Capitalizing Green Pavement: A Method and Valuation

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ABSTRACT: The use of recycling techniques in pavement construction offers significant benefits of resource conservation and emission reduction. While the environmental benefits are generally considered as business expenses, a new trend is to turn sustainable construction into profit. By generating financial revenue via carbon trading mechanism, asphalt producers and road builders can compensate their sustainable efforts and adoption of recycling techniques for reducing greenhouse gas (GHG) emissions. This carbon trading mechanism rewards emission reduction projects with carbon offsets that can be sold at a certain price in the market. This paper develops a framework for pavement recycling projects to verify GHG reductions and register for carbon offsets. Unlike most standards today that use a project-by-project method to quantify carbon offsets, a performance standard is presented based on the life cycle environmental impact analysis to facilitate credit assessment, generation, and verification. The results of thirteen pavement project cases demonstrate that, even with a 20% market share, cold recycling techniques will be able to achieve an emission reduction of 2.8 million tons of GHGs every year. If these GHG reductions can be quantified into carbon offsets for trading, cold recycling techniques will open up more than 20 million revenue sources beyond direct product sales.

1. INTRODUCTION

Asphalt is the most widely used pavement material in the world. In the United States, more than 92% of the 4 million kilometers (km) of paved roads and highways are surfaced with asphalt; in Europe, more than 90% of the total 5.2 million km are surfaced with asphalt. Canada has about 415,000 km of paved roads, of which about 90% are surfaced with asphalt (Mangum, 2006). The U.S. Environmental Protection Agency (EPA) reported that asphalt pavement emits 0.48 metric ton (t) of GHG equivalent per thousand dollar, which is approximately three times greater than that of power and communication lines (Truitt, 2009). In addition to GHG, asphalt pavement also emits 25~34t of air pollutants including sulfur dioxide (SO_2), nitrogen oxide (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and volatile hazardous air pollutant (HAP) organic compounds (EPA, 2009). Reclaimed asphalt pavement (RAP) has been increasingly used in road construction to reduce air pollutants. More than 90 million t of RAP are produced every year, which accounts for approximately 80% of asphalt pavement excavated in the United States (FHWA, 1993). New Jersey, in particular, has doubled the use of RAP since 2001 (Copeland, 2011). Increased use of RAP has significantly reduced GHG emissions during asphalt production, which has been demonstrated by the Fairfield consulting study (Fairfield, 2008).

As one example, foam stabilized base (FSB) is manufactured using 100% RAP in combination with a small amount of hot bitumen blended together with 1~2% potable water. The use of FSB reduces GHGs because it eliminates the use of energy stocks to heat aggregates and the need to quarry and transport virgin aggregates. Previous research showed the total GHG emissions of in-plant and in-situ FSB are 78.4 kg and

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23.4 kg CO_2 equivalent (CO_2e) per ton of FSB. This represents approximately 42% and 83% reductions in carbon emissions compared to the most conservative estimate of emissions from hot mix asphalt (HMA) (Liu et al., 2016). This result shows a great business opportunity for FSB producers to label their green products and potentially generate carbon offsets from FSB production and construction.

The challenge lies in the technical barriers to convert emission reductions to carbon offsets. The emission reductions from recycled pavements must be examined and verified by specific registries based on their standards and requirements for benchmark and additionality. First, existing carbon registries verify that emission offsets are real, additional, permanent, and verifiable on a project basis. There is a technical barrier to adapting emission reductions of recycled pavements, which are based on material processing and construction, to the existing project-based carbon credit framework. Second, existing registries require the demonstration of additionality by comparing to business-as-usual condition for the same emission source. There is a technical barrier to establish an acceptable business-as-usual benchmark for recycled pavements. Although HMA emissions seem an obvious and fair comparator, there is a need to establish an industry-wide benchmark that considers the differences among individual HMA plants to comply with carbon registry requirements.

The objective of this paper is to develop a framework for pavement recycling projects to verify GHG reductions and register for carbon offsets. Unlike most standards today that use a project-by-project method to quantify carbon offsets, a performance standard is presented based on the life cycle environmental impact analysis to facilitate credit assessment, generation, and verification. Carbon offsets are estimated based on the comparison of emissions from recycled pavements against those from HMA pavements that serve as performance benchmarks in the standard. The performance benchmarks are determined from the emission distribution of a group of hot mix facilities and placement projects. An illustrative example is presented to show the application of the performance standard in quantifying carbon offsets by using pavement recycling techniques. The results can be valuable to public agencies that are increasingly mandated to establish GHG emission standards used for attaining the low-carbon pavement practices, and asphalt producers who want to get recognition for their efforts to reduce GHG emissions.

2. CARBON TRADING FOR PAVEMENTS

2.1 Overview

Reducing GHGs from pavement projects has not been mandated in any states. Voluntary emission reductions efforts are rewarded through generating carbon offsets from carbon registries. Some pavement project proponents have joined carbon registries in order to document early actions taken to reduce their GHGs in advance of future mandatory regulations. By registering their emissions, these project proponents are likely to receive offsets for their early actions in future regulatory programs. Registering carbon emission reductions helps provide guidance, infrastructure, and quality standards for early carbon reductions, and encourage broad adoption of low-carbon practices with significant economic and environmental benefits.

The federal government first started a voluntary carbon reporting program in 1992, known as the "1605(b) program" of the Energy Policy Act, under the administration of the Department of Energy. This program was followed by the American Carbon Registry (ACR), the first non-profit nationwide private voluntary carbon registry. The ACR focuses on carbon emission reductions resulted from forestry and agriculture projects. It develops its own registering standards and protocols and provides an online registry system for registered projects to track and trade their verified emission reductions branded as Emission Reduction Tons (ERTs). At the state level, New Hampshire, Wisconsin and California have developed their own carbon reporting systems to support state-wide carbon emission reduction initiatives. These states encourage local facilities owners and project developers to voluntarily report emission reductions. A few states also collaborated together to establish regional carbon emissions registries. For example, 10 Northeastern and Mid-Atlantic states created the Eastern Climate Registry in 2003 to support voluntary carbon reduction programs and mandatory carbon markets in these states. The goal of the registry was to standardize the best practices in data reporting, verification, tracking, and management and therefore to establish a set of common quantification protocols that could be used throughout the region.

As two major carbon registries currently in the U.S., Verified Carbon Standard (VCS) and the Climate Registry started in 2008. These two registries standardized the best practices around the country and established a set of common reporting protocols that corporations, governments and nonprofit organizations can use and track across the states boundaries. Their common standards were based on previous registries, such as the California Climate Action Registry and the Eastern Climate Registry, and therefore were consistent with standards and protocols defined in ISO14064, PAC2050, and other standards accepted by the United Nations Framework Convention on Climate Change (UNFCCC). Proponents of the new registries view it as a critical first step to successfully implement emerging regulatory measures to reduce GHG emissions.

VCS is recognized as the world's most widely used voluntary carbon reduction program and has registered more than 1000 projects since 2008. As it features projects coming in all shapes and size, recycled pavement projects can be registered in the VCS. This provides the potential to create an alternative revenue stream from carbon offset trading in addition to tracking and managing their environmental liabilities. After award of verification from the VCS, project proponents could obtain 1) carbon offsets that can be traded in compliance and voluntary markets; 2) a verification-attached emission reduction logo, which usually has different levels showing the degree of their achievements; 3) a publicly acknowledged emission reduction dataset, which has a potential value of improving corporate reputation.

2.2 Carbon offset standards

Project-based standards have been widely used for years in the VCS. The standards produce carbon offsets based on the comparison of project emissions against a counterfactual baseline that represents a level of emissions that would occur in the absence of the project (Fischer, 2005). The standards have faced substantial criticism in the last few years, and there is evidence that a significant number of offsets come from projects that would have been undertaken anyway (Millard-Ball, 2013). These non-additional offsets, when traded to the regulated entities, implicitly expand the emission caps in compliance schemes and result in failing to achieve the desired emission targets. This means that the counterfactual baseline may be systematically biased. The bias is particularly prominent in evaluating project-based reduction against a counterfactual baseline that cannot be reasonably predicted. As the certifying agency is limited in its ability to propose such a counterfactual baseline, it must consign this task to the individual project proponents. This leaves great uncertainty regarding the integrity of baseline determination.

As an alternative approach, performance standards address this weakness in that they no longer rely on evaluating individual projects but use a pre-defined baseline to streamline the process of determining additionality (VCS, 2012). In this way, performance standards can establish an emissions threshold for a class of project activities. Individual projects that meet or exceed the threshold automatically qualify as additional projects, obviating the need for each project to determine additionality in its own right. Performance standards can be used by project developers, industry associations or governments to deliver reductions swiftly and affordably across multiple projects, industries or sectors. By lowering costs and helping speed project approval, this ensures industries and governments can curb GHG emissions at the pace and scale required to address climate change. The first comprehensive framework for performance standards were released by the VCS in 2012, which has been used in building and agriculture projects but has not been used for pavement projects.

2.3 Performance benchmark

Performance standards use benchmarks to both determine additionality and establish crediting baselines. A benchmark threshold is established at the outset, and all performance that meets or exceeds the threshold is considered additional, provided other qualifying criteria are met as well. A performance benchmark can also serve as the baseline for crediting emission reductions and removals. For pavement projects, the benchmark is determined based on emission distribution of HMA projects because more than 90% of pavements in the U.S. are constructed using HMA (NAPA, 2006).

HMA production throughout the country is being done in the same way other than difference in additives, such as crumb rubber, polymers, antistripping agents etc., even though the polymers are added their percent weight by mix is less than 2% (Mundt et.al, 2009). This can be understood as the process of manufacturing HMA is same throughout the country irrespective of the mix designs. GHG emission performance of HMA plants depends on their production variables including percentage of RAP used as aggregate in HMA, type of fuel used for plant combustion, and aggregate hauling distance. The current distributions of HMA production performance are summarizes as follows. The average percentage of RAP ranges from 13% to 19% according to the studies of NAPA (2013) and Federal Highway Administration (2011). Typical fuel types include natural gas, oil and propane. EPA (2000) reported that natural gas fuel is used to produce 70% to 90% of the HMA. The remainder of the HMA is produced using oil, propane, waste oil, or other fuels (EPA, 2000). Aggregate hauling distance is typically less than 40 miles when projects are using local aggregates and larger than 40 miles when projects are importing aggregates from other places.

Sixteen HMA producers and ten placement projects are surveyed to determine performance benchmarks. Performance benchmarks are represented by GHG emission intensities (CO_2 equivalent per metric ton HMA, CO_2e/t) from the sampling projects, which are the sum of emissions from raw material production, the hot mix facility and the placement process. Each producer reported the consumption of raw material and energy, and material delivery distance on a quarterly basis. The estimation of GHG emission intensities is detailed in our previous work (Cui, 2014). Due to the significant impact of project type and transport distance on GHG emissions, performance benchmarks are stratified on project types and one-way distances between the HMA plant and job site. Stratum 1 is for patching projects with hauling distance less than 40 miles, while Stratum 2 is for is for patching projects with hauling distance larger than 40 miles, finally, Stratum 3 is for roadway projects. The performance benchmarks for all three strata are summarized in Table 1.

The average emission intensity (μ) of surveyed HMA producers is 134.8 kgCO_2e/t HMA and the standard deviation (σ) is 15.5 kgCO_2e/t for Stratum 1, a represented in Figure 1. The average emission intensity (μ) of surveyed HMA producers is 170.3 kgCO_2e/t HMA and the standard deviation (σ) is 33.6 kgCO_2e/t for Stratum 2. The average emission intensity (μ) of surveyed HMA producers is 121.9 kgCO_2e/t HMA and the standard deviation (σ) is 19.8 kgCO_2e/t for Stratum 3. After stratification, each stratum has a performance benchmark. According to UNFCCC (2006), the performance benchmark is defined as a threshold that surpasses the 80th percentile of existing HMA producers. Given the HMA emission approximates a normal distribution, the performance benchmark 121.9kgCO_2e/t HMA (equals to μ- 0.84σ) for Stratum 1 (patching projects with hauling distance less than 40 miles), which is illustrated in Figure 1.

Projects that emit less than the predetermined benchmark are determined to have additionality. Mathematically, the additionality is determined using the project emission intensity (derived from section 3.2) minus the performance benchmark. The project can be determined additional if the figure is less than 0; otherwise the project is not additional.

Performance benchmarks change over time. The changing trend is decided in the following way: use of recycled raw materials saves significant GHG by eliminating the emissions from mining, processing and transporting crushed stone and bitumen binder. According to NAPA (2012), when the use of RAP increases by 1 t, 10kg emission can be avoided accordingly. As such, if the percentage of RAP increases by 1%, 0.1kg emission can be avoided for producing 1t HMA. According to NAPA (2013), the use of RAP in HMA is expected to increase by 1% every year. Therefore, performance benchmarks decreases by 0.1kgCO_2e/t annually.

Table 1: Performance Benchmark for Patching Projects and Roadway Projects kgCO_2e/t

Stratum	Project type	Hauling distance	Average emission intensity (μ)	Standard deviation (σ)	Performance benchmark
1	Parking lot	≤ 40 miles	134.8	15.5	121.9

2	Parking lot	> 40 miles	170.3	33.6	142.4
3	Roadway	Undefined	121.9	19.8	105.5

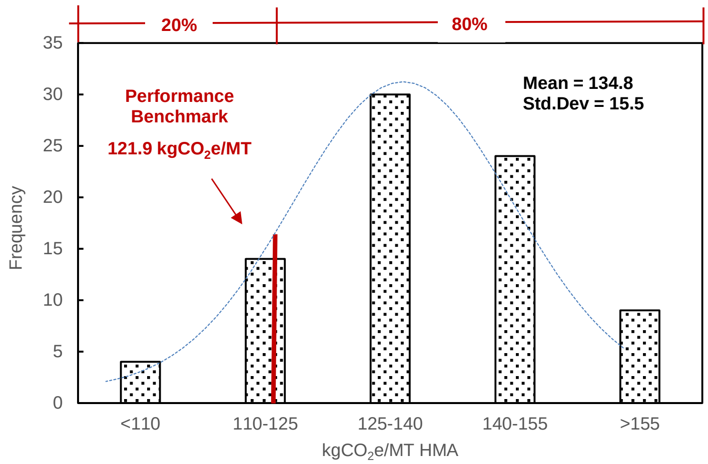

Figure 1: Illustration of performance benchmark for hauling distance less than 40 miles

3. RECYCLED PAVEMENT EMISSION REDUCTIONS

3.1 Types of recycled pavements

Five types of recycling methods are commonly used for asphalt pavements: (*i*) hot recycling, (*ii*) hot in-place recycling, (*iii*) cold in-place recycling, (*iv*) cold central plant recycling, and (*v*) full depth reclamation.

- Hot recycling is the process in which RAP materials are combined with new materials, sometimes along with a recycling agent, to produce HMA mixtures. Both batch and drum type hot mix plants are used to produce recycled mix. The RAP materials can be obtained by milling or ripping and crushing operation. The mix placement and compaction equipment and procedures are the same as for regular HMA.
- Hot in-place recycling (HIR) consists of a method in which the existing pavement is heated and softened, and then scarified/milled to a specified depth. New HMA and recycling agent may be added to the scarified RAP materials during the recycling process. HIR can be performed either as a single pass or as a multiple pass operation. In single pass operation, the scarified in-place material can be combined with new material if needed. In multiple pass operation, the restored RAP material is re-compacted first, and a new wearing surface is applied later. The depth of treatment varies between ¾ in to 2 in. The advantages of HIR are that surface cracks can be eliminated, ruts and shoves and bumps can be corrected, aged asphalt is rejuvenated, aggregate gradation and asphalt content can be modified, traffic interruption is minimal, and hauling costs are minimized.
- Cold in-place recycling (CIR) involves reuse of the existing pavement material without the application of heat. Except for any recycling agent, no transportation of materials is usually required, and aggregate can be added, therefore hauling cost is very low. The process includes pulverizing the existing pavement, sizing of the RAP, application of recycling agent, placement, and compaction. The processed material is deposited in a windrow from the mixing device, where it is picked up, placed, and compacted with conventional hot mix asphalt laydown and rolling equipment. The depth of treatment is typically from 3 to 4 in. The advantages of CIR include significant structural treatment of most pavement distress,

improvement of ride quality, minimum hauling and air quality problems, and capability of pavement widening.

- Cold central plant recycling (CCPR) is similar to both a traditional asphalt plant and a CIR process. With CCPR, material removed from an existing asphalt pavement is transported to a central location – either on the project site or an existing asphalt plant. The removed material can be crushed and screened to make a uniform product or and be simply screened prior to feeding the cold plant. The cold plant, like the CIR process, uses either asphalt emulsion or foamed asphalt as a binding agent. Once the material and the binding agent are mixed, it can be discharged into a truck and taken to a project for paving. An advantage of the CCPR process is the ability to use existing materials at an asphalt plant. In many urban areas, contractors have excess quantities of RAP. By processing the RAP on hand, asphalt contractors can use the cold plant to produce a new asphalt base mix that can be used in various ways including new construction.
- Full depth reclamation (FDR) is a recycling method where all of the asphalt pavement section and a predetermined amount of underlying base material is treated to produce a stabilized base course. It is basically a cold mix recycling process in which different types of additives are added to obtain an improved base. The four main steps in this process are pulverization, introduction of additive, compaction, and application of a surface or a wearing course. If the in-place material is not sufficient to provide the desired depth of the treated base, new materials may be imported and included in the processing. This method of recycling is normally performed to a depth of 4 to 12 in.

GHG emission reductions from recycled asphalt pavements versus conventional HMA pavements are as follows: (i) less or no virgin aggregates are required, eliminating the energy and resources needed for excavating machines and trucking, (ii) less liquid asphalt/bitumen is required, reducing embodied material emissions, and (iii) aggregates in cold recycling process do not have to be heated, which reduces the use of energy for heating. In most applications, but especially in rural areas, the GHG emissions from trucking are significantly reduced. This is because in-place recycling process are done on the project site.

3.2 Carbon offset quantification

Emission intensity of a pavement project (*EI*) represents the quantity of GHG emitted from producing and placing 1 metric ton of pavement. It is the summation of material emission intensity (EI_M), to-plant delivery emissions intensity (EI_{PD}), in-plant production emission intensity (EI_P), to-site delivery emissions intensity (EI_{SD}) and on-site installation emission intensity (EI_I). *EI* should be calculated as follows:

$$EI = EI_M + EI_{PD} + EI_{SD} + EI_P + EI_I \qquad \text{Eq.1}$$

The material *EI* (EI_M) should be calculated as follows:

$$EI_M = \frac{EF_M \times W_M}{Project\ amount} \qquad \text{Eq. 2}$$

where:

EI_M = Emission intensity of raw material production (kgCO_2e/t)
EF_M = Material emission factor (kgCO_2e/kg)
W_M = Material weight (kg)
Project amount = Amount of pavement product manufactured (t)

The to-plant delivery EI (EI_{PD}) and to-site delivery (EI_{SD}) should be calculated as follows:

$$EI_{PD} = \frac{Distance_P \times EF_T}{Project\ amount} \qquad \text{Eq. 3}$$

$$EI_{SD} = \frac{Distance_S \times EF_T}{Project\ amount}$$ Eq. 4

where:

EI_{PD}	=	Emission intensity of to-plant delivery ($kgCO_2e/t$)
EI_{SD}	=	Emission intensity of to-site delivery ($kgCO_2e/t$)
$Distance_P$	=	Distance to plant (mile)
$Distance_S$	=	Distance to site (mile)
EF_T	=	Truck emission factor ($kgCO_2e/mile$)
Project amount	=	Amount of pavement product manufactured (t)

The In-plant production *EI* (EI_P) should be calculated as follows:

$$EI_P = EI_D + EI_E$$ Eq.5

$$EI_D = \frac{EF_{EQ} \times HR_{EQ}}{Project\ amount}$$ Eq.6

$$EI_E = \frac{EF_{EL} \times C_{EL}}{Project\ amount}$$ Eq.7

where:

EI_P	=	Emission intensity of in-plant production ($kgCO_2e/t$)
EI_D	=	Emission intensity of diesel-consuming activities ($kgCO_2e/t$)
EI_E	=	Emission intensity of electricity-consuming activities ($kgCO_2e/t$)
EF_{EQ}	=	Equipment emission factor ($kgCO_2e/hour$)
EF_{EL}	=	Electricity emission factor ($kgCO_2e/kWh$)
HR_{EQ}	=	Equipment operation hours (hour)
C_{EL}	=	Electricity consumption (kWh)
Project amount	=	Amount of pavement product manufactured (t)

The on-site installation EI (EI_I) should be calculated as follows:

$$EI_I = \frac{EF_{EQ} \times HR_{EQ}}{Project\ amount}$$ Eq.8

where:

EI_I	=	Emission intensity of pavement installation ($kgCO_2e/t$)
EF_{EQ}	=	Equipment emission factor ($kgCO_2e/hour$)
HR_{EQ}	=	Equipment operation hours (hour)
Project amount	=	Amount of pavement installed (t)

Therefore, the net emission reductions for a pavement recycling project (*ER*) should be the emission intensity differences adjusted by the weight differences (φ)[5]. The reductions should be calculated according to Equation 9.

[5] Here is an example showing how to determine weight difference (φ). On average, various Departments of Transportation are considering a structural layer coefficient of 0.32 for FSB (Schwartz and Khosravifar, 2013). The structural layer coefficient for a 19mm HMA base mix is 0.40. Accordingly, substituting FSB and asphalt emulsions

$$ER = (PB - \varphi EI) \cdot Project\ amount / 1{,}000 \qquad \text{Eq.9}$$

where:
ER = Net emission reduction of a pavement recycling project (tCO_2e)
PB = Performance benchmark, referring to Table 1 ($kgCO_2e/t$)
φ = Adjustment factor for weight difference
EI = Emission intensity of a pavement recycling project ($kgCO_2e/t$)
Project amount = Amount of pavement product manufactured (t)

4. CASE STUDY

A case study of FSB projects is performed to illustrate the use of performance standards in project crediting. In this case, FSB is manufactured with CCPR process. The amount of carbon offsets from FSB projects are quantified and the gains from offset trading are analyzed to demonstrate economic viability of performing pavement recycling projects.

Production data relevant to CCPR was collected onsite at the Global Emissionairy, LLC. at Forestville, MD from March 2012 to May 2013. The company suspended the production from October 2012 to February 2013 due to cold weather. During the production periods, a total of 1,337t of FSB was produced using 95.6% RAP in combination with 2.3% hot bitumen blended together with 1% potable water and 1% Portland cement. Transportation distances for the shipment of input materials were collected from production records. Material production and transportation emission were calculated using Equations 2 to 7.

The placement procedures for a CCPR overlay are the same as for HMA. Similar to the estimation for HMA placement, the equipment operation information for CCPR was gathered from thirteen patching projects conducted in Maryland and Virginia. Primary equipment used for placing FSB includes milling machines, backhoes, loaders, sweeper, paver, rollers and trucks. The operation information for equipment was obtained from contractor's daily reports and truck driver reports. Equipment emissions were calculated using Equation 8.

Figure 2 shows the distribution of GHG emissions from FSB production and placement using CCPR. The GHG emission intensity of CCPR is 76.8 $kgCO_2e$ per metric ton of FSB pavement for the monitoring period. The top four emission sources are paving (20.2 kg CO_2e/t, 26.2%), milling (13.7 kg CO_2e/t, 17.8%), bitumen (11.7 $kgCO_2e/t$, 15.2%), and cement (9.1 kg CO_2e/t, 11.8%). Nearly half of emissions (54%) are generated at the job site and the remaining half (46%) are generated off site.

Comparing against the performance benchmark of 121.9 $kgCO_2e/t$, performing FSB projects is eligible to generate 43.5 $kgCO_2e/t$ of carbon offsets (Fig. 3). Within the three-month production periods, a total of 58.2 t of carbon offsets can be generated with the production of 1,337 t of FSB. The revenues from offset sales can amount to $582 assuming the offset price is $10/t CO_2e. In addition to the offset revenues, the use of FSB can save material costs by approximately $20/t. When cost savings from materials are accounted for, the total cost savings from replacing HMA with FSB are approximately $20.4/t. The National Asphalt Pavement Association (NAPA) estimated HMA production is 317 million t in 2014 (NAPA, 2015). Even with a 20% market share, FSB producers will be able to obtain 2.8 million t of carbon offsets in a year. If all of these offsets can be traded in the market, FSB producers will open up more than 20 million revenue sources beyond direct FSB sales.

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for HMA on a project would, on average, require the FSB layer to be approximately 25% thicker than the HMA layer. The densities of FSB and HMA are 130 lb/cu.ft and 160 lb/cu.ft. After factoring in these density differences, the use of FSB should be 2% more than HMA base by weight for the same length of paved road. The weight difference (φ) is therefore 1.02 for FSB project.

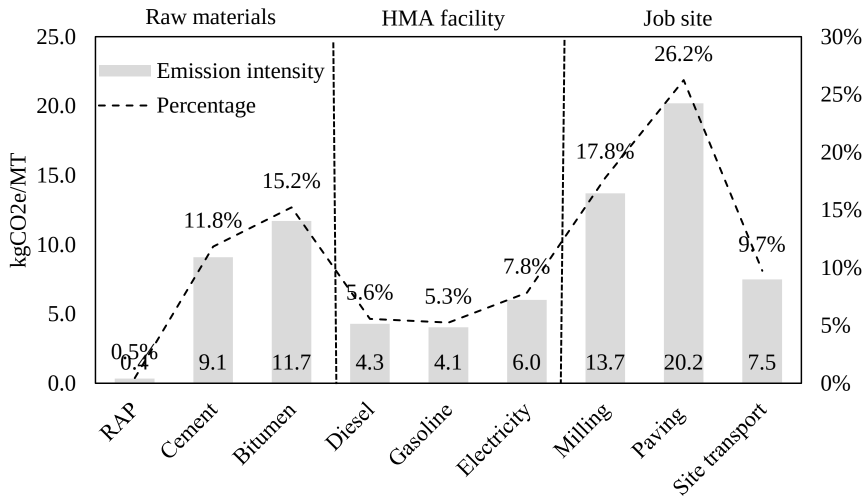

Fig.2. Distribution of GHG emissions from FSB pavement using CCPR

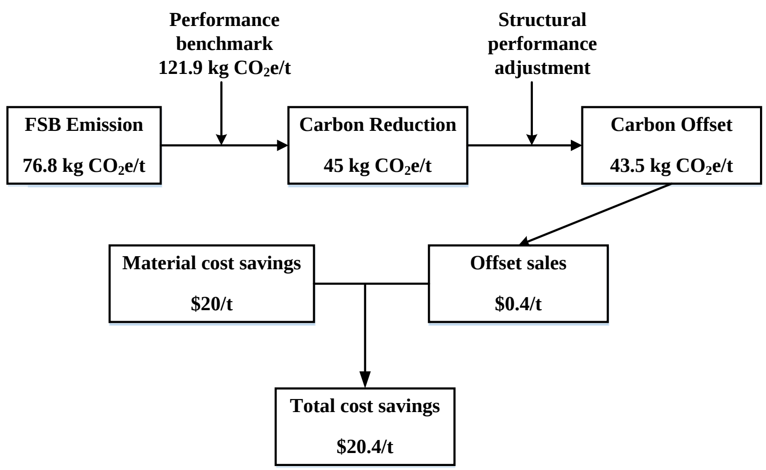

Fig. 3 Cost savings with the use of FSB pavement

5. CONCLUSION

Performance benchmarks have been developed to serve as baseline emissions for quantifying GHG removals by using recycled asphalt materials. The baseline configuration for determining the benchmarks is the production of conventional HMA. A carbon offset quantification method has been established to measure the GHG emissions from producing and placing HMA. Sampling surveys of typical HMA facilities and placement projects form a data pool to support the determination of conservative performance benchmarks that represent different geographic areas, pavement structures, and production techniques. An illustrative example is used to demonstrate that significant financial rewards can be granted by adopting recycled asphalt pavements, with the aid of the proposed benchmark under an increasingly expanded carbon trading market. Primary findings include:

- The performance benchmarks are determined as 121.9kgCO_2e/t HMA for patching projects with hauling distance less than 40 miles, 142.4kgCO_2e/t HMA for patching projects with hauling distance larger than 40 miles, and 105.5kgCO_2e/t HMA for roadway projects. These values represent emission levels that 80% of existing HMA producers are unable to reach and reasonably avoid the occurrence of free-riders. The boundary covers the GHG emissions from raw material production, hot mix facility and placement process.

- Rapidly evolving carbon trading markets increase the competitive advantages of "green" producers by generating financial revenues via offset sales. For example, performing FSB projects is eligible to generate 43.5 $kgCO_2e/t$ of carbon offsets. When cost savings from materials are accounted for, the total cost savings from replacing HMA with FSB are approximately $20.4/t. Considering 317 million t of HMA production per year, even with a 20% market share, FSB producers will be able to obtain 2.8 million t of carbon offsets in a year. If all of these offsets can be traded in the market, FSB producers will open up more than 20 million revenue source beyond direct FSB sales.

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