made for the absorption of moisture and binder materials (i.e., cement and asphalt), which may drive up the cost of the concrete or asphalt mixtures.

Additionally, the chemical composition of slag aggregate has been associated with premature deterioration of concrete pavements in some areas, with distress that resembles alkali-silica activity resulting in the area of some pavement joints where slag aggregate is used. This has been noted in many Pennsylvania concrete pavements. For this reason alone, it may be necessary to identify mitigating measures for slag aggregate applications in concrete pavements, or to avoid them altogether.

Other

There are no other significant industrial by-product sources of aggregate that are suitable for road construction applications at this time.

### 6.4.3. Alternatives for Construction Steel (Reinforcing Bars and Dowels only)

Fiber-reinforced Polymer (FRP) Reinforcing Bars

Fiber-reinforced polymer (FRP) composites typically consist of a matrix of polymeric material (e.g., polyester, vinyl ester or epoxy) that is reinforced by fibers of glass, carbon or graphite. Filler materials may be added to improve certain properties of the composite or to lower its cost (FHWA 2009).

The primary advantages to their use include corrosion resistance, high longitudinal strength, high fatigue endurance and light weight. They are also magnetically transparent, which makes them suitable for use anywhere electromagnetic vehicle detectors are used (e.g., toll collection booths, etc.) (Walton 2005). The disadvantages of FRP bars include their relatively high cost, low modulus of elasticity and low shear strength.

The physical and mechanical properties of FRP suggest some special considerations in the design of the concrete pavements in which they will be used. For example, the use of better and more uniform foundation support will reduce shearing stresses on FRP bars that cross joints and cracks, thereby reducing the probability of a shear failure in the bar. The use of an asphalt- or cement-stabilized subbase may provide the best performance potential. In addition, the relatively low elastic modulus of FRP may dictate that the area of reinforcing be increased (either through the use of larger diameter bars, more bars or both) to provide comparable restraint of crack and joint movements. The amount of added reinforcement area varies with the criteria being considered (e.g., crack patterns and widths for restrained structural members versus allowable joint movements across pavement joints), but may be as high as three times the area of conventional steel reinforcing under certain conditions (Koenigsfeld 2003).

FRP bars have recently been used in two experimental continuously reinforced concrete pavement (CRCP) projects: one in Quebec (containing 18 different experimental sections) in 2006, and one in West Virginia in 2007. Details concerning the design, construction and monitoring of these projects are presented in (FHWA 2009). They have also been used extensively in more than 75 bridge decks in the U.S. and Canada, all of which are performing well (Gremel 2009). Their use as tie bars across construction joints in concrete pavements is less well documented and established.

### Polypropylene, Polyolefin and Steel Fiber Reinforcing for Concrete Materials

Fiber reinforcing can supplement or replace traditional concrete reinforcing in certain design instances and offers the potential advantages of being noncorrosive (for nonmetallic fibers) and uniformly distributed (versus concentrated in the case of reinforcing bars).

It is generally accepted that fiber reinforcing is effective in reducing the incidence and magnitude of shrinkage cracking. Some fibers have proven to be effective in increasing the fracture toughness and impact resistance of concrete materials and they may significantly change the behavior of concrete beams and slabs during the propagation of any cracks (from abrupt, brittle failure to a more gradual, ductile failure). It is generally accepted that fiber reinforcing does not prevent the development of cracking, so it does not significantly increase concrete flexural or compressive strength (although it may significantly change the behavior of the material, as described previously). The specific behavior of any fiber-reinforced concrete mixture depends greatly on the type, design and quantity of fibers used, along with the properties of the concrete mixture in which they are incorporated.

Fiber reinforcing cannot replace the use of reinforcing bars placed across construction joints. Further, it may not be as effective as reinforcing bars in maintaining tightness of cracks for aggregate interlock shear transfer.

One historical problem with the use of fiber reinforcing has been difficulty in ensuring uniform distribution of fibers through the concrete mixture (i.e., preventing “balling” or agglomeration of the fibers). Newer systems of introducing the fibers to the mixture, combined with better guidance in mixer charging sequences and mixture design, have minimized these concerns.

The costs of fiber reinforcing vary significantly with the type and quantity of fibers being used. The added cost of fiber reinforcing can range from just a few dollars per cubic yard of concrete for low dosages (3 lb fiber/cubic yard of concrete) of polypropylene fibers to doubling the cost of the concrete for higher dosage of some newer, specially engineered fibers.

### Alternative Load Transfer Devices

#### *Solid FRP Dowels*

Fiber-reinforced polymer (FRP) materials have been used to produce dowel bars (as well as the reinforcing bars described previously). The primary advantages of these dowels is their noncorrosive nature and their light weight (which facilities handling in the field). A general discussion of FRP materials is not repeated here.

The relatively low specific gravity of FRP dowels has come into question when they are used with dowel bar inserters (rather than dowel baskets) in concrete paving operations, as it has been suggested that they may “float” within the concrete mixture, resulting in dowel misalignment problems. The nonmagnetic nature of these materials makes it difficult to use traditional alignment verification devices to check alignment after construction.

The lower elastic modulus of FRP dowels requires the use of more dowels or larger diameter dowels in order to achieve the same structural behavior as is found with metallic dowels. Even with the use of larger dowels, most structural testing performed to date in labs and select field installations suggests that FRP dowels develop unacceptable losses of load transfer at a relatively young age. The reasons for this behavior have not yet been determined.

#### *Steel or FRP Pipe [grouted or plugged] Dowels*

Steel and FRP pipe have been used as dowels in some trial installations. These dowels are sometimes filled with grout (to provide lateral support to the dowel walls) or are plugged with end caps when the walls are deemed structurally adequate without internal support. This approach is quite effective in reducing the cost and weight of the product. For example, the Minnesota Department of Transportation allows the use of stainless steel pipe (1.25-in nominal diameter, Schedule 40 pipe) as a dowel bar for high-performance concrete pavements. Laboratory tests of this particular design were conducted on the Minne-ALF accelerated pavement test platform at the University of Minnesota to confirm performance potential before adopting the product for use. Early tests of hollow dowels performed by FHWA at the

Turner Fairbank Highway Research Center in the 1980s were failures, but involved the use of much thinner tubes than the MnDOT pipe dowel.

*Elliptical and Plate Dowels*

While most dowels for concrete pavement are round in section, it has been proposed that elliptical or plate dowels can provide more effective uses of material in reducing concrete bearing stresses while providing adequate shear capacity and load transfer. While elliptical dowels have been installed only experimentally in concrete pavement applications and have not seen widespread acceptance, plate steel dowels have been widely used in industrial flooring applications for many years and are now being promoted for use in highway paving applications. Both of these types of devices offer the potential to continue using metallic dowels of smaller size (cross-section and/or length) in paving applications, which will save material costs.

*Shear Devices*

Installed in Core Holes

There have been many concepts for shear devices as replacements for dowel bars over the last 50 years, beginning with plate and stud connectors and most recently with double-vee devices. In most cases, these devices are installed retroactively in core holes that are drilled across the joint and are then backfilled into place using an epoxy- or cement-based mortar material.

The last incarnation of the double-vee device (which incorporated a pre-compression installation into core holes with kerfs cut in the walls) performed quite well in many installations in the U.S., including a long stretch of I-10 in Florida in the 1980s. Premature failures early versions of these devices, along with the improvement of technology for retrofitting dowels at a reduced cost, eventually led to the abandonment of these devices.

Installed in Slots

Another example is another patented noncorrosive fiber board that can be installed in narrow slots (rather than core holes) across pavement joints. This device appears to be effective in providing load transfer, but acts as a tie rather than a dowel, so it does not allow joint opening and closing movements. It must be limited to applications where tie bars would be used rather than dowels.

## 6.5. Alternative Construction Techniques

### 6.5.1. Two-Lift Construction for Concrete Paving

The construction of concrete pavements in two lifts is a process that has been used for almost as long as concrete pavements have been constructed. Some of the first two-lift concrete pavements were constructed under a 1906 patent for "Granitoid Concrete Streets," which required the use of normal ready-mix concrete using less expensive aggregates for the first five inches and a top lift of crushed granite rock (often referred to as "monument granite") and reduced quantities of fine aggregate to provide a very hard, durable surface to withstand the expected wear by horse drawn wagons with steel wheels. These streets, which were constructed in 1909 and 1910, are still in service today in Duluth (Minnesota), Grand Forks (North Dakota) and Calumet (Michigan), and are listed in the National Register of Historic Places (Cable and Frentress 1994).

Two-lift paving was used extensively from 1950–1990 in many states to facilitate the placement of welded wire mesh reinforcing in concrete interstate pavement construction. This process used the same concrete mix for both lifts and was quite successful in many states, including Iowa, Wisconsin, Illinois, Michigan, Pennsylvania, and Minnesota. After 1970, the concrete paving industry moved from mesh-dowel pavement designs with long panels to plain (unreinforced) concrete pavement designs, generally eliminating the need to pave with a two-lift process (Cable and Frentress 1994).

Two-lift paving is now being reconsidered and promoted for use as a way to improve the use of materials in concrete structures by using lower cost materials (e.g., less cement and/or increased use of fly ash and other supplementary cementitious materials, locally available aggregate sources, and recycled concrete and asphalt pavement aggregates) in the lower lift while optimizing the properties of the upper lift (e.g., through the use of harder or more polish-resistant [and possibly imported] aggregates, less permeable concrete mixtures, and the use of special chemical or mineral admixtures to achieve specific physical or mechanical properties). Austria, Belgium, the Netherlands, Germany, and the United Kingdom are all currently using this practice to economize the use of aggregates, recycle reclaimed paving materials, and construct pavement surfaces that have improved safety and noise characteristics (FHWA 2006). Two-lift construction can accommodate the use of an exposed aggregate surface to mitigate noise and enhance friction. This technology was the highest priority implementation topic recommended by the FHWA SCAN tour team in 2006 (Hall and al 2007).

The following are examples of recent two-lift construction projects that demonstrate the opportunities presented by this technique:

- U.S. 75 in Lyon County, Iowa was constructed in 1976 to demonstrate the feasibility of recycling a composite (asphalt over concrete) pavement into a new pavement. The composite pavement was crushed and used as aggregate in the lower lift while virgin natural aggregate was used in the upper lift (Bergen 1977). This combined use of recycled concrete and recycled asphalt pavement (with the recycled asphalt comprising about 40 percent of the aggregate used) is unique and demonstrates the ability to make the best use of materials that might not otherwise be considered for use in concrete paving mixtures. This pavement was included in a recent federally sponsored study of projects constructed using recycled concrete aggregate. It is still in service and is performing reasonably well after more than 30 years of service (Sturtevant 2007).
- Two-lift test sections were built in Florida in 1978 to incorporate the use of concrete with lower flexural strength (econocrete, with lower cement content) in the lower lift. At last report, these test sections were performing well (Cable and Frentress 1994).

- In 1994, the state of Michigan used a European version of the two-lift paving system on I-75 in Detroit by incorporating a high-quality aggregate in the top paving lift (for use in an exposed aggregate surface for high friction and noise reduction). Still in service after 15 years, the performance of this pavement has generally been very good, with less cracking and other distress than the control section constructed using standard paving techniques (although the levels of noise reduction achieved have not met expectations) (Smiley 1995; Smiley 1996).

In response to the recommendations of the 2006 FHWA Long-Life Pavements Scan Tour Team, a pilot demonstration project for two-lift concrete paving was performed on a section line road near Pleasanton, KS in June 2008. This project was followed by the construction of multiple two-lift sections on I-70 near Abilene, KS in September, 2008. These sections were the focus of a National Demonstration Open House in October 2008. The demonstration sections all featured a common lower lift comprising a local limestone coarse aggregate (with some polishing tendencies) while the upper lifts contained crushed rhyolite coarse aggregate, Class F fly ash, lower water contents (in some cases) and different surface textures. Details concerning the mix designs and other construction details can be found in (Fick 2008), which is available at www.cptechcenter.org. This report also provides recommendations for two-lift construction practices and additional research.

### 6.5.2. Manufactured Paving Systems

Precast Concrete Pavement

Precast pavement technology now includes new and innovative construction methods and systems that are well suited to meet the needs of rapid pavement repair and construction. They offer the advantage of being fabricated or assembled offsite, which allows for a greater degree of quality control that is often possible with cast-in-place products. As a result, they are often promoted as having exceptional durability and potential for long service life. Additionally, precast pavements require no curing time after installation and can be opened to traffic immediately.

These systems generally make use of traditional paving materials (i.e,. standard or high-performance paving mixtures, metallic dowels, aggregate foundation materials, etc.). While they could be engineered to incorporate nonmetallic and other nontraditional dowels, they offer no specific opportunities for doing so that are no described in previous sections of this report, so additional discussion of this technology is not presented here.

Additional information on the use of precast concrete pavement technology is available on the AASHTO Technology Implementation Group (TIG) website at http://tig.transportation.org/?siteid=57&pageid=1826.

Poroelastic Road Surfaces (PERS)

Poroelastic road surfaces are prefabricated paving layers of aggregate bound by a bitumen or polyurethane binder that are typically produced in panels or rolls. The aggregate particles typically consist of either pure rubber or rubber-related products, such as recycled vehicle tires, but may also include some sand and/or stone material. Aggregate particle shapes vary, ranging from elongated fiber-like particles that were used for a trial in Sweden, to almost cubic particles used elsewhere in Scandinavia (Rasmussen 2004). Other binders may also produce satisfactory performance, and can be used to bind the poroelastic material to the existing pavement surface.

When used as a wearing course, poroelastic surfaces can provide significant tire-pavement noise reductions (5 to 15 dBA when compared to conventional pavement surfaces) due to their high void content, which is often 25 to 40 percent (Sandberg and Ejsmont 2002). While PERS noise reduction potential is good, durability has been a challenge, as is described below.

Trial segments placed on an old airport surface outside of Gothenburg, Sweden in the early 1980s (and exposed to no traffic other than sound tests) remained in place for 10 years. This led to the placement of the material on a local Stockholm street in 1989, where it had to be removed within six months of construction because the rubber patches were becoming detached from the base course.

Norway constructed a 426-ft [130-m] segment of a 0.75-in [19-mm] thick poroelastic surfacing bound with 13 percent polyurethane. Although the surfacing reduced tire-pavement noise significantly, friction levels soon dropped to unacceptable levels and some areas began to loosen over time, presumably due to construction-related problems. A plow tore off segments of the surface during snow removal operations, leading to a subsequent complete removal of the surface by transportation authorities (Sandberg and Ejsmont 2002). In general, it appears that PERS can provide good noise reduction, but much development is still needed to make them durable and safe.

### 6.5.3. Rubber materials

Rubber materials can be used in asphalt pavements as binders, sealers, crack and joint sealants, and membranes (Hicks and Epps 1998). In the late 1990s, several DOTs used asphalt pavement (Rebala and Estakhri 1995). According to Xiao et al (Xiao, Amirkhanian et al. 2007) further research is needed in the area of rubber materials to asphalt pavements. Siddique and Naik (Siddique and Naik 2004) review previous research done of using scrap tires in Portland cement concrete and asphalt concrete.

# 7. In-depth investigation of identified alternative materials and construction techniques

Transportation infrastructure systems have significant environmental impacts (see Table 18) to air, water, and land. In order to account for all the impacts of the transportation infrastructure, and possibly offset costs from construction with benefits during use, it is necessary to consider all life cycle stages. Figure 42 illustrates typical life cycle stages of a transportation infrastructure project, ranging from planning and design to operation and demolition.

**Table 18: Example of potential environmental impacts from highways and roads (Myer 2008)**

| Air | Water Resources | Land Resources | Other Impacts |
|---|---|---|---|
| Engine and evaporative emissions of CO, HC, NOx, PM, lead | Surface and ground water pollution from runoff | Land for infrastructure development | Local Noise |
| Emissions from $CO_2$ from fossil fuel combustion | Modification of water systems from road construction | Extraction of road construction materials | Congestion |
| CFCs released during vehicle manufacture and disposal | | Abandoned rubble from roadwork | |
| | | Road vehicles withdrawn from service | |
| | | Waste oil, tires and batteries | |

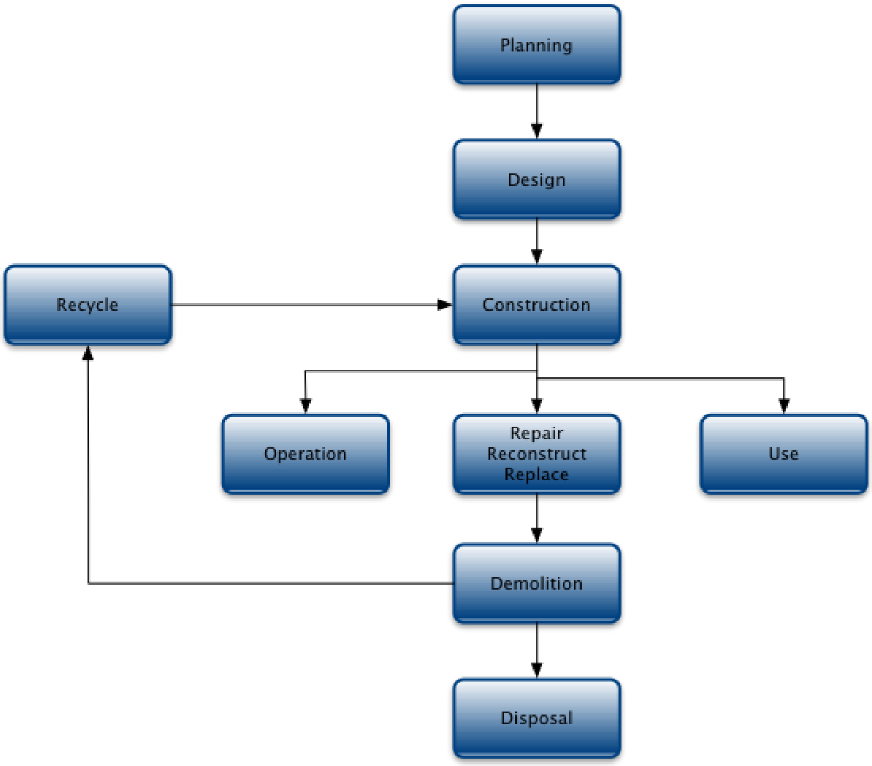

Figure 42: Life cycle stages for a transportation infrastructure project (Myer 2008)

### Life Cycle Assessment

Life cycle assessment (LCA) is a method and tool that quantifies the environmental impacts of a product or process through its entire life cycle. Figure 43 is an example of all the life cycle stages of a product. The beginning of the life cycle stages typically starts with raw material extraction and usually ends with an end of life scenario (e.g., disposal) of the product. Life cycle assessments are often referred to as cradle-to-grave, cradle-to-gate, and cradle-to-cradle. The cradle-to-grave scenario is when the product's end of life is disposal, cradle-to-gate ignores the impacts of the use phase, and the cradle-to-cradle scenario is when the product's end of life is the recycling or reutilization as a raw material to make the same (or different) product (Henrikke and Anne-Marie 2004).

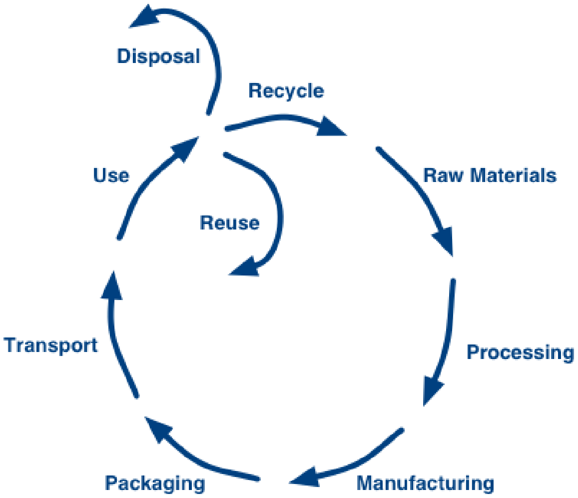

Figure 43 Typical life cycle stages for a product (UNEP 2004)

In order to perform an LCA, it is necessary to follow four steps: goal and scope, life cycle inventory, impact assessment and interpretation, in accordance with International Standardization Organization (ISO) 14040 guidelines (Henrikke and Anne-Marie 2004; Hendrickson, Lave et al. 2006). These steps are usually performed in sequential order; however, iterations between steps and changes can be made in order to fulfill (or redefine) the goal and scope. The goal and scope definition states the main purpose of the project along with additional information such as geography or timeframe. For the inventory analysis, a detailed database is assembled, and inflows and outflows are calculated (e.g., mass or energy). The impact assessment stage is when the outflows from the life cycle inventory are transformed and categorized into meaningful results to be interpreted. The interpretation stage may take place at any time of the assessment. Figure 44 is a graphic representation of the life cycle assessment stages.

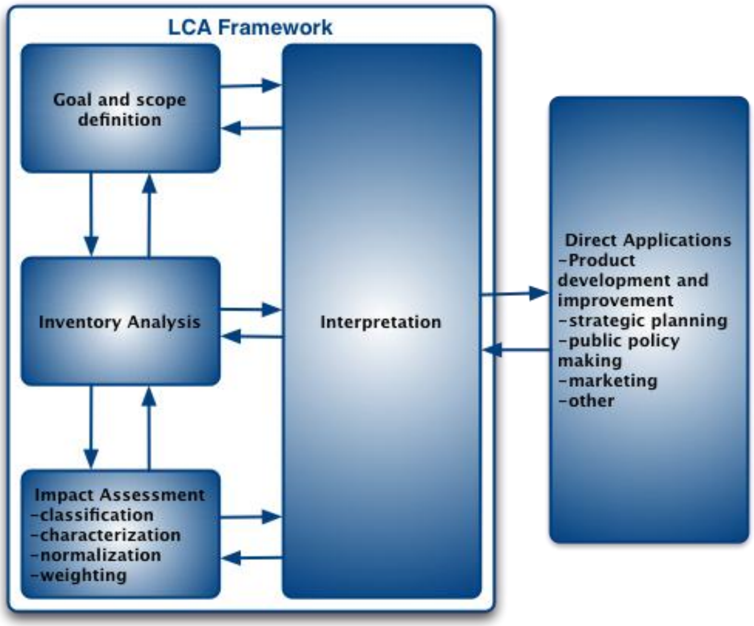

Figure 44: LCA stages and potential applications (Henrikke and Anne-Marie 2004)

Three modeling options exist for developing a life cycle inventory: process, input-output, and hybrid. Process and input-output methods are widely used and have strengths and limitations. Hybrid modeling combines both approaches and addresses the limitations in each approach. The process LCA method systematically models the known environmental inputs and outputs by utilizing a process flow diagram. The scope of the process model continues to the point where the process and emission flows are negligible. This approach requires data collection from public sources, company or product specific information, and published research. Several organizations have developed software and tools to support process based LCAs. Some software programs which mainly use the process framework include SimaPro (SimaPro 5.0 2001), GaBi (GaBi Software 1995), and Gemis (GEMIS 4.5 2008).

Another LCI method is input-output (I-O) analysis; economic I-O analysis was developed by Wassily Leontief (Leontief 1936), an interdependency model that quantifies proportional interrelationships among economic sectors in an economy. I-O LCA combines national sector-by-sector economic interaction data, which quantifies the dependencies between sectors, with sector level environmental effects and resource use data. Using matrix operations, a change in economic demand from a sector can be quantified in environmental effects or resource use. The U.S. economy is represented by about 500 sectors (U.S. Department of Commerce 1997). Given the range of economic products, the sectors may represent a wide range of product types. I-O LCA considers both direct and indirect impacts. Carnegie Mellon University has developed publicly available I-O based LCA tool, Economic Input-Output LCA (EIO-LCA) (Lave, Cobasflores et al. 1995; Hendrickson, Horvath et al. 1998).

Transportation infrastructure analysis was first introduced as a feasible LCA field by Hovarth and Hendrickson (1998), and their method, the hybrid approach, was one of the best for the time (Horvath and Hendrickson 1998). Bilec et al (2006) describes the advantages and disadvantages of performing a hybrid LCA rather than a solely process or economic based LCA. The main advantage is the flexibility to use the data through the whole process; however, major disadvantages are the occasionally high level of aggregation of data and the necessity for various assumptions. This hybrid approach is used in parallel with the EIO-LCA tool (CMU 2008) which is specific to the US.

## Literature Review: Life Cycle Assessments of Pavement Types

Hovarth and Hendrickson (1998) performed an LCA using EIO-LCA comparing asphalt and steel-reinforced concrete pavements with results showing that asphalt has a higher energy requirement than steel-reinforced concrete pavement (Horvath and Hendrickson 1998). Zapata et al (2005) compared the energy use of a concrete highway and an asphalt highway. This process-based study was conducted in the US, and the main findings conclude that concrete pavements require more energy than asphalt pavements. Zapata also mentions the possible conflicting results and opposing effects if a solely economic input-output approach or a process based approach is used (Zapata and Gambatese 2005).

In analyzing at the amount of waste generated in concrete and asphalt pavements, Sathyanarayanan and John (2007) concluded that wastes are mainly generated in the manufacturing phase of construction materials and at the end of life (EOL) of the highway. This research article encouraged further thinking about ways to maximize material usage at the EOL phase so materials are not landfilled. Further research into the construction, use, and end of life phases for a highway was conducted by Zhang et al (2008) which examined the advantages of overlays for rigid pavements.

Horvath (2003) analyzed the environmental and economic impacts of various construction practices, such as the reuse of construction materials, and found the use of recycled material to be economically beneficial (Horvath 2003). Chiu, Hsu et al (2008) found through their comparative study that recycled hot mix asphalt has about 20% less environmental "burden" than traditional hot mix asphalt while having the same service life (Chiu, Hsu et al. 2008). There is still concern over the chemical leaching implications associated with recycled aggregates, however for concrete, Petkovic et al. (2004) and Carpenter et al. (2007) state that leaching issues can be handled individually based on the original chemical content while Rao et al. (2007) recommend recycled aggregates in lower end applications for concrete (Petkovic, Engelsen et al. 2004; Rao, Jha et al. 2007) (Carpenter, Gardner et al. 2007).

## PALATE Description

In order to perform the LCA of the alternative materials compared to the virgin materials, we used Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), a tool that developed in 2003 by Dr. Horvath, Dr. Sergio Pacca, Eric Masanet and Rachel Canapa at the University of California, Berkeley (Horvath, Manufacturing et al. 2003). Table 19 summarizes the main features present in PaLATE. This software calculates the environmental impacts of different types of highway materials and pavements. PaLATE is specific to the US and has the opportunity of incorporating life cycle assessment and life cycle costing (LCC) of the pavement under consideration.

Table 19: Characteristics from PaLATE (Horvath 2003; Hovarth 2004; Horvath 2009)

| **Objective** | **Tool for performing LCA and LCC of pavements** | |
|---|---|---|
| **Advantages** | • Free<br>• Excel Based<br>• Easy to incorporate data<br>• Ability to compare two scenarios (mainly for materials and recycled content materials)<br>• Ability to compare material transportation scenarios<br>• Multiple ways of performing LCC | |
| **Inputs** | Economics | • Material Costs<br>• Initial Costs<br>• Process Costs |
| | Equipment | • Type<br>• Distance transporting material |
| | Pavement Design | • Material type<br>• Material quantities |
| **Outputs** | Economics | • NPV (life cycle stage or product/process/material)<br>• Annualized costs (life cycle stage or product/process/material) |
| | Environmental | • Energy consumption<br>• Water consumption<br>• $CO_2$ emissions<br>• Air/chemical emissions<br>• Cancer and non cancer Human Toxic Potential |
| **Data Sources** | US Data sources (US EPA AP 42 (EPA 2009), EIO-LCA 1997 Model(CMU 2009), multiple equipment types and manufacturers) | |
| **Target Audience** | Designers, Engineers, Decision-Makers, Researchers and Students | |
| **Need of Previous knowledge** | YES | |

One limitation that PaLATE has is that data availability is limited; also it requires manual updates of databases and the references. Even with these limitations, PaLATE's advantages outweigh its limitations with respect to analyzing the environmental impacts of pavements specifically in the US.

## 7.1. Alternative Materials

### 7.1.1. Recycled Asphalt Pavement

(Note: much of the material in this section concerning recycled asphalt pavement is drawn directly from the FHWA publication "Pavement Recycling Guidelines for State and Local Governments – Participants Reference Manual" by Kandahl and Mallick. Additional references are cited where appropriate.)

**Descriptions**

There are four general approaches to asphalt pavement recycling: hot-mix recycling, hot in-place recycling, cold in-place recycling and full-depth reclamation.

Hot Mix Recycling

Hot mix recycling (or hot recycling) has been defined as a method by which reclaimed asphalt pavement (RAP) is combined with new aggregate and an asphalt cement or recycling agent to produce hot mix asphalt (HMA). Of the various types of recycling options available, hot mix recycling can probably be considered to be the most useful and proven method. It can be used to correct mix design problems in existing pavements, to correct and maintain horizontal geometrics, or as a rehabilitation alternative where curb and bridge clearances are a problem.

The method of hot mix recycling includes removal of existing HMA pavement, crushing, stockpiling of RAP, mixing, lay down, and compaction. The RAP may be obtained by pavement milling with a rotary drum cold milling machine or from a ripping/crushing operation (ARRA 1992). Except for lay down and compaction, which are similar to conventional hot mix construction, the other processes require some relatively minor modifications to existing plants or some new equipment.

The most commonly used method of hot recycling in batch plants is the heat transfer method. The virgin aggregates are superheated to a certain temperature to transfer heat and dry the RAP material. Proper care must be taken in crushing to smaller sizes, and stockpiling the RAP to prevent contamination, consolidation or moisture retention. Production of recycled hot mix must be made under strict quality control to ensure satisfactory performance of the mix.

Hot mix recycling can use the same materials repeatedly, requires little (if any) modifications to existing equipment, eliminates the problem of disposal of reclaimed materials, and can be done in compliance with existing air pollution control standards.

Factors controlling the percentage of RAP that can be used are the temperature to which new aggregates must be heated, moisture content of RAP, temperature of the RAP in stockpile, desired recycled HMA mix temperature, HMA production rate, exhaust capacity of the pugmill or weigh hopper, and the percentage of RAP passing the 0.075 mm (#200) screen (ARRA 1986). According to the Asphalt Recycling and Reclaiming Association, the practical limit on RAP content for hot mix recycling in a batch plant is 20 percent, although up to 40 percent RAP can be used and as high as 50 percent RAP has been used if the moisture content of the RAP is minimal and the RAP is fed to the plant at the ambient temperature. Generally, 30 to 35 percent RAP is considered to be the practical limit with 10 to 20 percent RAP being a typical range.

In base course applications, the allowable percentage of RAP ranges from 15 to 100, with a large number of states (27.1 percent) allowing 50 percent. Many states (22.9 percent) have no limit on the amount of RAP that can be used. For binder course applications, the allowable percentage ranges from 15 to 100. Approximately equal number of states (25.1 and 20.8 percent) allow 50 percent and unlimited amounts, respectively. Only one state does not allow the use of RAP in batch plants for binder courses. For surface course applications, the allowable percentage ranges from none to 100. A significant percent of states (22.9 percent) do not allow any RAP in surface layers, while 16.6 percent of the states allow unlimited RAP in this layer. Some states have special provisions for allowing RAP in the surface mixes.

Hot mix recycling has been proven to be a viable rehabilitation technique. When designed and constructed properly, hot mix recycled pavements have performed comparably to or better than conventional HMA pavements.

### Hot In-Place Recycling

*Hot in-place recycling* (HIR) has been described as an on-site, in-place method that rehabilitates deteriorated asphalt pavements and thereby minimizes the use of new materials (ARRA 1998). Basically, this process consists of four steps: (1) softening of the asphalt pavement surface with heat; (2) scarification and/or mechanical removal of the surface material; (3) mixing of the material with recycling agent, asphalt binder, or new mix; and (4) laydown and paving of the recycled mix on the pavement surface. The primary purpose of hot in-place recycling is to correct surface distresses not caused by structural inadequacy, such as raveling, cracks, ruts and holes, and shoves and bumps. It may be performed as a single-pass operation or a multiple-pass operation. In a single-pass operation the virgin materials are mixed with the restored reclaimed asphalt pavement (RAP) material in a single-pass, whereas in the multi-step process, a new wearing course is added after recompacting the RAP materials. The advantages of hot in-place recycling are that elevations and overhead clearances are preserved, it is comparatively economical, and needs less traffic control than the other rehabilitation techniques. This process can also be used to recoat stripped aggregates, re-establish crown and drainage, modify aggregate gradation and asphalt content, and improve surface frictional resistance. Hot in-place recycling is usually performed to a depth of 20 mm to 50 mm (3/4 to 2 in), with 25 mm (1 in) being a typical depth.

The Asphalt Recycling and Reclamation Association (ARRA) recognizes three basic types of hot in-place recycling processes: (1) surface recycling, (2) repaving, and (3) remixing. Recycling agents for rejuvenating the aged asphalt binder may be added in all the three methods, but virgin aggregate is used only in repaving and remixing operations.

## Cold In-place Recycling

*Cold In-place Recycling* (CIR) is defined as a rehabilitation technique in which the existing pavement materials are reused in place (ARRA, 1992). The materials are mixed in place without the application of heat. The reclaimed asphalt pavement (RAP) material is obtained by milling, planing, or crushing the existing pavement. Virgin aggregate or recycling agent or both are added to the RAP material which is then laid and compacted (Wood, White et al. 1988). The use of cold in-place recycling can restore old pavement to the desired profile, eliminate existing wheel ruts, restore the crown and cross slope, and eliminate pothole, irregularities and rough areas. It can also eliminate transverse, reflective, and longitudinal cracks (ARRA 1992). Some of the major reasons for the increased use of cold in-place recycling are the increased scarcity of materials, particularly gravel and crushed rock, the method’s high production rate and potential of cost savings, minimum traffic disruption, ability to retain original profile, reduction of environmental concerns, and a growing concern for depleting petroleum reserves (Wood, White et al. 1988). Cold in-place recycling is more suitable than cold central plant recycling particularly for secondary low-volume roads that are located at a considerable distance from a central plant (Kandhal 1984).

Cold in-place recycling can be performed in two ways: full depth and partial depth. In full-depth recycling (reclamation or stabilization), both asphalt and portions of unbound subbase or base layers are crushed, mixed with binder, and placed as a stabilized base course. In partial-depth recycling, a portion of the asphalt layer, normally between 50 and 100 mm (2 and 4 in) thick is used to produce a base course – usually for low-to-medium traffic volume highways. With recent improvements in cold milling techniques, full-depth recycling can now be used to include a substantial portion of underlying unbound materials. As a result, the Asphalt Recycling and Reclaiming Association (ARRA) defines cold in-place recycling as a partial-depth recycling process involving 75 to 100 mm (3 to 4 in) of the existing pavement and defines full-depth recycling as full-depth reclamation, which is considered a separate procedure (ARRA 1992).

The steps in cold in-place recycling consist of preparation of construction area, milling the existing pavement, addition of recycling agent and virgin materials, laydown, compaction, and placement of the surface course. The addition of new aggregates may not be necessary in some projects. One of two different methods is typically used for cold in-place recycling: the single machine and the single-pass equipment train.

### Full Depth Reclamation

*Full depth reclamation* has been defined as a recycling method where all of the asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base layer (ARRA 1992). Treatment of the materials can be performed using one or more of the following additives: asphalt emulsions, calcium chloride, portland cement, fly ash and/or lime.

The five main steps in this process are pulverization, introduction of additive, shaping of the mixed material, compaction, and application of a surface or a wearing course. If the in-place material is not sufficient to provide the desired thickness of the treated base, new materials may be imported and included in the processing (ARRA 1992). This method of recycling is normally performed to a depth of 100 to 300 mm (4 to 12 in) (Epps 1990).

The major advantages and benefits of full depth reclamation are as follows (Epps 1990; ARRA 1992):

1) The structure of the pavement can be improved significantly without changing the geometry of the pavement and shoulder reconstruction.
2) It can restore old pavement to the desired profile, eliminate existing wheel ruts, restore crown and slope, and eliminate potholes, irregularities, and rough areas. Pavement widening operations can also be accommodated in the process. A uniform pavement structure is obtained by this process.
3) It can eliminate alligator, transverse, longitudinal, and reflection cracking. Ride quality can be improved.
4) Frost susceptibility may be improved.
5) The production cost is low, and only a thin overlay or chip seal surfacing is required on most projects.
6) Engineering costs are low.
7) Materials and energy are conserved, and air quality problems resulting from dust, fumes, and smoke are eliminated. The process is environmentally desirable, since disposal problems are avoided.

Full depth reclamation has been recommended for pavements with deep rutting, load-associated cracks, nonload-associated thermal cracks, reflection cracks, and pavements with maintenance patches such as spray, skin, pothole, and deep hot mix. It is particularly recommended for pavements having base or subgrade problems.

When properly selected and implemented, all of the asphalt recycling methods described above are usually cheaper than conventional asphalt pavement rehabilitation methods, although the actual savings will depend on the specific project and the kind of recycling technique used. The primary savings in hot and cold mix recycling come from reductions in the amount (and, therefore, total cost) of virgin asphalt cement, while the savings in hot in-place recycling comes from the use of very little additional virgin material and from eliminating the costs associated with transporting materials between the job site and batch plant. The major savings in the case of cold in-place recycling comes from the elimination of the need for heating fuel and emission control systems (because the process is done at ambient temperatures), elimination of transportation costs, and the addition of only a small percentage of virgin asphalt binder.

## Use of Recycled Asphalt Pavement

Hot-mix recycling was practiced as early as 1915, but few large-scale projects were conducted until 1974 when the price of asphalt increased dramatically. Since that time, hot-mix recycling has grown to become a widely used rehabilitation technique. Recent data indicates that nearly every state has at least some experience with hot-mix recycling (Roads and FHWA 1990; Bridges 1992).

The first use of full-depth reclamation is generally reported as having taken place sometime during the 1910s or 1920s (Epps 1990; Rogge, Hicks et al. 1990). By 1987, 48 percent of all state highway agencies (and many county and city agencies) reported that they used (or had used) cold in-place recycling for their pavements (Wood, White et al. 1988). These numbers have certainly increased since that time. County and secondary highways make up the largest proportion of cold in-place recycling projects (e.g., 62 percent of all reported projects in 1987), followed by city street projects. Interstate pavements were reported to make up only 7 percent of all in-place recycling projects (Wood, White et al. 1988).

Hot in-place (surface) recycling, which dates back to the 1960s, has been used much less extensively than hot-mix or cold in-place recycling and full-depth reclamation, and the market for this technique has been primarily on city streets (FHWA 1985). This limited use probably relates to the applicability of hot in-place surface recycling, which is less universal than cold in-place and hot-mix recycling techniques, and there is greater potential for its misapplication (the most common of which is to apply this treatment for surface deficiencies to pavements with deeper structural problems. It is most effective in urban areas as a relatively inexpensive rehabilitation technique that easily maintains existing curblines, drainage features and other structures.

Kandhal and Mallick (1997) presents several case studies of the design, construction and performance of each of these asphalt pavement recycling techniques.

## Implementation Requirements and Strategies

Each of these asphalt recycling technologies offers specific economic advantages when properly applied. They are mature technologies and PennDOT already uses some of them, but development and improvements have continued to take place and it may be to PennDOT’s advantage to update and improve current specifications and guidelines that pertain to the use of asphalt recycling. For example, current practices in many states allow the use of higher quantities of reclaimed asphalt pavement in hot mix recycling by modifying the points at which the RAP is introduced into the mix and by more carefully controlling the temperatures and times of mixing. Additionally, the introduction of chemical modifiers has facilitated these processes in some cases.

If PennDOT chooses to implement these types of changes, it will be necessary to develop training materials and host seminars, webinars and demonstrations to assist PennDOT staff (engineers and inspectors) and contractor staff in successfully implementing these technologies.

## Environmental Analysis

The environmental analysis for RAP consists in the comparison of one mile of constructed highway. The life cycle stages that this analysis encompasses are raw material extraction, transportation, and construction. The two alternatives compared in this analysis are a road constructed with all virgin materials and a road that contains certain amount of RAP. Table 20 provides the goal, scope and functional unit for this particular analysis.

**Table 20: Goal, scope and functional unit for environmental analysis or RAP in asphalt pavements**

| | |
|---|---|
| Goal and scope | Compare the environmental impacts of typical asphalt pavement with all virgin materials to an asphalt pavement with a percentage content of RAP and RCA |
| Functional Unit | 1 lane-mile of highway (13 ft wide, 1 mile long, 21 in deep) |

The environmental analysis that is presented throughout graphs looks at the possibility of having RAP and RCA in asphalt pavements. The percent of RAP that was present in the wearing course was varied in our analysis from cero to a hundred percent. In the same way, the RCA present in the subbase was also varied in the same scale. The graphs below show that there is a linear relationship between the increase of energy (Figure 45), CO2 emissions (Figure 46) and PM10 (Figure 47) with the percent of recycled material present in the pavement. It is theoretically possible to achieve the highest reduction of energy use, CO2 emissions and PM10 when constructing a highway that utilizes 100% of RAP in the wearing course and 100% or RCA in the subbse when compared to constructing a highway with all virgin materials. Other categories considered in this analysis are shown in Figure 74, Figure 75 and Figure 76 located in Appendix B: Environmental Analysis.

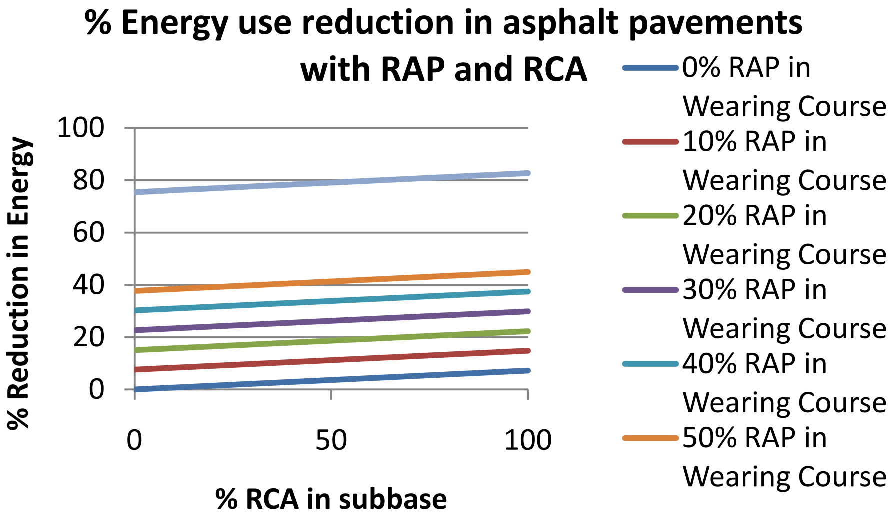

Figure 45: Percent of energy reduction in asphalt pavements with RAP (in the wearing course) and RCA (in the subbase)

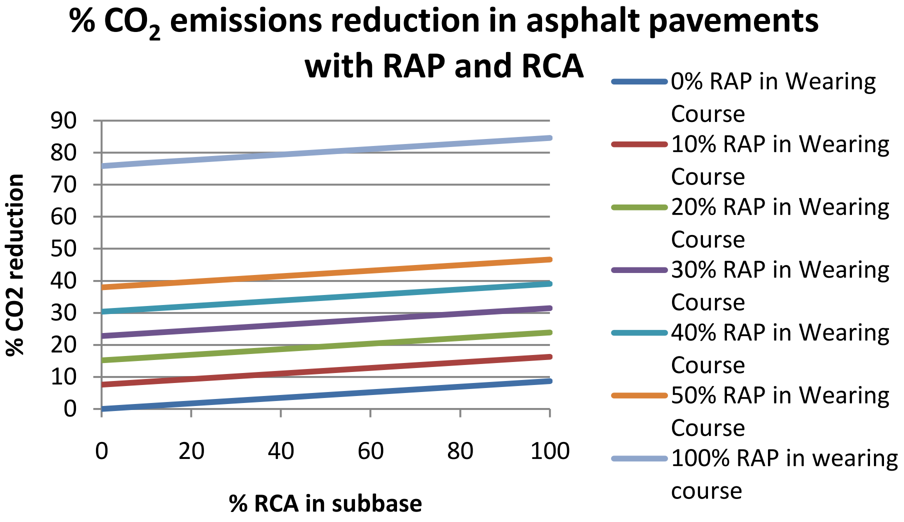

Figure 46: Percent of CO2 emission reduction in asphalt pavements with RAP (in the wearing course) and RCA (in the subbase)

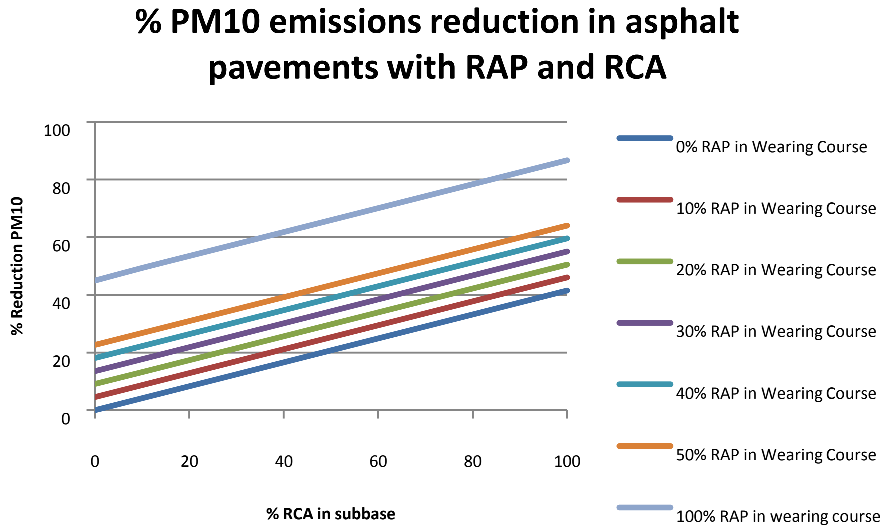

**Figure 47: Percent of CO2 emission reduction in asphalt pavements with RAP (in the wearing course) and RCA (in the subbase)**

The scenario of asphalt pavements with 30% of RAP in the wearing course and 30% of RCA in the subbase was compared to an all-virgin materials asphalt pavement. The contribution of energy use per stage (material extraction, transport of materials and process of constructing a highway) is shown in Figure 48. The material extraction contribution decreased around 0.5 TJ of energy when using recycled materials compared to virgin materials. For the transportation and construction stages, there was a slight increment of energy use when compared with the recycled content scenario to all-virgin materials.

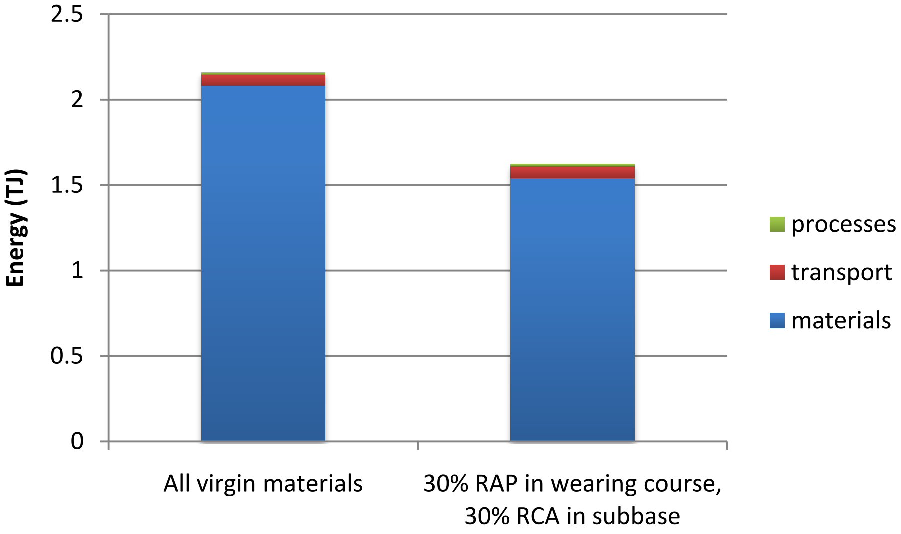

**Figure 48: Energy usage per life cycle stage in asphalt pavements**

Similar to energy use (from Figure 48), it can be seen in Figure 49 that there is a decrease of CO2 emissions in the material extraction stage recycled materials was modeled. The transportation and construction stages displayed a slight increase in CO2 emissions when using recycled materials. The trend of PM10 emissions was similar to the energy use and CO2 emissions. The decrease of PM10 when using recycled materials was around 157 kg (see Figure 50).

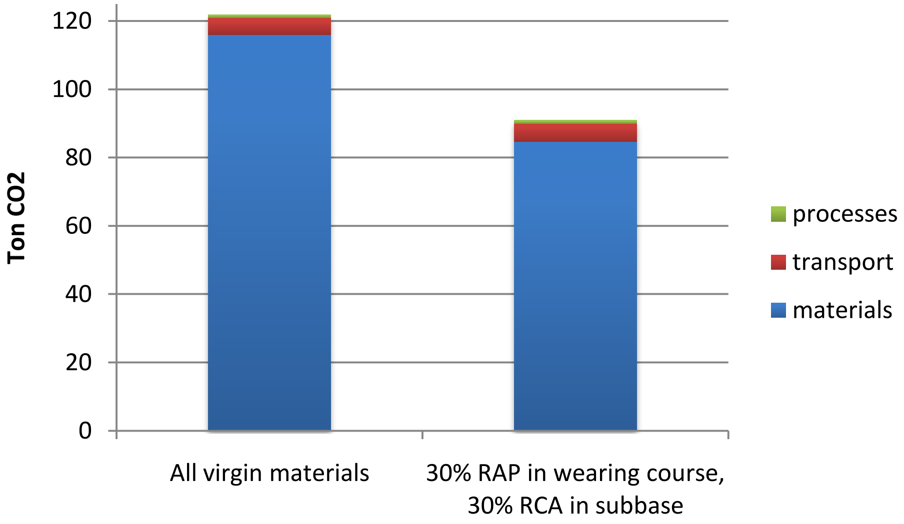

Figure 49:: CO2 emissions per life cycle stage in asphalt pavements

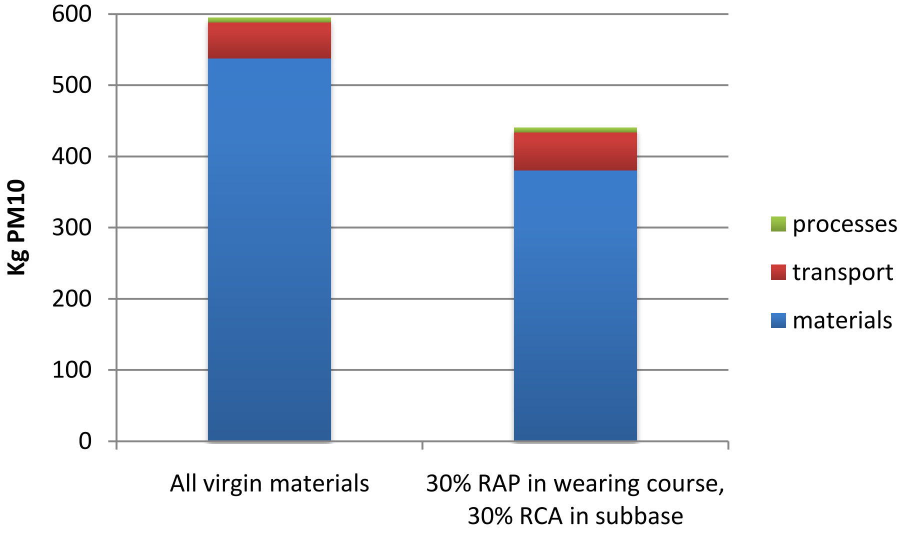

Figure 50: PM10 per life cycle stage in asphalt pavements

Following the scenario described with asphalt pavement consisting of 30% RAP (in wearing course) and 30% RCA (in subbase), the impact of transportation distance of the recycled materials to the site was investigated. There was a linear relationship between the distance traveled and the increase of energy use, CO2 and PM10 emissions. The results of this analysis are shown in the following figures: energy use increase (Figure 51), CO2 increased emissions (Figure 52) and PM10 increased emissions (Figure 53). The results transportation and water use, NOx and SO2 is illustrated in Figure 77, Figure 79 and Figure 79.

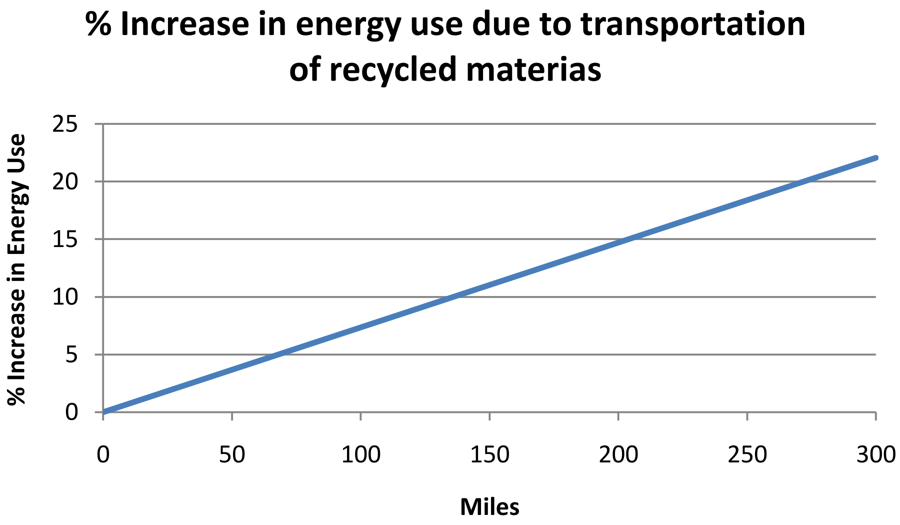

Figure 51: Energy use increase with transportation of RCA and RAP

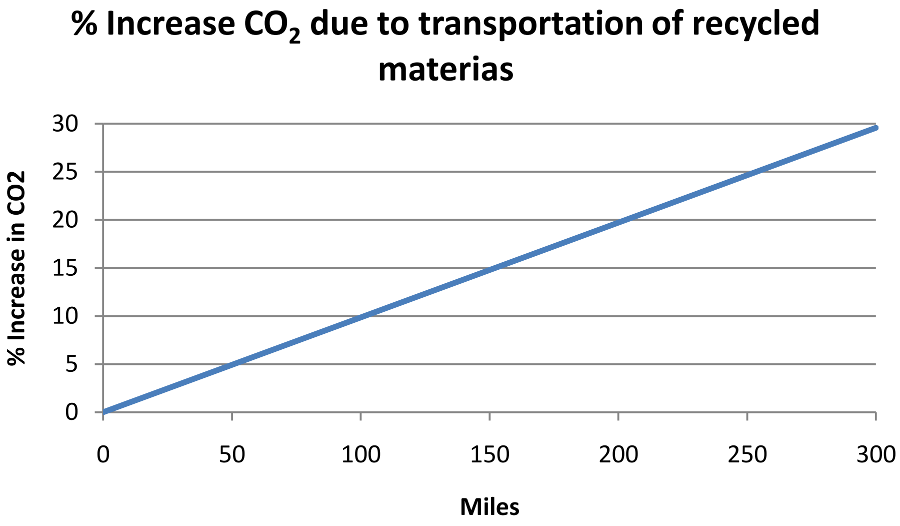

Figure 52: CO2 increase with transportation of RCA and RAP

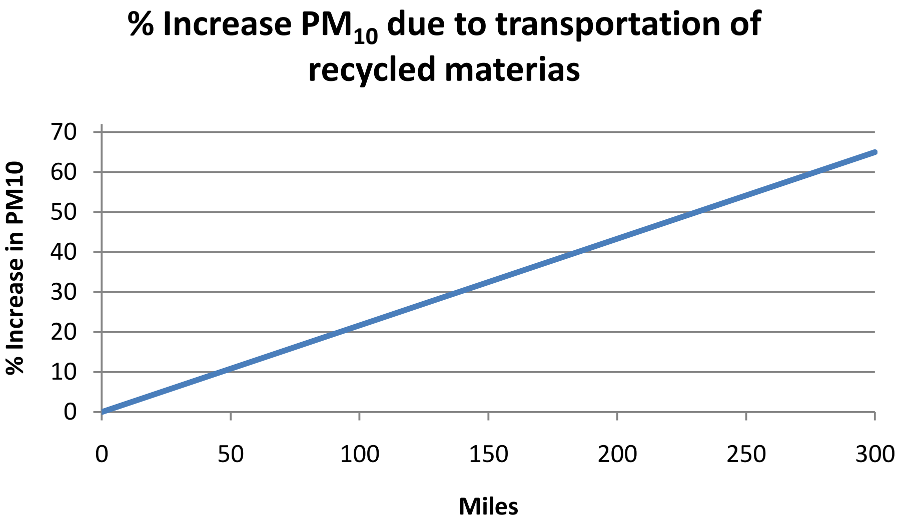

Figure 53: PM10 increase with transportation of RCA and RAP

## Current Costs/Cost Projections

Association), the cost of producing reclaimed asphalt concrete for use in hot mix recycling (including milling, trucking, screening and stockpiling) is about $6/ton, with some variability regionally due to contractor capabilities and equipment, local regulations, etc.. Putting a value on the material is much more difficult because RAP is not typically listed as a bid item on contract documents and the implicit value seems to vary greatly with location. For example, the value tends to be higher in rural areas where there is a lack of RAP sources and lower in metropolitan areas where there is generally an abundance of asphalt paving. In addition, the value of the material can be related directly to the value of the asphalt and aggregate that it replaces, and the price of asphalt has been volatile in recent years while aggregate prices are generally rising steadily (and rapidly in some areas).

The actual of RAP in any specific instance can be considered in terms of its value as replacement material in hot mix. It is often reasonable to assume that reclaimed asphalt bount within RAP can be used to replace about 4 percent asphalt cement content plus 100 percent of the volume of aggregate provided. The current local prices for asphalt cement and aggregate can then be used to determine a fair value for the RAP in hot mix recycling. (per telephone communication with D. Newcomb of NAPA, September 2009).

Cost savings have been reported on almost every project where hot mix recycling costs have been tracked and reported. For example, Wisconsin DOT has reported savings that ranged from $4.52/ton of paving material to more than $6.75/ton, depending on the percentage of RAP in the final mixture. A 1985 FHWA survey showed savings of between $0.50/ton and $11.45/ton (FHWA 1985).

Costs for hot in-place recycling vary widely with the depth of recycling, the geographic area, the equipment used, and whether or not new material is added during the recycling process. Cost savings of up to 20 percent have been reported for just heating, scarifying and compacting the top 1 inch of asphalt (over the costs of placing 1 inch of new material).

Costs for cold in-place recycling vary widely with the type of work being performed, the use of additives, concurrent placement of overlay materials as part of the rehabilitation strategy, etc. For example, a 1990 study indicated that Oregon expected (at that time) that cold in-place recycling of the asphalt material (without additives) on lower volume roads would range from $1.25 - $1.75/s.y. and would provide a service life of 7 to 12 years, depending upon whether it was topped with a chip seal or open-graded asphalt emulsion mixture. This compared with a cost of about $6.00 to $8.00/s.y. for a typical 2-inch asphalt overlay, which would provide a service life of 10-15 years (Scholz, Hicks et al. 1990). However, Vermont reported that cold in-place recycling was not cost-effective for at least one project in 1979, with cold in-place recycling topped by 2 inches of bituminous mix costing $7.90/s.y. and providing 9 years of service, while the placement of a typical 1.5-in asphalt overlay over the same pavement cost only $1.83/s.y. and provided 7 years of service (Frascoia and Onusseit 1979).

### 7.1.2. Recycled Concrete Aggregate

(Note: much of the material in this section concerning the recycling of concrete pavements is drawn directly from the American Concrete Pavement Association publication “Recycling Concrete Pavements” by Snyder and Rodden. Additional references are cited where appropriate.)

#### Description

Concrete recycling is a relatively simple process that involves breaking, removing and crushing hardened concrete from an acceptable source to produce “recycled concrete aggregate (RCA),” a granular material that can be used as a substitute for natural aggregate. Old concrete pavements (including highway and airfield pavements, parking lots, sidewalks, curb and gutter, etc.) that are to be removed are often excellent sources of material for producing RCA because they are generally of good quality and are free of the contaminating materials that must often be removed from concrete building demolition debris.

#### Where has it been used?

Concrete recycling has been used extensively in Europe since the 1940s and in the U.S. since the 1970s (NHI 1998). One of the first U.S. applications of RCA in pavement construction was U.S. Route 66 in the 1940s (Epps, Little et al. 1980).

Production of RCA in the U.S. currently averages about 140 million tons/year. The primary applications of RCA have been base and subbase materials, but it also has been used in portland cement concrete and asphalt concrete paving layers, high-value rip-rap, general fill and embankment, and other applications.

Concrete recycling for paving applications is now performed in at least 41 states (see Figure 54) and has the support of the Federal Highway Administration, which states that “reusing the material used to build the original highway system ... makes sound economic, environmental, and engineering sense." (FHWA 2002; FHWA 2007). FHWA further states that “the engineering feasibility of using recycled materials has been demonstrated in research, field studies, experimental projects and long-term performance testing and analysis. When appropriately used, recycled materials can effectively and safely reduce cost, save time, offer equal or, in some cases, significant improvement to performance qualities, and provide long-term environmental benefits (FHWA 2002).”

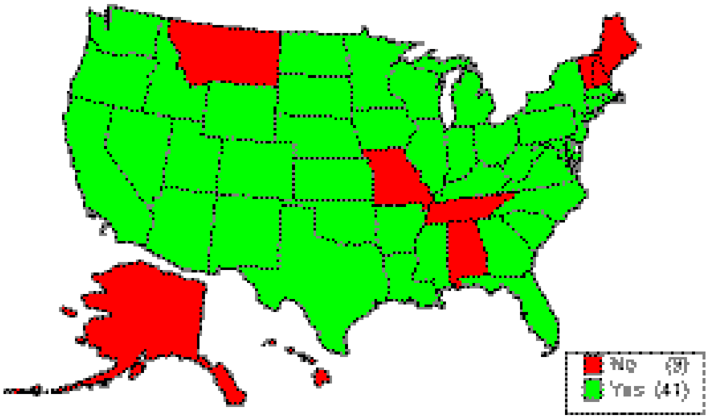

Figure 54: States that currently use recycled concrete in pavement applications (FHWA 2004).

Recycled concrete aggregate has been used in the construction of hundreds of highway construction projects in the U.S. (and around the world) since the 1970’s. These projects have included the use of RCA in pavement fill, foundation, subbase and surface courses (both asphalt and concrete). Projects have included relatively low-volume roads and some of the most heavily traveled roadway in the world (e.g., the Eden’s Expressway in Chicago). They also have included the recycling of pavements that were severely damaged by D-cracking or alkali-silica reactivity (ASR) damage back into new concrete pavements.

Table 21 presents a listing of about 30 projects (out of nearly 100 identified at the time) where concrete pavement was recycled for use as aggregate in a new concrete surface. There have been many more such projects constructed since that time. Case histories for some of these projects and others can be found in publications Wade et al (1997), Gress et al (2009) and ACPA (2008), as well as other publications. Comprehensive listings of hundreds of other concrete recycling projects constructed before 1993 (with RCA used in many types of applications) can be found in Tunison et al (1993) and Tunison et al (1993).

Table 21: A partial listing of RCA concrete pavements in the U.S. (Snyder, et al1995)

| State | Highway/ Location | Year Recycled | Remarks |
|---|---|---|---|
| Connecticut | I-84, Waterbury | 1979-1980 | Also has control section |
| Iowa | U.S. 75, Lyon County | 1976 | Two courses placed monolithically |
| | I-680, Pottawattamie County | 1977 | |
| | Rt. 2, Taylor & Page County | 1978-1979 | |
| Kansas | I-235, Wichita | 1985 | D-cracked JRCP into JPCP |
| | K-7, Johnson County | 1985 | Pavement showed signs of D-cracking |
| Michigan | Garfield Road., Macomb Co. | 1982 | JRCP into JPCP |
| | I-94, Battle Creek | 1983 | First of 10 projects on I-94 |
| | I-94, Albion | 1985 | 30 percent recycled fines |
| | I-94, Kalamazoo | 1985 | 100 percent natural sand |
| | I-94, Paw Paw | 1986 | EB in good condition, WB in poor condition |
| | Lodge Freeway, Detroit | 1987 | |
| | I-75, Monroe County | 1988 | 5 additional projects on I-75 since 1985 |
| | I-96, East County | 1988 | 5 additional projects on I-96 since 1986 |
| Minnesota | U.S. 59, Worthington | 1980 | First use of recycled D-cracked aggregate in new PCC pavement |
| | T.H. 15, Martin County | 1982-1983 | |
| | I-90, Beaver Creek | 1984 | D-cracked pavement recycled |
| | I-94, Fergus Falls | 1987-1988 | D-cracked pavement recycled |
| | I-94, Brandon | 1988 | |
| | T.H. 60, Mountain Lake | 1988 | |
| North Dakota | I-94, Cleveland | 1983 | Pavement showed signs of D-cracking |
| | I-29, Hillsboro | 1984 | CRCP into JPCP |
| | I-94, Eckelson | 1984 | Pavement showed signs of D-cracking |
| Oklahoma | I-40, Oklahoma City | 1983 | Moderate D-cracking, nondoweled JPCP |
| | I-35, Edmond | 1988 | CRCP with epoxy-coated steel |
| Wisconsin | I-94, Menomonie | 1983 | JRCP into JPCP |
| | I-90 & I-94, Madison | 1984 | Addition of two lanes and shoulders |
| Wyoming | I-80, Pine Bluffs | 1985 | First use of recycled alkai-silica reactive aggregate in new PCC pavement |
| | I-80, Green River | 1985 | |

Most of these projects have performed very well, frequently exceeding all expectations. Some projects, however, have failed prematurely in ways that were noteworthy. Some of these failures provided lessons in the design and construction of pavement details while others have led to mixture design modifications to produce concrete properties and pavement performances similar to (and, in some cases, superior to) those of conventional concrete materials and pavements.

In the state of Pennsylvania, one highway does have RCA in the subbase. I-80 utilizes a percent of recycled concrete aggregates in its subbase. From discussions with the Department, it is believed that the RCA content has not caused any failures.

### Implementation requirements/strategies

Implementation of any new technology demands that there is a need for the technology. Since some areas of Pennsylvania are located at significant distances from durable, desirable and available natural aggregate resources, concrete pavement recycling may provide alternate sources of locally available engineered aggregate materials that can be used as a substitutes for conventional aggregate sources. Therefore, implementation should begin by identifying areas of the state where concrete pavements (either bare-surfaced or overlaid with asphalt materials) require major rehabilitation or reconstruction and where the economics of concrete pavement recycling are favorable (with respect to the suitability and availability of local aggregates) for producing either foundation/subbase materials or aggregate for use in new pavement surface layers.

ACPA (2008) provides excellent general guidance concerning the properties of recycled concrete materials, and also provides (in three appendices) comprehensive guidelines for producing RCA and for using it in either new concrete mixtures or unbound foundation layers. AASHTO M319 (“Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course”) and AASHTO MP16 (“Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete”) also provide excellent starting points for the development or refinement of state specifications governing the use of recycled concrete products.

### Environmental Analysis

When performing the environmental analysis of RCA, the same approach was used for RAP. In the case for RCA, we identified two scenarios: RCA used as aggregate for concrete pavements, and RCA used as aggregate for asphalt pavements. For the first scenario, Table 22 summarizes the goal, scope and functional unit for this particular analysis. The comparison for this particular case is a concrete road built with virgin materials analogized to a concrete road containing certain percent of RCA in the wearing course and in the subbase.

**Table 22: Goal, scope and functional unit for environmental analysis of RCA in concrete pavements**

| | |
|---|---|
| Goal and Scope | To compare the environmental impacts of a typical concrete pavement with all virgin materials to a concrete pavement with a percentage content of RCA |
| Functional Unit | 1 lane-mile of highway (13 ft wide, 1 mile long, 20 in deep) |

The environmental analysis presented in the following pages below, looks at the case where concrete pavements contain RCA. The percent of RCA that was present in the wearing course and in the subbase was varied in our analysis from cero to a hundred percent. In this scenario (and similar to the scenario of asphalt pavements with RAP and RCA), there is a linear relationship between the increase of energy (Figure 55), $CO_2$ emissions (Figure 56) and PM10 (Figure 57) and percent of recycled material contained in the design. It is theoretically possible to achieve the highest reduction of energy use, $CO_2$ emissions and PM10 when constructing a highway that utilizes 100% of RCA in the wearing course and 100% or RCA in the subbase when compared to constructing a highway with all virgin materials. The categories of water use, $NO_x$ emissions and $SO_2$ emissions also considered in this analysis are shown in Figure 80, Figure 81 and Figure 82 located in Appendix B: Environmental Analysis respectively.

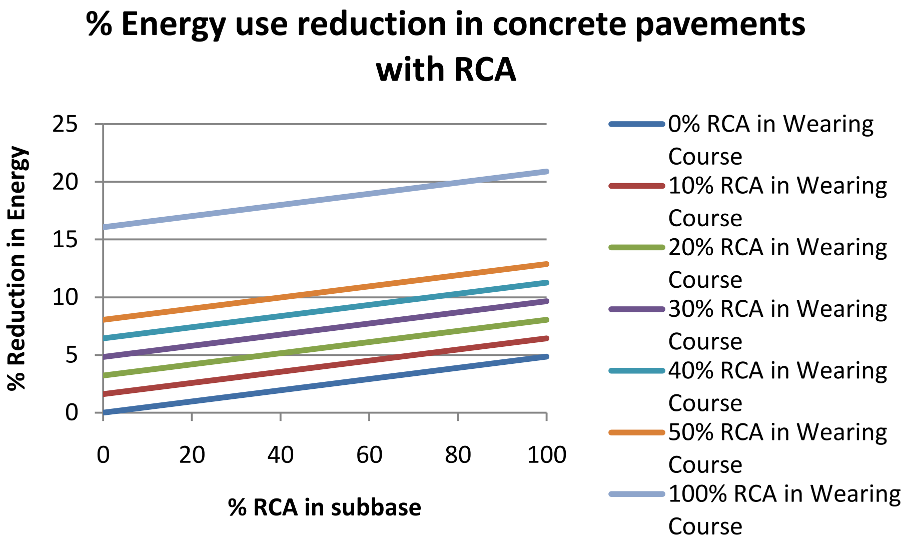

Figure 55: Percent of energy reduction in concrete pavements with RCA (in the wearing course) and RCA (in the subbase)

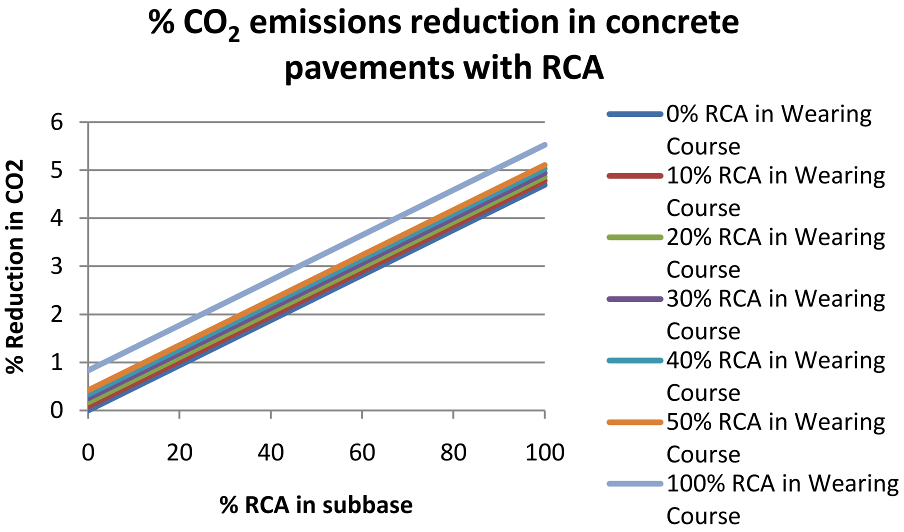

Figure 56: Percent of CO2 emission reduction in concrete pavements with RCA (in the wearing course) and RCA (in the subbase)

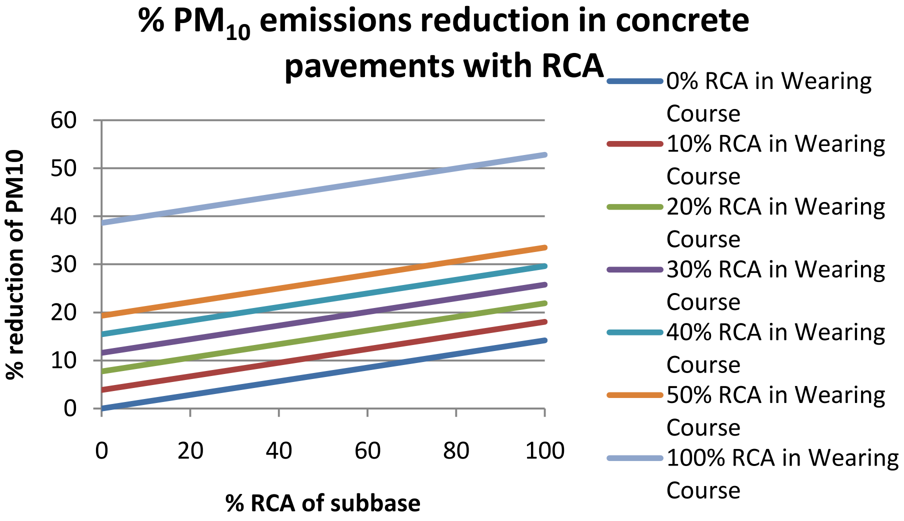

Figure 57: Percent of PM10 emissions reduction in concrete pavements with RCA (in the wearing course) and RCA (in the subbase)

For concrete pavements with 30% or RCA in the subbase and in the wearing course, an analysis was performed to determine the impacts (energy use, $CO_2$ emissions and PM10 emissions) from transportation from production site of recycled materials to the highway construction site. The results are illustrated in Figure 58, $CO_2$ emissions, PM10 emissions, water use, $NO_x$ emissions and $SO_2$ emissions.

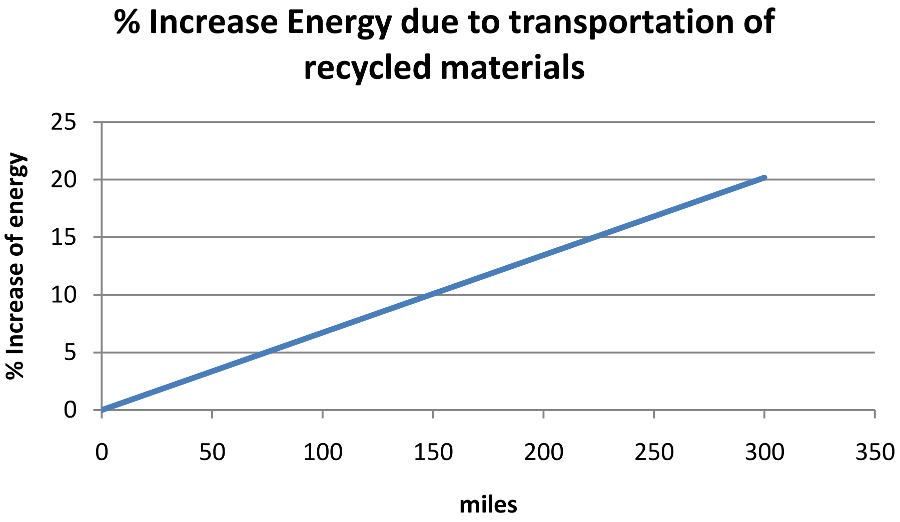

Figure 58: Energy use increase with transportation of RCA

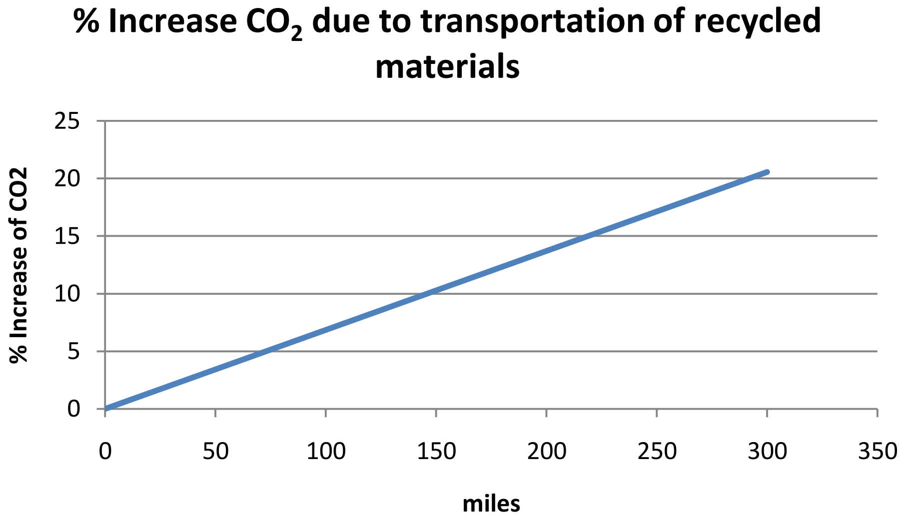

Figure 59: CO2 emissions increase with transportation of RCA

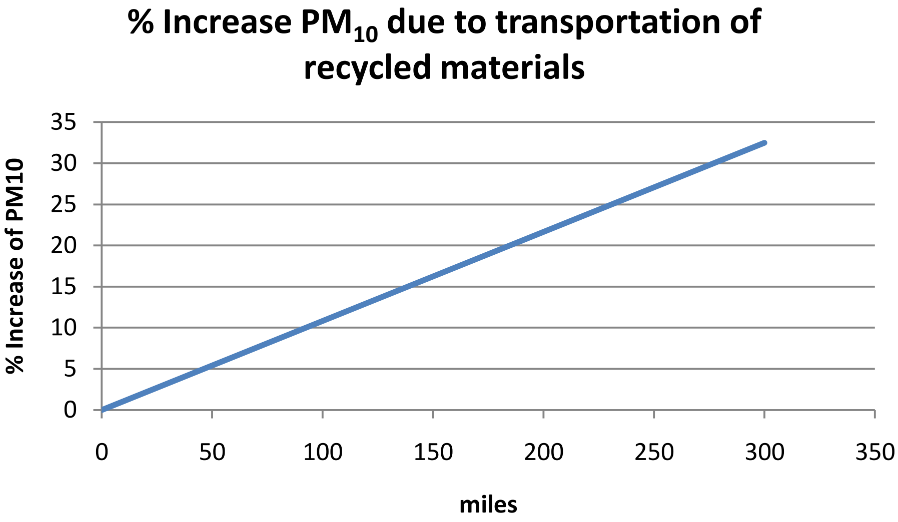

Figure 60: PM10 emissions increase with transportation of RCA

Similar to the aforementioned scenario with concrete pavements designed with 30% of RCA in the wearing course and subbase, each life cycle was evaluated to determine the contribution of each phase with respect to total energy use, $CO_2$ emissions and PM10 emissions. For energy use (Figure 61), the decrease of energy use when utilizing RCA is small (in the order of 0.13 TJ) in the materials extraction stage. For $CO_2$ emissions (Figure 62), the decrease was shown in the materials extraction and transportation stages. The result from the materials extraction phase illustrated a decrease in $CO_2$ emissions of about 2.5 tons. For PM10 emissions (Figure 63), all three stages illustrated a reduction between recycled materials and all-virgin materials.

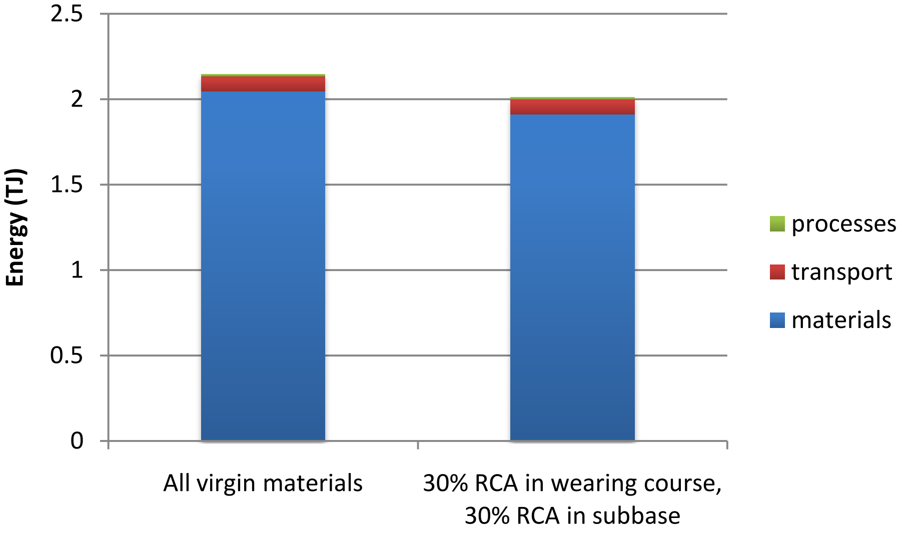

Figure 61: Energy use per life cycle stage in concrete pavements

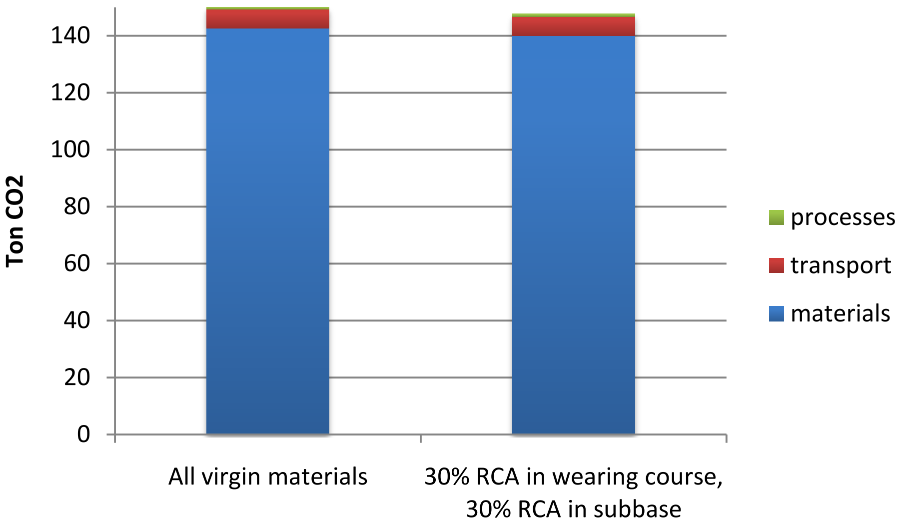

Figure 62: CO2 emissions per life cycle stage in concrete pavements

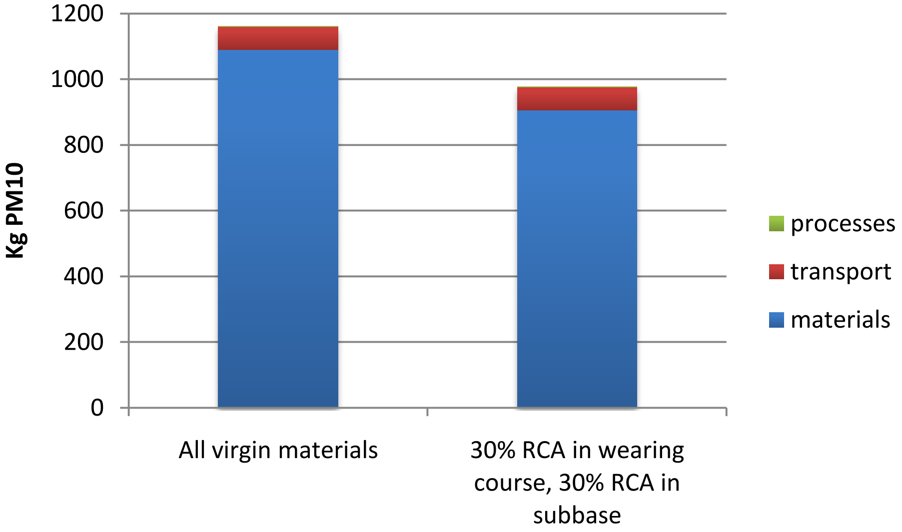

Figure 63: PM10 emissions per life cycle stage in concrete pavements

For the second scenario of using RCA as aggregate for asphalt pavements, our analysis goal, scope and functional unit are summarized in Table 23.

Table 23: Goal, scope and functional unit for environmental analysis of RCA in asphalt pavements

| | |
|---|---|
| Goal and Scope | To compare the environmental impacts of a typical asphalt pavement with all virgin materials to an asphalt pavement with a percentage content of RCA |
| Functional Unit | 1 lane-mile of highway (13 ft wide, 1 mile long, 21 in deep) |

The environmental analysis for asphalt pavements using RCA is presented below. The percent of RCA that was present in the wearing course and in the subbase was varied from zero to a hundred percent. In this analysis, there was a linear relationship between the increase of energy (Figure 64), $CO_2$ emissions (Figure 65) and PM10 (Figure 66) and percent of recycled material contained in the pavement cross-section. The categories of water use, $NO_x$ emissions and $SO_2$ emissions also considered in this analysis are shown in Figure 86, Figure 87 and Figure 88 located in Appendix B: Environmental Analysis respectively.

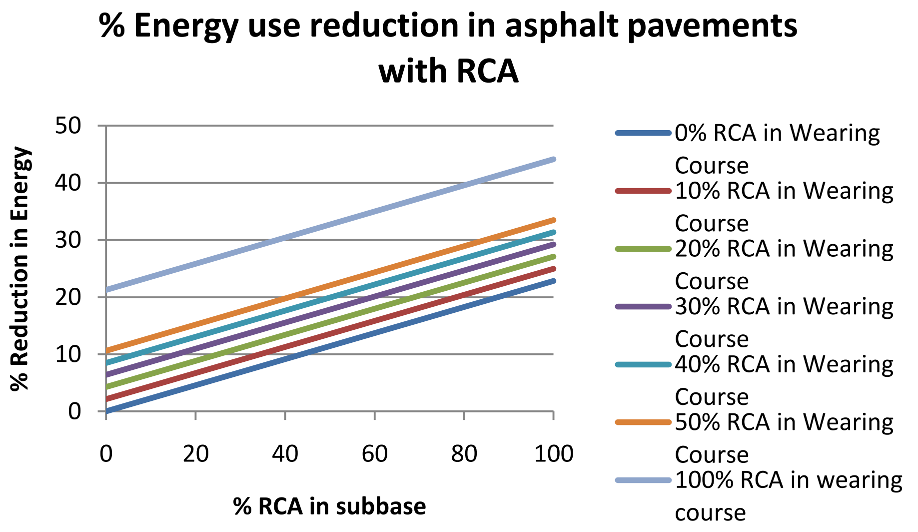

Figure 64: Percent of energy reduction in asphalt pavements with RCA (in the wearing course) and RCA (in the subbase)

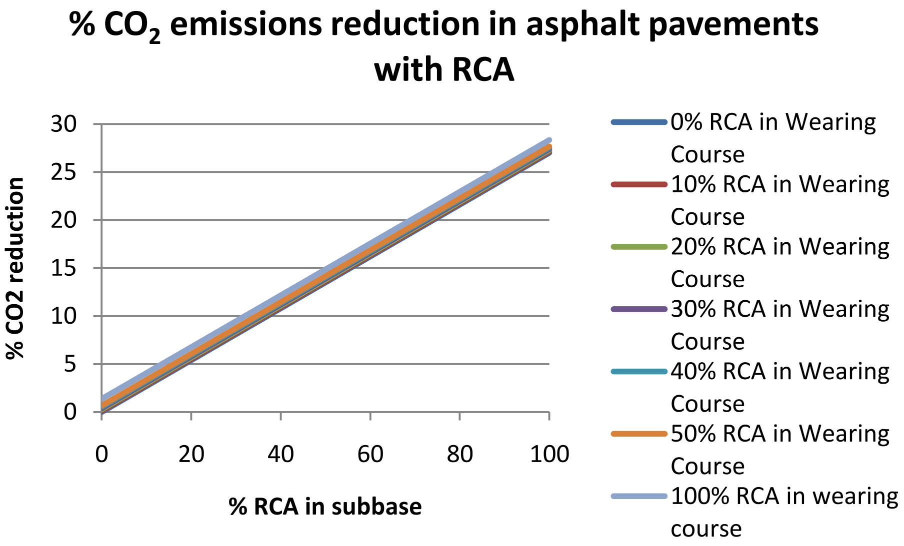

Figure 65: Percent of CO2 emissions reduction in asphalt pavements with RCA (in the wearing course) and RCA (in the subbase)

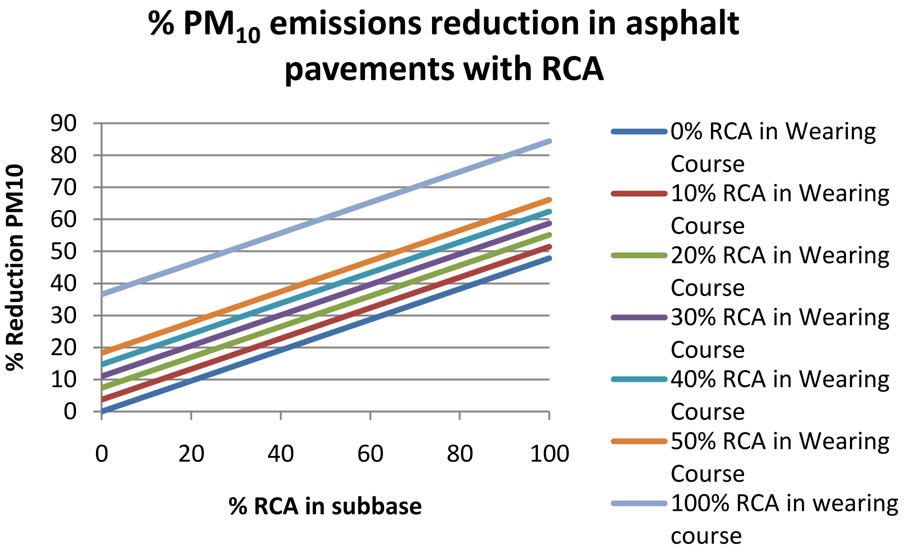

Figure 66: Percent of PM10 emissions reduction in asphalt pavements with RCA (in the wearing course) and RCA (in the subbase)

When varying the transportation distances, linear relationships exists between the distances traveled and the increase of energy use, $CO_2$ emissions and PM10 emissions. For this analysis, an asphalt pavement with 30% or RCA in its subbase and wearing course was assumed with results illustrated for energy use (Figure 67), $CO_2$ emissions (Figure 68) and PM10 emissions (Figure 69). More categories were studied with and results are displayed in Appendix B: Environmental Analysis (Figure 89, Figure 90 and Figure 91).

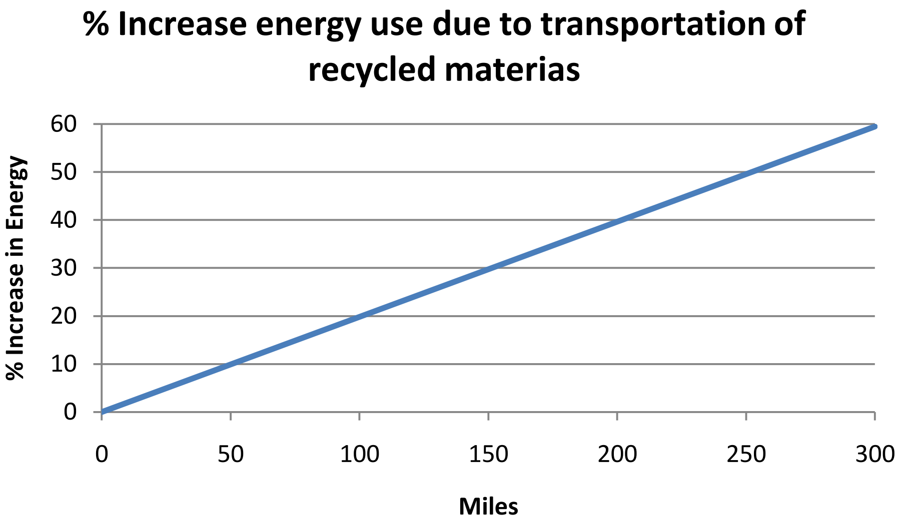

Figure 67: Energy use increase with transportation of RCA

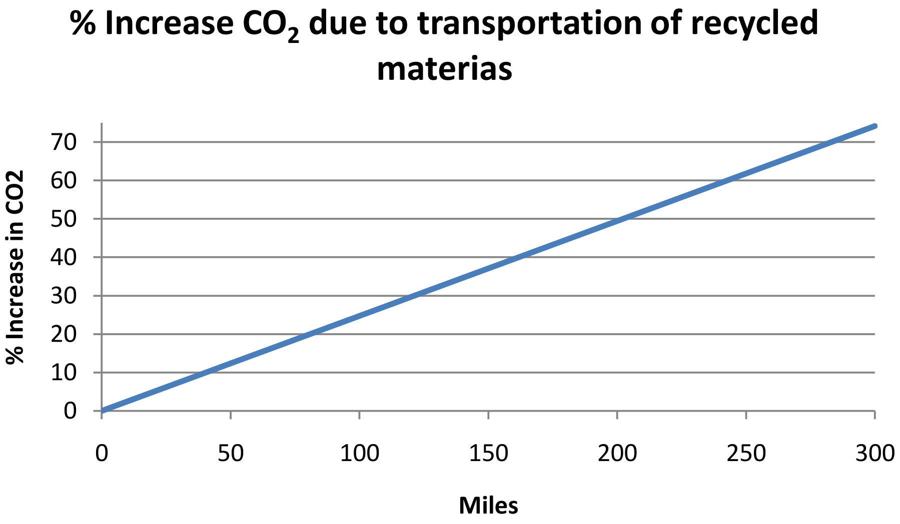

Figure 68: CO2 emissions increase with transportation of RCA

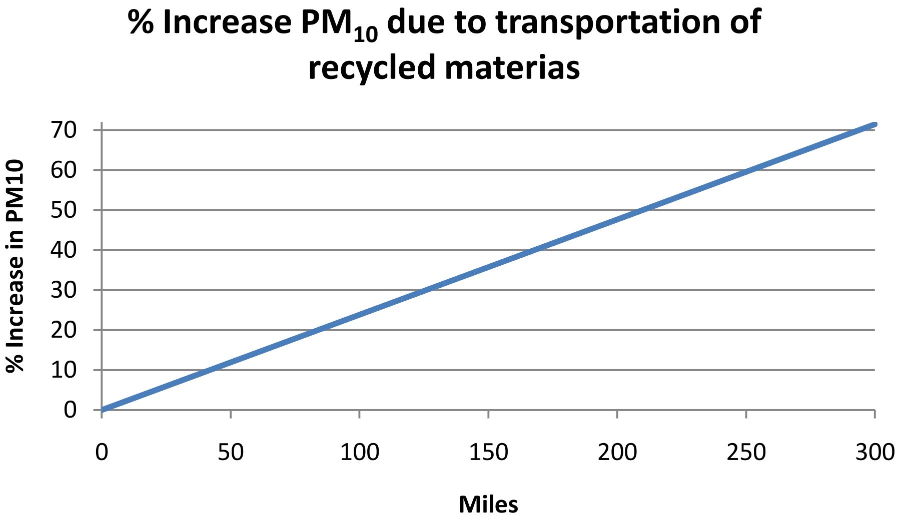

Figure 69: PM10 emissions increase with transportation of RCA

With the same scenario described above for the distance traveled of recycled materials, the contributions per life cycle stage were examined for energy use, $CO_2$ emissions and PM10 emissions. For energy use (Figure 70), the decrease of energy in the pavement containing recycled materials was small (about 0.1 TJ) corresponding to the decrease of the materials extraction and processing stage. For $CO_2$ emissions, the recycled content pavement had a reduction of approximately 3.6 tons of $CO_2$ (Figure 71) and for PM10 the recycled content pavement had a reduction of 132 kg of PM10 (Figure 72); in both cases, the materials extraction and processing stage is the one that has those differences.

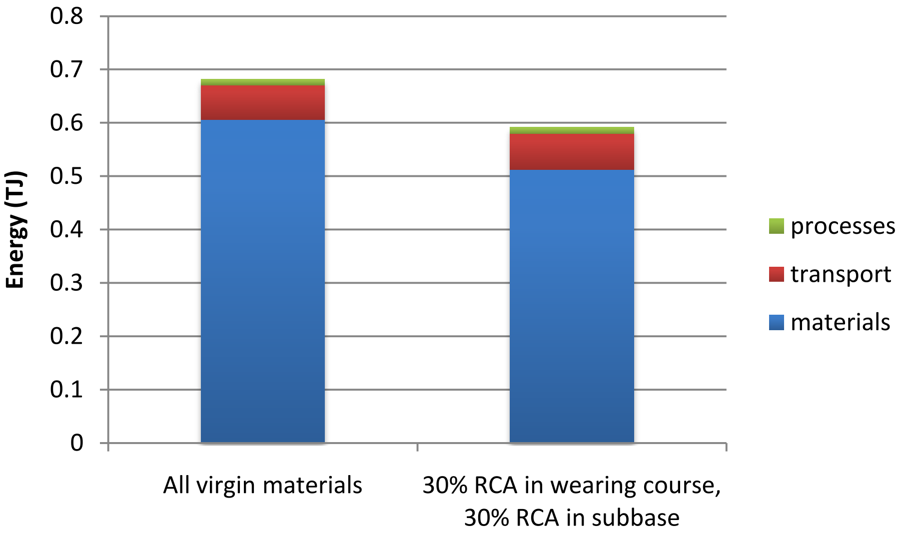

Figure 70: Energy use contribution per life cycle stage in asphalt pavements

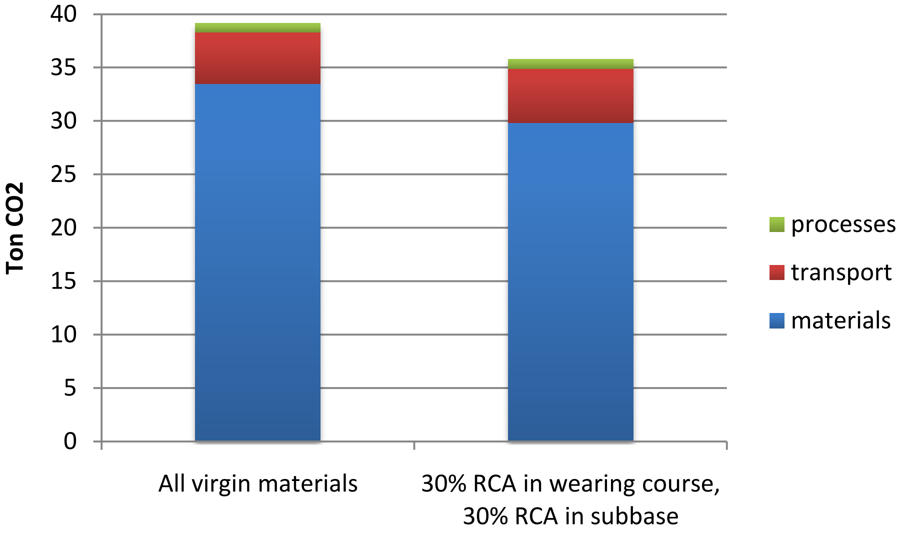

Figure 71: CO2 emissions contribution per life cycle stage in asphalt pavements

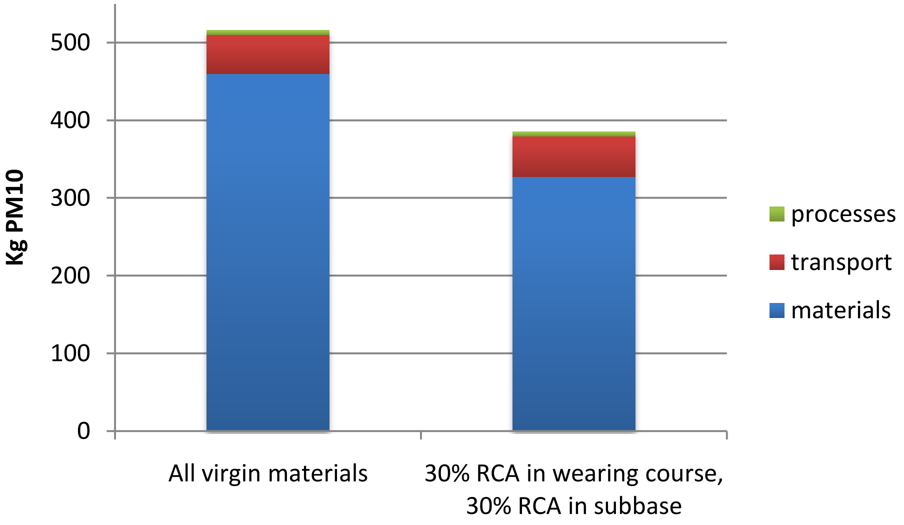

Figure 72: PM10 emissions contribution per life cycle stage in asphalt pavements

## Current Costs/Cost Projections

The cost of producing RCA can be considered to be limited to the costs of crushing the demolished concrete and screening and backhauling the RCA (along with quality control costs). The costs of concrete demolition, removal and hauling are required whether the pavement is recycled or simply discarded. RCA production costs may be offset by savings in hauling and disposal costs, especially if the RCA is produced on site.

Concrete pavement recycling costs vary widely and depend upon the location and source of the pavement being recycled, the type of pavement being recycled (i.e., reinforced vs. plain concrete), whether the concrete is being processed onsite or offsite, the type of material being produced (e.g., degree of crushing required) and intended use of material (i.e., amount of pavement preparation and product processing that must be done to ensure the quality and lack of contaminants in the product). Higher cost (and higher value) is associated with more processing for use of RCA in concrete layers, lower costs for base layers, fill, and rip-rap applications where contamination with soils, asphalt, joint sealant materials, etc. pose a smaller risk. Because of all of these variables, costs of producing RCA typically range from $1 to $16 per ton, but these costs are at least partially offset in most instances by reductions in costs from the mining, production and transport of virgin materials, elimination of landfill and disposal fees for old concrete slabs, etc.

Given that aggregate costs are one of the greatest costs in highway construction, comprising between 20 and 30 percent of the cost of materials and supplies, the potential for savings is great (Halm 1980). Cost savings from concrete pavement recycling vary but have been reported to be as high as $5 million on a single project (CMRA 2008). On average, the complete recycling of an existing concrete pavement into a new pavement structure can reduce paving costs by about $4 per square yard of pavement (ACPA 2008).

In addition, concrete pavement recycling is a smart and environmentally sustainable choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy, reduces greenhouse gas emissions and captures carbon dioxide ($CO_2$) from the atmosphere. Concrete recycling can eliminate the need for mining or extracting new virgin aggregates, and can reduce haul distances and fuel consumption associated with both aggregate supply and concrete slab disposal.

### 7.1.3. Warm-Mix Asphalt

A number of new technologies have been developed to lower the production and placement temperatures of hot-mix asphalt (HMA). HMA produced and placed using these technologies is generically referred to as warm-mix asphalt (WMA). WMA has been used in all types of asphalt concrete, including dense-graded, stone matrix, porous, and mastic asphalt. It has also been used in a range of layer thicknesses, and sections have been constructed on roadways with a wide variety of traffic levels.

#### Benefits

The potential benefits of WMA include the following:

*Reduced emissions:* Studies indicate that asphalt plant emissions are significantly reduced as fuel consumption is decreased and fewer volatile organic compounds (VOCs) are driven off at lower temperatures. Typical expected reductions are 30 to 40 percent for CO2 and sulfur dioxide (SO 2), 50 percent for VOCs, 10 to 30 percent for carbon monoxide (CO), 60 to 70 percent for nitrous oxides (NOx), and 20 to 25 percent for dust. Technologies that result in greater temperature reductions are expected to have greater emission reductions (D'Angelo 2008).

*Reduced fuel usage:* WMA burner fuel savings typically range between 11 and 35 percent, although higher savings are possible with some processes (Davidson 2005; D'Angelo 2008; Harde 2008).

*Paving benefits:* These include the ability to pave in cooler temperatures and still achieve density, the ability to haul the mix over longer distances and still have sufficient workability for placement and compaction, reduced compaction effort requirements, and the ability to incorporate higher percentages of reclaimed asphalt paving (RAP) at lower mix temperatures.

*Reduced worker exposure:* Studies suggest a 30 – 50 percent reduction in asphalt fumes and polycyclic aromatic hydrocarbons (PAHs) when compared with comventional HMA (D'Angelo 2008).

### WMA Technologies

Warm-mix technologies fall into two basic categories. One category use small amounts of water to create a foaming of the asphalt (which reduces its viscosity), and the other uses organic chemical or wax additives to reduce mix viscosity. Both approaches result in mixes that can be placed and compacted at lower temperatures (215 - 275°F) than is possible with conventional hot-mix asphalt (280 - 340°F) (Acott 2008).

### Performance

The first warm-mix sections in the U.S. were constructed in 2004, so long-term performance data for these pavements are not yet available. However, test sections constructed at the National Center for Asphalt Technology (NCAT) test track have been subjected to accelerated loadings simulating 10-12 years or more of traffic damage, and these sections have performed well, exhibiting little rutting (Prowell, Hurley and Crews 2007).

European experience with warm-mix technologies is a bit more extensive and was documented by the U.S. Federal Highway Administration during a 2007 scanning tour. This group found that "WMA mixes appear to provide the same performance as or better performance than HMA. Poor performance was observed on limited sections in Norway; the poor performance was not directly attributed to WMA use." (D'Angelo 2008).

There has been speculation that reducing production temperatures might reduce oxidation of the asphalt binder, thereby reducing the potential for future cracking, but this theory does not appear to have been proven.

### Use of WMA

WMA is being heavily promoted as a "green" technology in the U.S. and trial sections are being (or have been) constructed in many states. In Europe, the FHWA scanning team found that the use of WMA was not as high as expected, noting that “WMA, in most cases, is allowed but not routinely used.” (D’Angelo 2008).

One factor that may increase the willingness of European agencies to allow WMA is that short (2- to 5-year) workmanship warranties are included in most European paving contracts. In addition, many countries have evaluation systems that combine laboratory performance tests and controlled field trials to assess and approve new products. A similar process was recommended for development in the U.S. for WMA and other innovative processes. (D’Angelo 2008).

In most cases, WMA costs more than HMA, even when fuel savings are considered. Representatives of the French Department of Eure-et-Loir noted that they were willing to pay more for WMA because they believed it would last longer. (D’Angelo 2008).

Based on European experience and FHWA scan team recommendations, WMA should be considered as an acceptable alternative to HMA at the contractor’s discretion, provided the WMA meets applicable HMA specifications.

### Challenges to Implementation

The production of WMA often appears to involve the modification of the asphalt binder (with the potential to modify the grading of the binder). This is an area where most U.S. contractors probably have little, if any experience (given that the performance grade (PG) binder system is based on supplier certification). This may present a challenge for U.S. agencies and contractors alike, requiring the use of performance (laboratory) tests as well as field trials to assess the suitability and performance potential of various WMA technologies for specific applications.

The FHWA scanning group noted that “European contractors appear to be better equipped in terms of research and development capabilities than U.S. contractors. This capability aids European contractors in developing and selecting innovative materials like WMA (D’Angelo 2008).

### Recommendations for Implementation

According to the FHWA scanning tour team (D’Angelo 2008), key goals for implementing warm mix asphalt technologies should include:

“An approval system needs to be developed for new WMA technologies. The approval system must be based on performance testing and supplemented by field trials.”

“Best practices need to be implemented during WMA production for handling and storing aggregates to minimize moisture content, burner adjustment, and WMA in general or specific technologies.”

“More WMA field trials with higher traffic are needed. The field trials need to be large enough to allow a representative sample of the mixture to be produced. The trials should be built in conjunction with a control. The WMA Technical Working Group has developed guidelines that describe minimum test section requirements and data collection guidelines. The guidelines are at www.warmmixasphalt.com."

### 7.1.4. Rubber Pavement Materials

#### Description

The term "rubber pavement materials" refers to the use of crumb rubber, often derived from sources such as recycled automotive and truck tires, to modify asphalt binders for use in joint/crack sealants and asphalt-based paving materials.

There are two types of materials with similar names comprising asphalt and crumb rubber; but these products may perform and behave quite differently.

On one hand, "asphalt-rubber" has been defined in ASTM D 8-88 as "a blend of asphalt cement, reclaimed tire rubber and certain additives, in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles." The production of asphalt rubber takes placed under what is called a "wet process" in which ground recycled rubber is mixed in a specialized blending unit with liquid paving grade asphalt, and is heated to 375°F to 400°F to produce a thick, fluid binder. The binder is pumped from the blender to a distributor equipped with heat and an auger, where a "reaction" takes place. The reacted asphalt-rubber is then pumped directly into the pug mill or drum mixer and mixed with the aggregate. Ultraviolet inhibitors, anti-oxidants and other chemicals in the ground scrap tire rubber are transferred to the asphalt, giving the reacted asphalt-rubber material improved resistance to oxidation and greater crack resistance, which contribute to longer pavement life.

"Rubberized asphalt," on the other hand, is produced under a "dry process" in which solid crumb rubber is added as a substitute for up to 5 percent of the aggregate in the asphalt concrete mix. The paving grade asphalt binder is the same as for conventional mixes, but higher mixing temperatures (usually between 320° and 370° F) and higher compaction temperatures (300° to 320° F) are required. No specialized equipment or significant plant modifications are required for the manufacture or applications of the rubberized asphalt, and, unlike asphalt-rubber, little or no reaction takes place between the rubber and asphalt particles, leaving the asphalt unmodified and not allowing the release of the ultraviolet inhibitors and anti-oxidants contained in the scrap tire rubber.

Proponents of asphalt rubber pavements claim many benefits to the product, including the ability to use the material in pavement surfaces in reduced thickness (when compared with conventional asphalt concrete materials). Reduced thickness can be translated into reduced quantities of both aggregate and binder, which results in conservation of resources and reduced material costs (to the extent that they offset the increased cost of the rubber asphalt material). In addition, the replacement of 15 to 20 percent of the asphalt with crumb rubber results in a direct savings of asphalt materials for any given quantity of asphalt binder (RPA 2009).

The more well-known benefit of rubber asphalt pavement surfaces is the reduction of tire-pavement noise, which has been documented in several studies. This noise reduction can be used in some cases to avoid the construction of sound walls, which typically cost \$1M to \$5M per mile to build (Hanson and Waller 2005).

One of the most notable side benefits of using rubberized asphalt paving materials is that it consumes scrap tires. The Rubber Pavement Association estimates that a two-inch thick overlay of rubberized asphalt hot mix will use about 2,000 tires per lane mile, and that a spray-applied rubberized asphalt seal coat will use about 500 tires per lane-mile (RPA 2009).

One area of potential concern with using rubber paving materials is the possibility of increased health hazards to workers and others in production and placement of rubberized asphalt paving materials. A report by the National Institute for Occupational Safety and Health (NIOSH 2001) concluded that "… [crumb rubber-modified hot-mix asphalt] exposures are potentially more hazardous than [conventional asphalt paving material] exposures. Regardless of the type of asphalt being used, however, skin contact with asphalt and any clean-up solvents should be avoided and exposure to asphalt fume should be reduced whenever possible …"

Another area of potential concern is with the recyclability of rubber-asphalt products. While the rubber-asphalt paving industry correctly states that "… [rubber-asphalt] has been successfully recycled on many occasions …" (RPA 2009), there is also anecdotal evidence that the use of conventional mix technology in the recycling process can result in air quality problems if the temperature of the reclaimed material is not carefully controlled.

The Rubber Pavement Association reports that crumb rubber costs about \$.12 - \$.15 per pound a pound (as of the date of the last update to their website). Their cost estimates for asphalt-rubber and conventional hot mix are roughly \$2.50 per square yard-in and \$1.35/s.y.-in, respectively. They further estimate that the costs for asphalt-rubber and conventional pavement friction courses (thin, open-graded surface layers) are about \$2.15/s.y-in and \$1.55/s.y.-in, respectively (RPA 2009). A 2002 economic analysis by Jung et al. (2002) estimated costs of rubber-asphalt paving, rubber-asphalt friction course and conventional asphalt paving at \$2.40/s.y.-in, \$2.50/s.y.-in and \$1.70/s.y.-in, respectively (Jung, Kaloush et al. 2002).

### Use of Rubber Paving Products

While there have been many trials, demonstrations and regular construction projects constructed using asphalt-rubber and rubberized asphalt paving technology in many states (including Oregon, Louisiana, Tennessee, Florida, Texas and more), the heaviest use of this technology has taken place in Arizona and California. In both Arizona and California, one of the strongest motivators for the widespread adoption of rubber-asphalt pavement technology has been in efforts to reduce traffic-related noise.

### Use of Asphalt-Rubber Products

In the early 2000s, the Arizona DOT responded to apparent public demand for quieter pavements by initiating a program to overlay all concrete-surfaced pavements on Interstate highways and major state routes in the Phoenix area using asphalt-rubber hot mix (ARHM). This was done even when the concrete pavements were new because the transverse tining pattern that was provided for high friction was considered too noisy. Similar noise concerns were raised in California and other areas of the country, leading to additional installations of rubberized asphalt pavement in many areas (primarily in major metropolitan areas). These events also led to the initiation of major studies of pavement/traffic-related noise by government and industry groups alike, eventually resulting in the development of quieter (but still safe) pavement surface textures for both asphalt and concrete pavements.

Case studies for several AHRM pavement installations in California can be found at www.asphaltrubber.org.

The use of asphalt-rubber has been tested in many cold regions. The State of Arizona routinely uses a combination of gap graded asphalt-rubber hot mix and an open-graded asphalt-rubber friction course in the Flagstaff area, where the elevation is over 7,000 ft and the winters are extremely harsh, with temperatures dipping to -20°F. The State of California has also successfully used A-R in the high Sierra Mountains where it is reported to have performed remarkably well (source: www.rubberpavements.org). While some states with colder climates (e.g., New Jersey) are showing increased interest in using A-R products, A-R use remains primarily in states with warmer climates (Source: personal communication with Dr. David Newcomb, Vice-President – Research and Technology, National Asphalt Pavement Association). Internationally, A-R is being used to pave roads in Siberia (Russia), China, northern Spain, Germany, Canada, Sweden and Portugal.
http://ecopathindustries.com/index.php?option=comcontent&view=article&id=82&Itemid=62

A more common application of asphalt-rubber has been the construction of A-R Stress Absorbing Membrane (SAM) and Stress Absorbing Membrane Interlayer (SAMI), which have been placed between paving layers to prevent or delay the development of reflection cracks. In both procedures the binder is spread by a distributor and then covered by hot, pre-coated aggregate.

### Use of Rubberized Asphalt Products

The rubber modified asphalt concrete pavements produced by the "dry" process have generally been used as overlays and surface wearing courses and have been marketed as having good skid resistance and de-icing properties. For example, an Iowa study published in 2002 concluded that the use of rubber chips in a surface lift produced better crack control (but lower friction values) than conventional asphalt concrete materials (Engle 2002). For these reasons, these products piqued the interest of cold region states like Alaska, which uses rubber as an aggregate substitute to help mitigate studded tire wear. Similarly, a proprietary rubberized asphalt product called “PlusRide” was developed for use in Sweden. However, Iowa researchers found that the cost of the pavement with rubber additives was significantly higher than conventional asphalt paving and it was determined that the potential benefits did not outweigh the costs of using this recycled rubber process in pavements in Iowa (Engel et al. 2002).

The Alaska Department of Transportation and Public Facilities (ADOTPF) has come to different conclusions regarding the costs and benefits of using recycled rubber in hot mix asphalt pavement applications. They cite benefits that include increased skid resistance under icy conditions, improved flexibility and crack resistance, elimination of a solid waste, and reduced traffic noise. While they note the high relative cost of these pavements (when compared to conventional asphaltic concrete pavements, their economic analyses show the rubber-modified system to be cost-effective. (source: http://cedb.asce.org/cgi/WWWdisplay.cgi?8801605)

### Implementation Requirements/Strategies

The implementation of rubberized asphalt paving technology in Pennsylvania should be predicated on a determination of whether one or both of the following conditions exist:

1) there is a significant problem with traffic/tire-pavement interaction noise in areas (presumably urban) where noise mitigation cannot be accomplished in a more cost-effective manner, and/or
2) the use of crumb rubber modifiers can be shown to allow sufficient reductions in required pavement thickness and associated asphalt demand to offset the increased cost of producing the material.

In addition, research should be performed to verify industry claims of recyclability of the product (essential for sustainability) and to determine the factors that must be incorporated in the product design to ensure all performance parameters (i.e., ride quality, durability, structural capacity, etc.) while also ensuring the recyclability of the material.

If it is determined that this product can be used to address a real PennDOT need, there is a wealth of information available on industry websites (most notably at http://www.asphaltrubber.org/ari/), including user guides, sample product and construction specifications, design guidelines, case studies and research reports.

### 7.1.5. Supplementary Cementitious Materials

The term "supplementary cementitious materials" (also called "SCMs") refers to the family of industrial by-products that reacts with by-products of cement hydration (particularly calcium hydroxide), usually in the presence of water, to form additional cementitous products. Examples of commonly used SCMs include, fly ash from the combustion of coal, ground granulated blast furnace slag (GGBFS) from the production of steel, silica fume from the production of silicon and ferrosilicon alloys. More than 15,000,000 tons of fly ash are used every year in the U.S.; lesser, but still significant, amounts of silica fume and GGBFS are also used as concrete admixtures.

The benefits of using supplementary cementitious materials in Portland cement concrete mixtures are very well documented and they include (when properly used): reduced concrete permeability, increased long-term concrete strength, reduction/elimination of alkali-silica reactivity, reduced use of portland cement (and accompanying reduction in greenhouse gas emissions per unit of concrete placed), reduced disposal/landfill of materials that might otherwise be considered to be hazardous or environmentally deleterious, and sequestration of those products in a relatively inert product (i.e., concrete).

Steps need to be taken to modernize and update PennDOT specifications and guidance concerning the use of these products to take full advantage of the research that has been done over the last 20 years or more. The successful accomplishment of this task will result in the use of stronger, more durable, and more sustainable concrete materials in pavements and other transportation applications.

## 7.2. Construction Techniques

### 7.2.1. Two-lift Concrete Paving

**Description**

Two-lift concrete paving involves the placement of two layers of concrete (wet-on-wet) instead of placing a single homogeneous layer, as is typically done in the U.S. *Two-lift paving offers the opportunity to optimize the use of local aggregates, recycled materials, and premium aggregates to produce an economical, durable and sustainable pavement system with the most desirable surface characteristics (with respect to noise, friction and smoothness).*

The bottom layer typically comprises 80-90 percent of the total pavement thickness and generally contains locally available or recycled aggregates that may not be suitable for use in wearing surfaces. These aggregates are typically obtained at a lower cost than aggregates used in a traditional paving project. Since the bottom lift is usually subjected to less environmental exposure, a wide range of recycled aggregates (including both recycled concrete and asphalt) can be used without sacrificing the durability of the pavement system.

The top layer is typically relatively thin and usually contains dense, wear-resistant aggregates that provide excellent durability, reduced noise and increased pavement surface friction. These aggregates are typically more expensive and are often imported, but their impact on the overall pavements system cost is usually low because they are required in relatively small quantities.

A common application of modern two-lift concrete pavements is to provide a relatively quiet, high-friction pavement surface through the use of exposed aggregate. This application requires the use of extra-hard, wear-resistant aggregates, generally of a smaller-than-usual size (<1/2 in top size). The use of smaller aggregate requires the use of additional cement paste, which increases the cost of the concrete mix and impacts the carbon footprint of the mix, but these impacts are usually minor and can be offset by savings in the lower layer, which can use recycled materials and lower cement contents.

## Where has it been used?

### Early U.S. Experience

Two-lift concrete paving has been used in various forms since the very first concrete pavement was constructed in the U.S. in 1891 in Bellefontaine, Ohio (n.b., the first concrete pavement in U.S. was a two-lift pavement). The lower lift was approximately 4 inches thick and had maximum-sized aggregate of 1-1/2 inches with a water-cement ratio of 0.60, while the top lift had maximum-sized aggregate of 1/2 inches and a water-cement ratio of 0.45 (Snell and Snell 2002). That pavement, which was designed and constructed to withstand service to horse-drawn wagons with steel wheels, is still in service today (Shields-Cook and Taylor 2009).

Fourteen years later, a patent was taken out on “Granatoid Concrete Streets”, a two-lift paving process that used normal ready-mixed concrete and inexpensive local aggregates for the first five inches and a thinner top lift comprising crushed granite rock and reduced quantities of fine aggregate to provide a very hard durable surface (Cable and Frentress 2004). Many of these Granatoid pavements were constructed in the early 1900s in Michigan, Minnesota and North Dakota and several are still in service today.

In 1915, a similar process was used to construct streets in Madison and Sheboygan, Wisconsin. In Madison, the bottom layer of the street was constructed from locally available dolomite limestone rock and the top layer from quartzite rock obtained from Baraboo, Wisconsin. The streets in Sheboygan used locally available limestone for the bottom lift and used granite for the top even though the closest granite quarries were more than two hundred miles away (Cable and Frentress 2004).

### Two-Lift Paving in U.S. Mesh-Reinforced Pavements

In the 1950s and 1960s, two-lift paving was performed extensively in many states, including Iowa, Wisconsin, Illinois, Michigan, Minnesota and Pennsylvania. The use during this period was to facilitate the placement of mesh steel reinforcing in jointed concrete pavements with long panels and the concrete mixture was typically the same in both layers.

During the 1970s, highway agencies began to move toward the use of shorter, unreinforced slabs (jointed plain concrete pavement, JPCP) and the apparent need for two-lift paving to facilitate mesh steel placement disappeared.

### Early U.S. Experiments in Two-Lift Pavements with Different Materials

A handful of experimental two-lift paving projects were constructed after 1970 to investigate the relative costs and benefits of using two-lift paving to better utilize recycled or other local materials in the lower lift or to use an improved material in the top lift.

- The Iowa DOT reconstructed a portion of US 75 using two-lift paving in 1976, incorporating about 60 percent recycled concrete and 40 percent recycled asphalt pavement in the 9-inch lower lift and all virgin materials in the 4-inch top lift. The upper lift was paved 24 ft wide and encapsulated the 23-ft lower lift. This pavement is still in service today.

- The North Dakota DOT constructed a portion of US 2 between Rugby and Leeds using two-lift paving in 1976, using a single aggregate base material in the 6-in lower lift and crushed rock and sand in the 3-in top lift. The upper lift was paved 27 ft wide and encapsulated the 25-ft lower lift. This was cracked and seated and overlaid with asphalt in 1997 due to the development of longitudinal cracking in the right wheel path of the 15-ft wide truck lane.
- The Florida DOT constructed a portion of US 41 using two-lift paving in 1978. Various strengths were used successfully for the 9-inch lower lift (econocrete) in different test sections: 750 psi, 1250 psi and 2000 psi compressive strength. The top lift was 3 inches thick. Thirty-three test sections were constructed and 23 were still in service and had required no maintenance as of 2004. The other ten sections were removed after 2 years of service.

### European Development of Two-Lift Paving

Major portions of the Austrian Salzberg-Vienna A-1 concrete motorway, which had been resurfaced with asphalt concrete in the early 1980s, were deteriorating rapidly by the end of the 1980s due to heavy traffic, deicing salt, studded tire wear (up to 4 cm deep) and joint faulting. Growing awareness of environmental problems led the Viennese Cement Research Institute and the Salzburg Motorway Administration to develop a method of recycling that would reuse 100 percent of the old concrete in a high-grade manner in a new pavement system.

They developed and adopted a two-lift concrete pavement system that used the crushed pavement (both asphalt and concrete) particles sized 4mm – 32mm in a 19-cm [7.5-in] lower lift, which was capped with a 3-cm [1.2-in] surface layer of high-quality concrete which was used to produce an exposed aggregate surface for friction and noise reduction. The crushed pavement fines (sized 0 mm – 4 mm) were mixed into the old pavement frost blanket to stabilize it (Kreen and Stinglhammer 1994).

Savings of natural materials on the first project alone were estimated at 205,000 metric tons of gravel, and associated savings of 30,000 trucking operations. Overall savings were estimated at a minimum of 10 percent when compared to the conventional use of natural aggregate (Kreen and Stinglhammer 1994).

The success of this project led to construction of 75 km of roadway in the Salzburg and Lower Austria provinces between 1991 and 1994 and two-lift paving using recycled materials in the lower lift is now standard practice in Austria. Austrian successes led to increased use of this paving technique in other European countries (mainly in France and Germany, but also Belgium and others) where safety, noise, and economic reasons are cited as primary reasons for implementing the two-lift paving method.

### France

In France, continuously reinforced concrete pavement was placed on two traffic lanes of highway A71 using the two-lift paving method. The bottom layer used local limestone aggregates and top layer, which was approximately 2 inches thick, was made up of harder aggregates to provide a low-noise, high-friction exposed aggregate surface. These harder aggregates were hauled from a great distance, which increased the cost of the top layer, which was offset by the use of local aggregates in the lower lift.

### Germany

Two-lift paving is often used to reduce noise and increase friction (exposed aggregate surfacing) as well as to reduce overall pavement costs and achieve a smoother profile. The Munich airport was paved using the two-lift method, with a bottom layer approximately 9.5 inches thick (using local gravel aggregate) and a 5.5-inch top layer comprising crushed granite aggregate. The same two aggregates were used for the two layers of an Autobahn project in Berlin (Cable and Frentress 2004).

Wirtgen GmbH, a German construction equipment manufacturer, produces a two-lift slip-form paver that can placement pavement in widths between 16.5 and 50 ft and at depths up to 17 inches. The top paver can be equipped with a super smoother or an oscillating beam to produce the desired surface texture.

### Austria

As noted previously, two-lift paving is standard practice for most concrete roads in Austria. Austrian pavement authority Dr. Hermann Sommer offers the following justification for that policy (personal communication, October 6, 2009):

“Aggregates that are resistant to wear and polish are less readily available and more expensive than other aggregates. Moreover, on motorways we use a fine-grained exposed aggregate concrete in order to obtain a surface which will stay noise-reducing and skid-resistant for a long time (in our conditions, a burlap-drag surface – which may also be very satisfactory at the beginning - is worn away within a few years on heavily trafficked roads). That fine-grained concrete is rich in cement and would lead to more heat of hydration and cracking if used for the whole thickness of the pavement.

“Even in the rare cases where aggregate of 22 mm maximum size is used for the top lift (and – apart from costs– could be used for the bottom lift as well) paving generally is done in two lifts. Our slipform pavers are equipped with a dowel inserting device and dowels and tie-bars are inserted into the compacted bottom lift before placing the top lift. Inserting the dowels from the surface of the pavement is forbidden on the ground of unfavourable experience. The main reason for the dowel inserter is that most of our construction is reconstruction under traffic and that construction traffic has to use the lanes that are being reconstructed: Dowel baskets would be extremely difficult to use.

“In the urban area we often use super-plasticized concrete (and dowel baskets), but – for evenness - always two lifts: the top lift is placed when the bottom lift has already stiffened a bit. Single lift paving is only used for secondary roads (a few only) and for roundabouts (quite numerous recently, mostly with a small slipform paver and dowel baskets).

“So you see, under our circumstances there has been no real incentive for comparing the costs of single and two-lift construction.”

### European Two-Lift Technology in the U.S.

The Michigan DOT constructed a “European-style” two-lift paving system on a one-mile section of northbound I-75 in Detroit in 1994. It consisted of 16 inches of compacted subbase with an enclosed drainage system, a 6-inch lean concrete base, and a two-layer composite system with a 7.5-in lower lift comprising a Michigan dolomitic limestone coarse aggregate and a w/c = 0.41, topped with a 2.5-in top lift comprising Ontario trap rock (to provide a durable exposed aggregate surface) and a w/c of 0.37 (FHWA 2004). This pavement (and the companion control section that was constructed using standard MDOT practices) are in good condition today, although there do not appear to be significant differences in noise characteristics between the two. The cost of the European-style pavement was more than double that of the traditional MDOT pavement; a significant part of the added cost was the use of a European contractor and their patented equipment and process to produce the exposed aggregate surface.

The Kansas DOT constructed a series of thirteen experimental test sections on K-96 in Reno County in 1997, most about 0.6 miles long, to examine a wide range of design, materials and construction variables. Three of these test sections featured two-lift concrete pavement construction:

- one using 15% recycled asphalt concrete in the 7-in lower lift (3-in surface lift using traditional concrete materials),
- one using rhyolite (a hard igneous rock) and calcined clay pozzolan (to reduce ASR susceptibility) in the upper layer and a softer, absorptive limestone in the lower layer, and
- one using a water-cement ratio (w/c) of 0.42 and standard concrete aggregate in the top layer and the standard w/c of 0.47 with the softer absorptive limestone in the lower lift (Wojakowski, 1998).

These three sections had better initial ride quality (25 percent lower profile indices) than any of the other pavement sections. Two of the three sections are performing acceptably well today. The section containing rhyolite coarse aggregate developed extensive transverse and longitudinal cracking (KDOT 1998-2003).

KDOT noted that the cost of paving these small sections was about double that of traditional construction due to the use of a second batch plant, extra hauling of material, a concrete belt placer/spreader (in place of a second paving machine), and extra labor for hauling.

## Recent US Experience with Two-Lift Paving

### Kansas Demonstration Project

After a team of pavement and materials specialists from the U.S. surveyed European pavements and practices in May 2006 and identified two-lift paving as its first priority for technology transfer and adoption in the U.S., the FHWA, National Concrete Pavement Technology Center and Kansas DOT coordinated to plan a major demonstration project on eastbound I-70 near Solomon, KS, which was constructed in 2008.

The basic design for this project was similar to one of the sections constructed on K-96 11 years earlier, featuring the use of a standard KDOT paving mix and locally available porous limestone aggregate for the 300-mm bottom lift, and rhyolite aggregate (imported from Oklahoma) along with 20 percent replacement of cement with a class F fly ash-gypsum blend in the 40-mm top layer. The pavement was placed on a 150-mm cement-treated aggregate base that was produced using recycled concrete aggregate from the pre-existing concrete pavement. The pavement also featured test sections with several different pavement surface textures, including longitudinal tining, exposed aggregate, grooving, and Astroturf drag (Shields-Cook and Taylor 2009).

KDOT did not do a benefit/cost analysis of two-lift pavement construction for this project. The project was originally let as a standard single-lift paving project and a change order was negotiated to perform the demonstration project and to incorporate several different mixtures and surface textures. These factors, plus the fact that each test section was relatively short, drove up the project costs significantly (per personal communication with A. Gisi of KDOT, October 2009).

Figure 73:Kansas I-70 two-lift paving operation.

## Pennsylvania Experience

A portion of the Mon-Fayette Expressway was constructed in 2008 by Hi-Way Paving using two-lift paving techniques. This 12-inch concrete pavement was placed in two lifts: an 8-in lower lift and a 4-in top lift. The same concrete mixture was used in both the top and bottom lifts. The contractor opted for two-lift construction to improve production (maximize plant production rates and have more consistency matching field placement and paving rtes with plant production rates). In addition, this project offered ride quality incentives and the contractor believed that it would be easier to maximize payment of those incentives (i.e., to produce a smoother pavement) by using two-lift construction techniques. (This belief was proven true when several sections of the project were measured with initial IRI values in the 40s!)

In Pennsylvania, PennDOT has a two lift pavement project. The project is located in I-99.

## Implementation requirements/strategies

It seems clear that PennDOT could use two-lift paving techniques to make better use of VanPort limestone, recycled concrete and other aggregate sources and materials that may not be suitable for use in concrete pavement surface layers. One key to successful implementation may be to ensure that the adoption of this technology can be done cost-effectively and that the concrete paving industry does not perceive it as a threat to their ability to compete with the asphalt industry (i.e., that two-lift paving doesn't become a more expensive standard for concrete paving that would result in more pavement type selections going to asphalt surface type).

Cable and Frentress (2004) surveyed ACPA promoters, engineers and contractors to determine their views concerning the use of two-lift concrete pavements. Many people expressed interest in using different quality concretes for the lower and top lifts, but many of them also believed that the cost of the two-lift process outweighs the benefit of building an improved top lift (using the documented costs of the 1994 and 1997 two-lift projects in Michigan and Kansas, respectively, to show that the concrete paving costs could double when two-lift paving was used). Many of those surveyed also expressed concern about the extra permits and land space required to set up the two paving plants that would probably be necessary for a two-lift paving project, further noting that many contractor don't have an extra plant available for use. It was pointed out that the biggest expense for using two paving plants is the cost of hiring more workers to run the batch plant and second paving machine. Survey respondents seemed to recognize that the benefits of the two-lift technique may be greater in the future, when aggregate sources become scarce in some locations. It was also considered possible that, if a contractor could use a lower-quality (lower durability or strength) concrete in the bottom lift by incorporating recycled asphalt or crushed concrete aggregate, and place higher-quality concrete in the top two or three inches, the savings might be enough to justify the additional costs in equipment and permits.

The contractor who did the 2008 Mon-Fayette Expressway two-lift project noted that it is possible to do two-lift paving using a single batch plant and paver by using additional aggregate bins present at the single batch plant (enough for all sizes and varieties of aggregate in each of the two mixes) and by using a spreader to place the lower lift. However, he also noted that careful coordination would be required to ensure adequate production of both mixtures to avoid having to stop and restart either paver (particularly the top lift paver), which could result in irregular surface quality and smoothness problems. He further noted that two-lift paving is probably best suited for large paving projects that require high production quantities (e.g., thick mainline highway pavement or airfield paving projects).

Guidance on the implementation of two-lift paving technology (design guidelines and guide specifications, along with case histories from Europe and the recent Kansas demonstration project) are available from Federal Highway Administration and the National Center for Concrete Pavement Technology.

### Environmental analysis

According to the National Concrete Pavement Technology Center (NCPTC), Kansas DOT has a two-lift pavement construction project. The NCPTC and theRightenvironment (a consulting company in TX) performed an LCA of this project in Kansas. The results show that there is a 15% reduction of global warming potential when a two-lift pavement technique is used compared to a traditional technique. In terms of energy, a 20% reduction can also be observed when using the two-lift pavement technique (NCPTC 2009; theRightenvironment 2009).

### Current Costs/Cost Projections

Recent (post-1990) costs for two-lift paving projects in the U.S. that have taken full advantage of the potential to include different paving mixtures in the top and bottom lifts have generally ranged in cost from about 30 percent more (Kansas 1997 project) to more than double (Michigan 1994) the cost of standard single-lift concrete. Both of these projects were demonstration or experimental projects that featured short paving lengths (i.e., too short to take advantage of the economies of scale), unusual contracting aspects (i.e., change order in Kansas and international subcontractor in Michigan), and represented nonstandard practice for the contractors. Therefore, it is unlikely that the costs of these projects accurately represent the probable costs of a normally contracted two-lift paving project of sufficient size and performed by an experienced contractor. This conclusion is supported by the extensive Austrian experience with two-lift paving, as well as the recent Pennsylvania experience of the contractor who used two-lift paving (with a single material) at no added expense to the owner agency in order to achieve superior pavement ride quality.

While it is likely that there are significant added expenses with two-lift paving (e.g., for an extra paver or spreader and crew and possibly for a second batch plant and other equipment, permits and space required for production of two mixtures), these added costs may be partially or wholly offset by increases in productivity, the ability to use recycled or other lower-cost materials in the lower lift, and by longer pavement life (a probable side benefit of smoother initial ride quality).

## 7.3. Summary of Recommendations

As a summary, some of the benefits that can be present when considering recycled materials include(Te Cement Sustainability Initiative 2009):

1. Proximity of materials to the construction site if the materials are recycled on site resulting in lower transportation costs
2. Recycled materials can be used in non-critical stages of the design, thus saving good quality materials for the rest of the project

When we look at the benefits of using recycled materials for construction projects, it is important to consider both the environmental and economic impacts. The potential for an economic advantage exists according to Horvath (2003) (Horvath 2003). With respect to environmental benefits, specifically, energy, water and $CO_2$ emissions, the results presented are only for one lane mile. While the environmental benefits are low, the environmental impacts are greater when considering the scale issues (e.g., 100 miles of highway results in greater improvements). The scalability of the savings should be put into perspective when the total savings are being calculated. When an LCA is performed and specific data is used, the inventory is complete and will result in better representation of reality.

It is important to mention that tradeoffs exist when focusing on reducing one environmental impact over the other.  In the case of energy use and $CO_2$ emissions, at the same amount of recycled material content, the energy reductions are higher than the $CO_2$.

# 8. Conclusions

For Task 1, the following tasks were completed:

Obtained all of price histories for commodities under consideration.
Discussed price information with heavy and highway contractors and trade organizations.

For task 2, we completed an analysis which included consumption, production, and pricing for the next five (5), ten (10), and twenty (20) years, based on the major market influences. The primary output was graphical projections. The graphs included the following:

- Consumption and production: mass functions on the y-axis with time on the x-axis
- Pricing: Dollars/mass function on the y-axis with time on the x-axis
- Environmental: $/mass of carbon on the y-axis with time on the x-axis.

Additionally from a local perspective, the University looked at the regional availability (supply) within Pennsylvania of the aggregates by quality including a specific discussion on Skid Resistance Level (SRL), concrete quality sands and type A, B and C aggregates. The University conducted interviews with state-based suppliers to obtain additional data on supply and quality. This portion was completed and delivered in Task 1 in section 5

The University used the predictions from the analyses to discuss what the highway and bridge construction industry might look like in the five (5), ten (10) and twenty (20) year periods. This portion was done by identifying alternative materials or construction techniques that can be used to supplement or replace these materials should it become uneconomically feasible to continue using that specific resource in the manner currently being utilized.

For Task 3, the University developed a draft Final Report, which explored alternatives materials and a construction technique. For each alternative, the University provided a description, past uses, implementation strategies, environmental factors, and cost. We focused on the following:

*Aggregate: Recycled Concrete Aggregate (RCA)*
*Asphalt: Recycled Asphalt*
*Rubber materials in pavement mixtures*
*Construction Technology: Two-Lift Concrete Paving (to use local materials in lower lifts)*

One of the challenges of conducting this research project is the extreme volatility in the market place at the writing of this report (October and November 2008). Given that the Chicago Mercantile Exchange has recently seen extreme low points, followed by an unprecedented growth on October 13, 2008, the historical price trends for respective commodities are still relevant, but predicting future trends in the existing market place is challenging. As of October 6, 2008, Engineering New Record is reporting that construction inflation is cooling off, along with a cooling off of global commodities. The recession in the residential construction market is impacting those related commodities, such as gypsum wall board, resulting in a surplus of materials. The housing market, which makes up 25% of the total cement shipments, will continue to drive the decrease in the price of cement. In terms of metal products, steel, economists are predicting a general upward trend, but without the large range in the spikes (ENR 2008). Given the cooling off of cement prices and the rise of asphalt prices, the short-term financial decision of concrete paving versus asphalt paving may result in concrete paving be more viable in the near future.

### *Future Research*

Additional alternative construction materials are available. For this research, the alternative materials list was developed in collaboration with the Department. Additional materials that merit consideration are biofuels, biolubricants, nanomaterials, bioasphalt, and fiber reinforced plastics, amongst others. It should be noted that given the expected increase in diesel prices, and, therefore, the increase in all construction commodities, research investment in understanding alternative materials is recommended.

## 9. Appendix A: Resources

AASHTO: American Association of State Highway and Transportation Officials
http://www.transportation.org

ACI: American Concrete Institute
http://www.concrete.org/general/home.asp

ACPA: American Concrete Pavement Association
http://www.acpa.org

AI: Asphalt Institute
http://www.asphaltinstitute.org

AISI: American Iron and Steel Institute
http://www.steel.org

ARRA: Asphalt Recycling and Reclaiming Association
http://www.arra.org

ASTM: American Society for Testing and Materials
http://www.astm.org

BTS: Bureau of Transportation Statistics
http://www.bts.gov

CAC: Cement Association of Canada
http://www.cement.ca

CCE: Chicago Climate Exchange
http://www.chicagoclimatex.com/index.jsf

CMRA: Construction Materials Recycling Association
http://www.cdrecycling.org

CRSI: Concrete Reinforcing Steel Institute
http://www.crsi.org

ECCO: Environmental Council of Concrete Organizations
http://www.ecco.org/

EIA: Energy Information Administration
http://www.eia.doe.gov

| | |
|---|---|
| ENR: | Engineering News Records<br>http://enr.ecnext.com |
| EPA: | U.S. Environmental Protection Agency<br>www.epa.gov |
| FHWA: | Federal Highway Administration<br>http://www.fhwa.dot.gov/ |
| MEPS: | MEPS (International) Ltd - Independent Steel Industry Analysts, Consultants, Steel Prices, Reports and Publications:<br>http://www.meps.co.uk/ |
| NAPA: | National Asphalt Pavement Association<br>http://www.hotmix.org/ |
| NCAT: | National Center for Asphalt Technology<br>http://www.eng.auburn.edu/research/centers/ncat |
| NCPTC: | National Concrete Pavement Technology Center<br>http://www.cptechcenter.org |
| NHI: | National Highway Institute<br>http://www.nhi.fhwa.dot.gov/Home.aspx |
| NISOH: | National Institute for Occupational Safety and Health<br>http://www.cdc.gov/niosh/ |
| NSSGA: | National Stone, Sand and Gravel Association<br>http://www.nssga.org |
| PCA: | Portland Cement Association<br>http://www.cement.org |
| PCI: | Prestressed Concrete Institute<br>http://www.pci.org |
| PAPA: | Pennsylvania Asphalt Pavement Association<br>http://www.pahotmix.org/index.asp |
| PACA: | Pennsylvania Aggregates and Concrete Association<br>http://www.pacaweb.org |
| RPA: | Rubber Pavement Association<br>http://www.rubberpavements.org |

TFHRC: Turner-Fairbank Highway Research Center
http://www.tfhrc.gov

USGS: United States Geological Survey
http://www.usgs.gov

# 10. Appendix B: Environmental Analysis

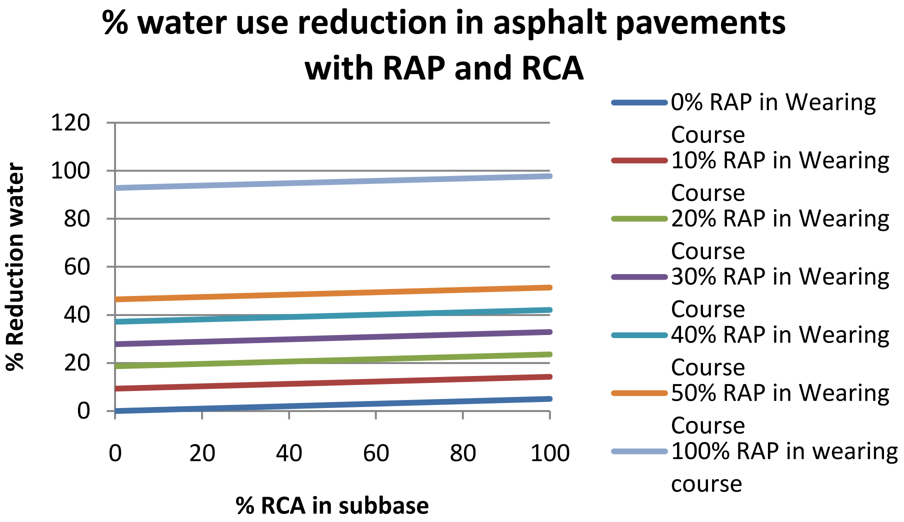

Figure 74: Percent of water use reduction in asphalt pavements with RAP (in the wearing course) and RCA (in the subbase)

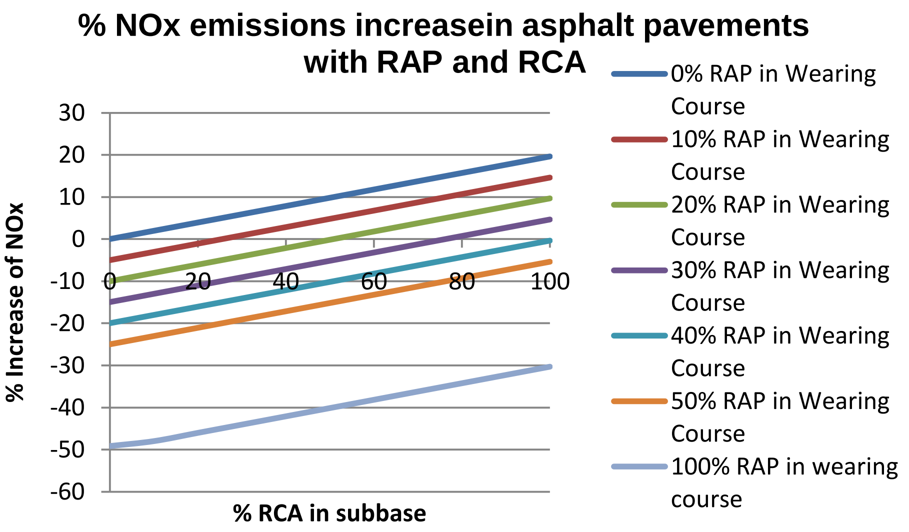

Figure 75: Percent of NOx emission increments in asphalt pavements with RAP (in the wearing course) and RCA (in the subbase)

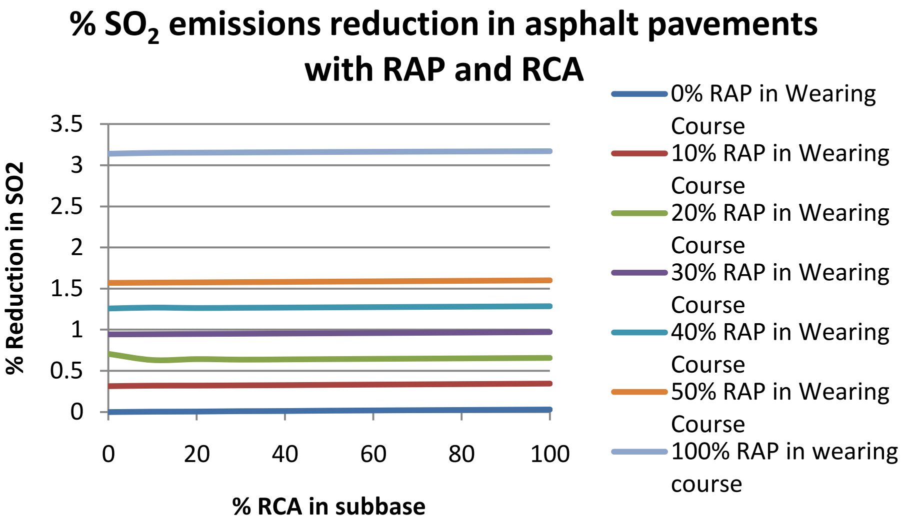

Figure 76: Percent of SO2 emission reduction in asphalt pavements with RAP (in the wearing course) and RCA (in the subbase)

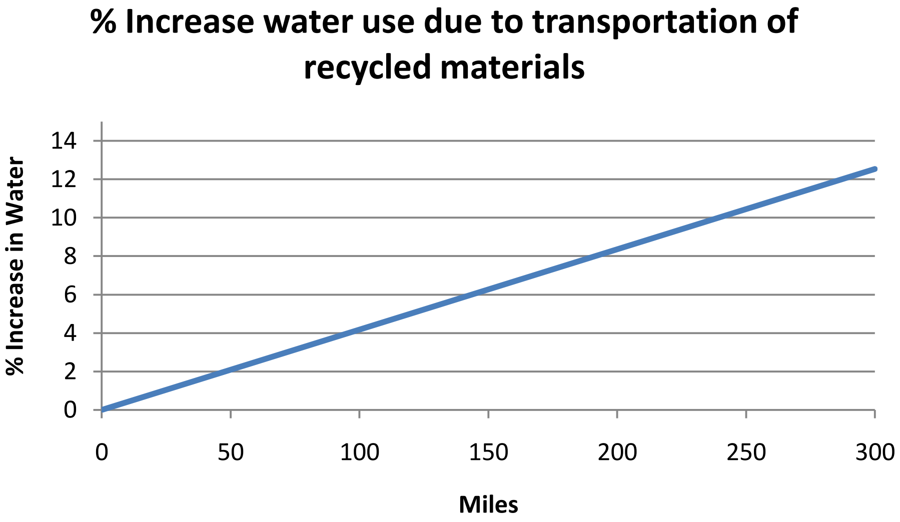

Figure 77: Water use increase with transportation of RCA and RAP

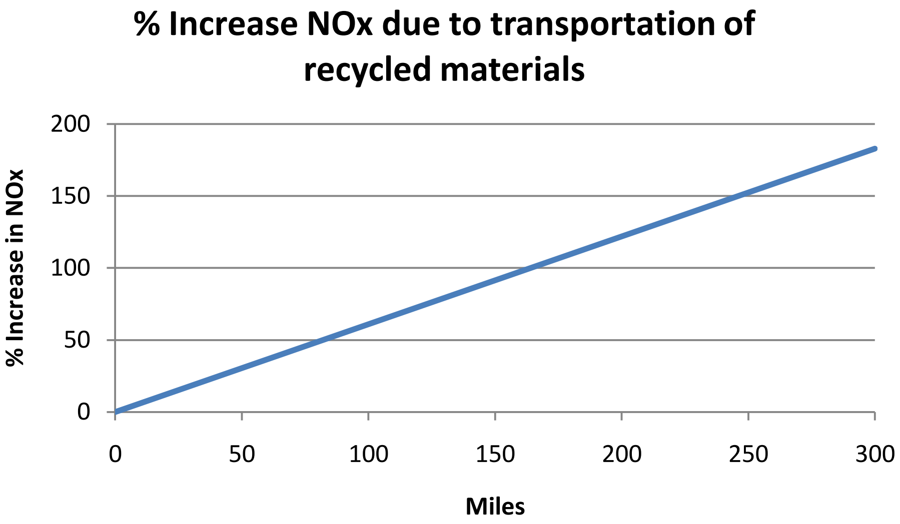

Figure 78: NOx emissions increase with transportation of RCA and RAP

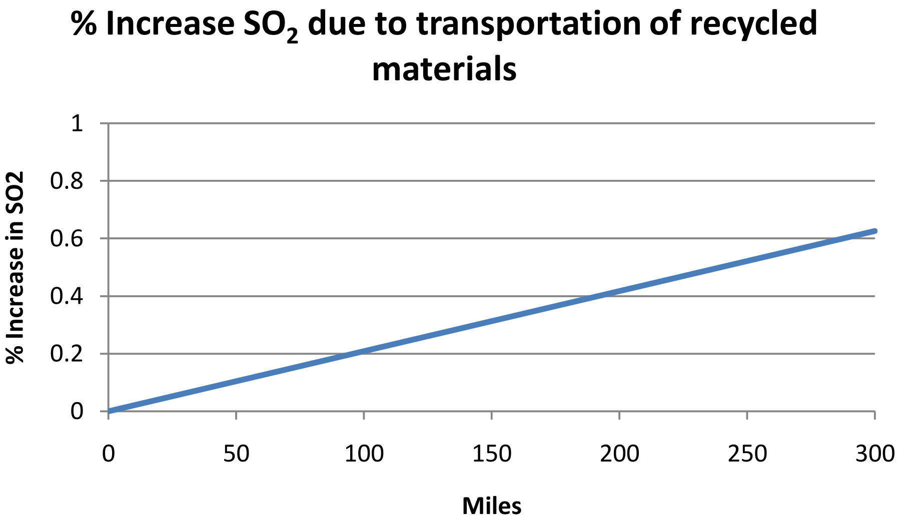

Figure 79: SO2 increase with transportation of RCA and RAP

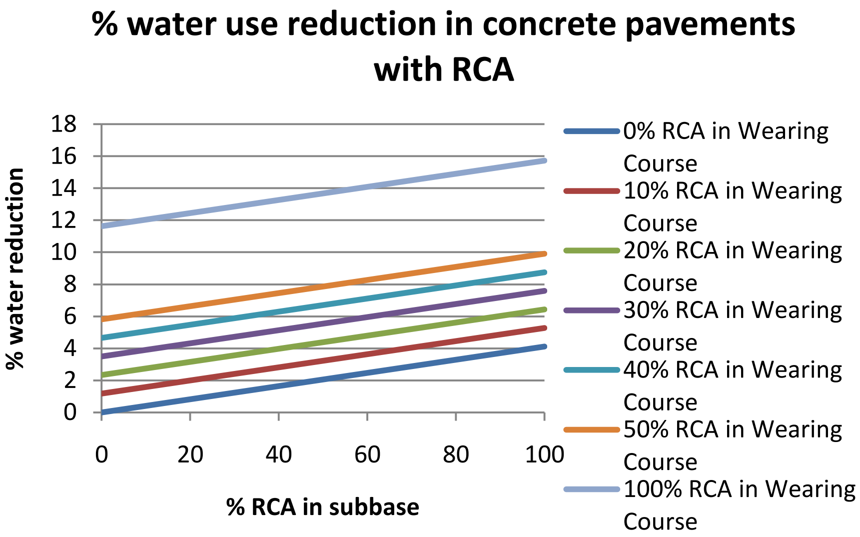

Figure 80: Percent of water use reduction in concrete pavements with RCA (in the wearing course) and RCA (in the subbase)

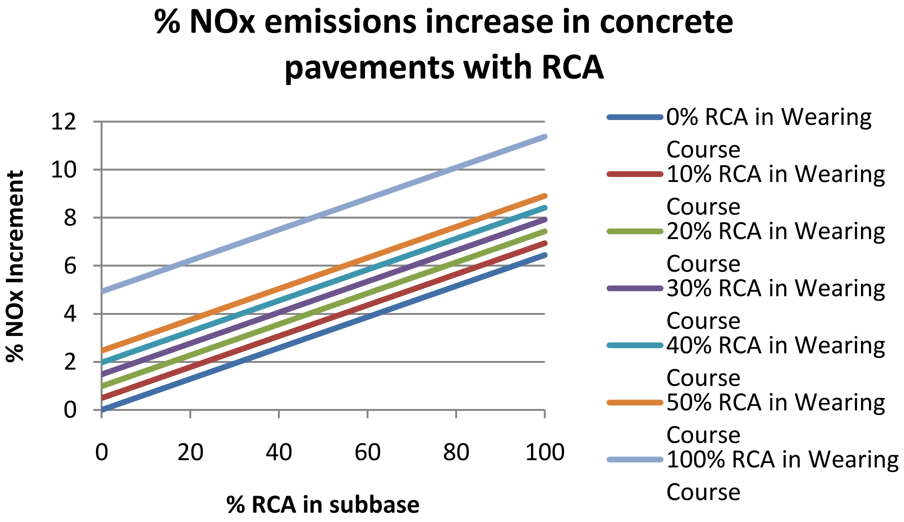

Figure 81: Percent of NOx increase in concrete pavements with RCA (in the wearing course) and RCA (in the subbase)

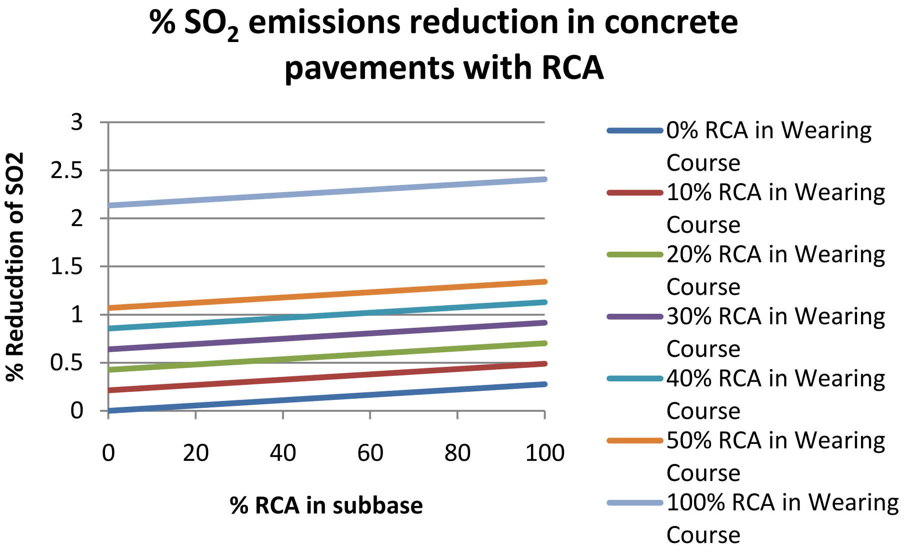

Figure 82: Percent of SO2 reduction in concrete pavements with RCA (in the wearing course) and RCA (in the subbase)

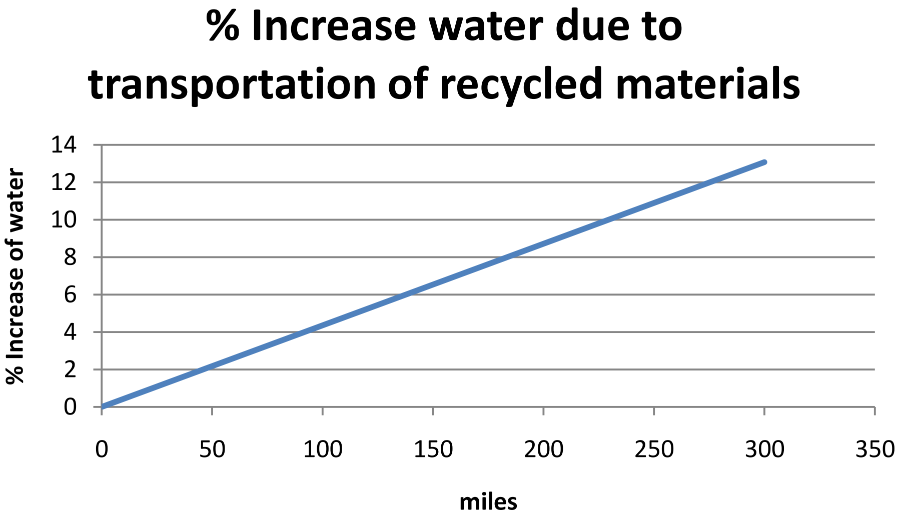

Figure 83: Energy use increase with transportation of RCA in concrete pavements

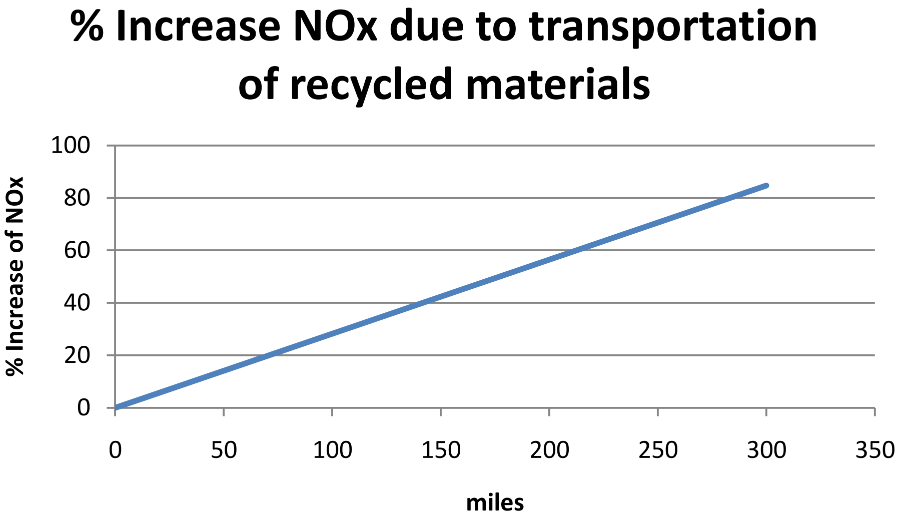

Figure 84: Energy use increase with transportation of RCA in concrete pavements

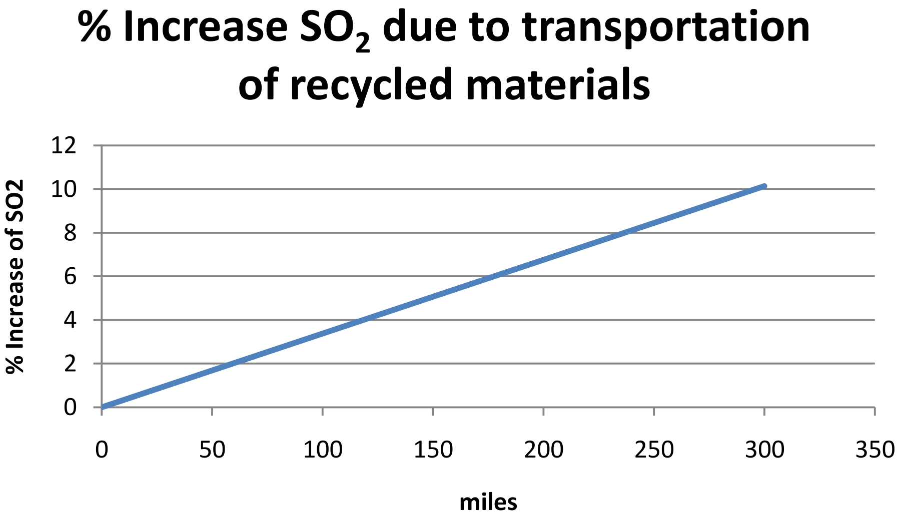

Figure 85: Energy use increase with transportation of RCA in concrete pavements

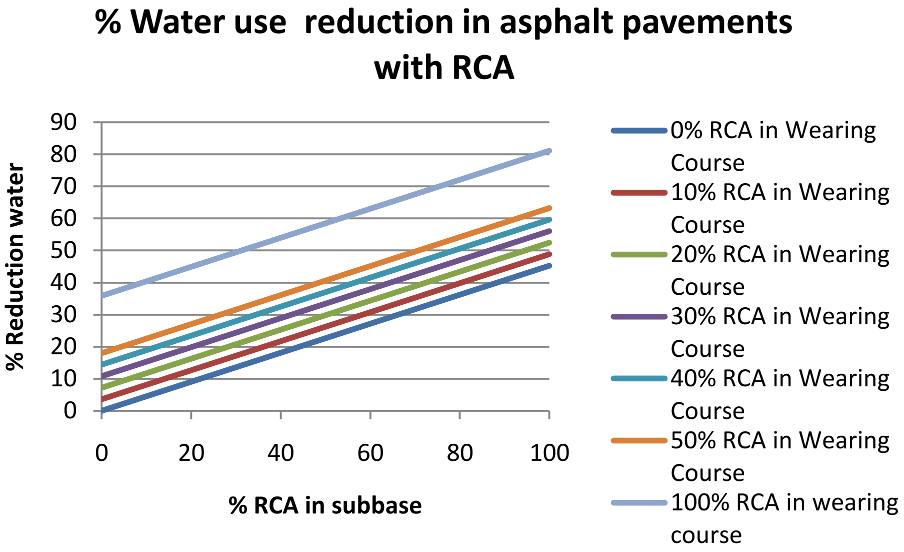

Figure 86: Percent of water use reduction in asphalt pavements with RCA (in the wearing course) and RCA (in the subbase)

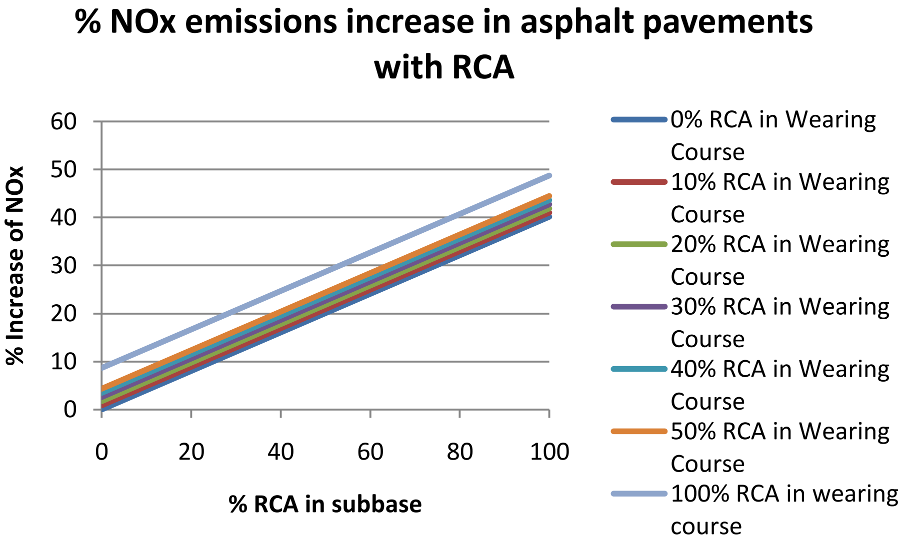

Figure 87: Percent of NOx emissions increase in asphalt pavements with RCA (in the wearing course) and RCA (in the subbase)

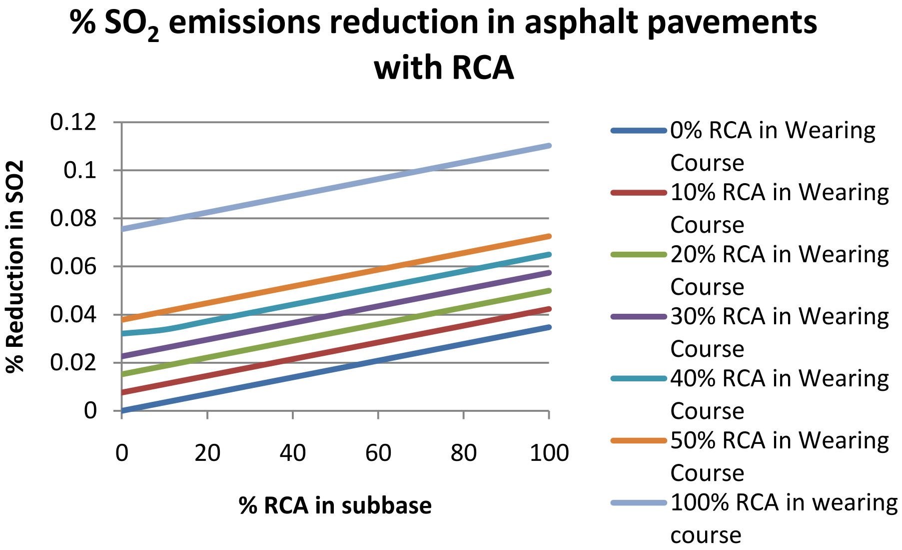

Figure 88: Percent of SO2 emissions in asphalt pavements with RCA (in the wearing course) and RCA (in the subbase)

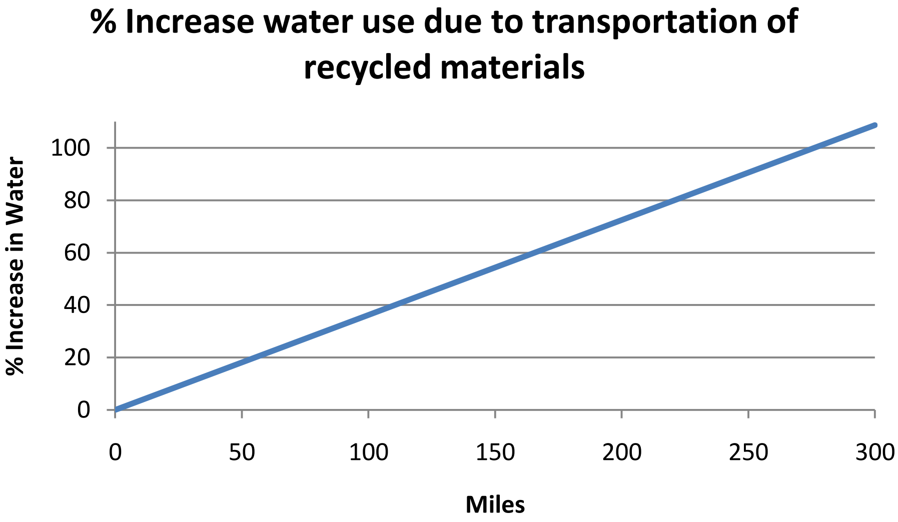

Figure 89: Water use increase with transportation of RCA

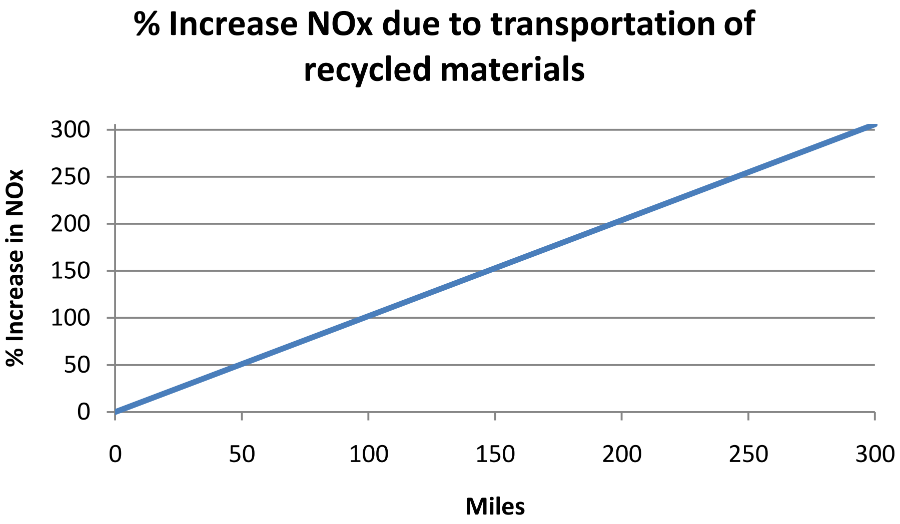

Figure 90: NOx emissions increase with transportation of RCA

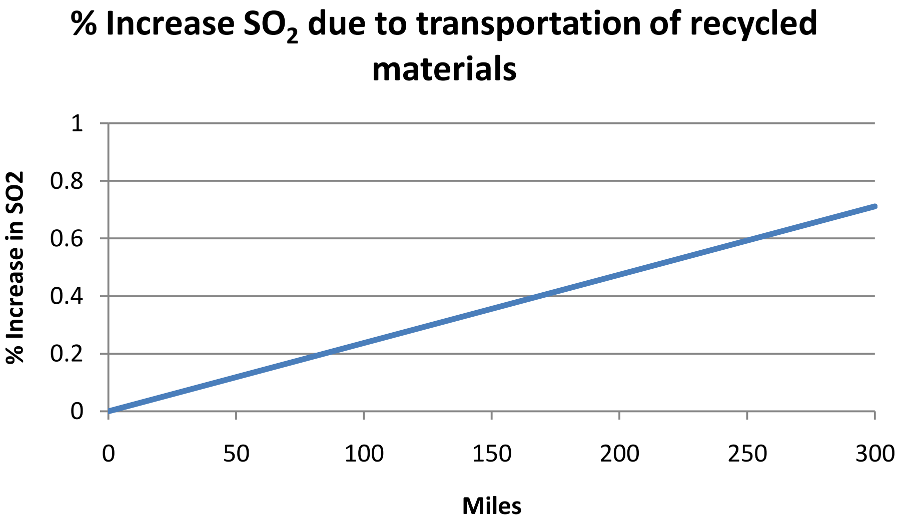

Figure 91: SO2 emissions increase with transportation of RCA

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