Tools for Sustainability Management in Pavement Industry

Arash Saboori[1], Magdy Abdelrahman[2], Anthony Waldenmaier[3]

[1,2,3]Civil Engineering Department, North Dakota State University,
NDSU Dept. 2470, PO BOX 6050, Fargo, ND 58018-6050, USA

[1]arash.saboori@ndsu.edu; [2]m.abdelrahman@ndsu.edu; [3]anthony.waldenmaier@ndsu.edu

***Abstract*-Sustainability is defined as human stewardship towards resources of our planet. Researchers recognize 7 general tools for implementing sustainable practices, which can be applied to project alternatives or decision making. Considering the significant amount of materials, energy, and other resources involved in pavement industry and the impact it has on the environment, implementation of sustainability in pavement industry is of grave importance. This could be achieved either through: (1) optimization of current processes or (2) development of new processes and technologies for pavement construction. For optimizing current processes, this paper targets quality as the main channel for promoting sustainability in pavement construction. Quality is the main parameter in construction activities which is constantly controlled and could serve as a measure on how efficiently resources have been used in the project. In other words promoting quality could act as a method for implementation of sustainable development. In pavement projects incentives/disincentives for quality are applied using pay factors. Life-cycle cost analysis (LCCA) is introduced as a rational method for calculating pay factors, discussed as a method for quantifying the quality performance and providing a method to choose the most sustainable alternative through cost evaluation. Besides improving quality, new technologies that allows reduction in use of resources (such as fuel) and CO_2 emission are of interest in pavement construction. In this regard Warm Mix Asphalt (WMA) is discussed as an alternative to Hot Mix Asphalt (HMA), which would promote sustainable development. The paper finalizes the discussion with a review of recycling in pavement industry and use of recycled materials in construction.**

Keywords- Sustainability; Quality; Pay Factors; Life Cycle Cost Analysis; Warm Mix Asphalt; Recycled Materials

I. INTRODUCTION

Sustainability is defined as the capacity to endure [1], referring to the concept of stewardship of human to the environment and natural resources to minimize the impact of human activities on the planet earth for future generations to benefit from the earth the same way as we do [2]. The concept has continuously gained more popularity among researchers of different fields in the past few decades. Implementation of sustainable practices can be facilitated by using some general tools recognized by researchers. These tools include climate change tools (mitigation and adaptation), energy efficiency tools (resources and energy), environmental assessment tools (pollution and ecosystem health), cultural and sustainability education tools (cultural heritage and contribution to local economy), economic and life-cycle-cost tools (environmental impact assessments and life cycle cost analysis), recycling and waste management tools (waste handling), and resource management tools (resource conservation and impact on agriculture, forestry, and fisheries).

This article briefly discusses the concept of sustainability, sustainability tools, and sustainable development. The main focus of this article is the pavement industry, which uses a large amount of resources and has significant environmental impacts. An important aspect of each construction project that is directly related to sustainability is the quality of the final product, in fact the quality of the constructed pavement is a measure of how efficient the materials, energy, and resources have been used in the project. Therefore, the article continues discussing how quality is actually controlled and promoted in pavement construction through using pay factors. A review of current practice of pay factors is conducted and the idea of application of life cycle cost analysis, as a rational method for comparing alternatives and making decisions, is explained. Furthermore, Warm Mix Asphalt (WMA) is discussed as a more sustainable alternative than conventional Hot Mix Asphalt (HMA). Bringing materials back to the construction through recycling is a popular topic that has been under investigation for years. Recycling in pavement industry and use of recycled materials in construction is the last topic discussed focusing on use of crumb rubber in asphalt binder as a means of recycling used tires in asphalt pavements.

II. LITERATURE STUDY

A. *Sustainability*

1) *Definition*

The word sustainability means the capacity to endure; how an ecological system could remain diverse and productive over time, which is vital for human well-being for the current and future generations [2]. To achieve this goal the impact of human activities should be monitored and managed. This could be approached by environmental management, which is largely based on information obtained from experts in the fields of earth science, environmental and conservation sciences. Another approach would be to manage the consumption of resources [3].

In its current use sustainability has three dimensions or three pillars: environmental, economic, and social, as pictured in Fig. 1.

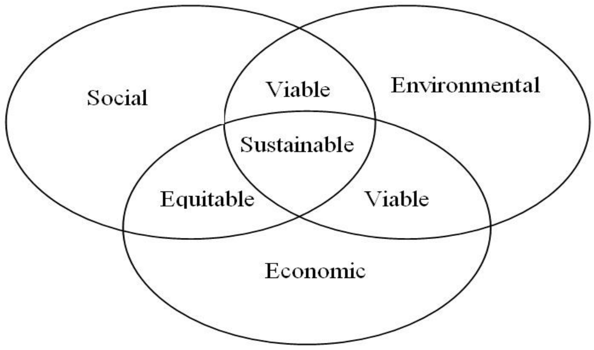

Fig. 1 Dimensions of sustainability (figure developed from materials in [4])

In other words the aim of sustainability is the “triple bottom line” concept, which is to consider the three primary principles: Social (known as social equity or people), Environmental (known as ecology or planet), and Economic (known as money or profit) [4].

2) Sustainable Development

The term sustainable development is frequently used as the implementation of sustainability. In 1987, the United Nations released the Brundtland Report [5], which included what is now one of the most widely recognized definitions: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Sustainable development is the pattern of growth which focuses on managing resource use in a way that meets human needs while preserving the environment, so that these needs could be met for the future generations too (sometimes taught as ELF: Environment, Local people, Future). The United Nations 2005 World Summit Outcome Document refers to the “interdependent and mutually reinforcing pillars” of sustainable development as economic development, social development, and environmental protection [6].

3) Sustainability Measurement

Sustainability measurement is the quantitative basis for the informed management of sustainability [7]. This involves direct measurement of metrics in the management plan such as costs or materials used, and indirect effects such as fuel usage or emissions. The metrics used for the measurement of sustainability are still evolving and include indicators, benchmarks, audits, indices and accounting, assessment, appraisal and other reporting systems [8]. These measurements involve all aspects of sustainability: environmental, social and economic domains, both individually and in various combinations. Measuring sustainability can help with tracking and assessing progress, encouraging broad participation, evaluating sustainability tradeoffs, meeting or anticipating new requirements, finding programmatic barriers, rewarding excellence and communicating benefits and goals [4].

4) Sustainability in Pavement Engineering

Federal Highway Administration (FHWA) considers sustainable highways as an inherent part of sustainable development. Therefore, it should satisfy life cycle functional requirements of social development and economic growth, while striving to enhance the natural environment and reduce consumption of natural resources. To reach this goal, the project should be assessed in sustainability characteristics of throughout its life cycle, from conception through construction, operations, and maintenance [4]. According to an NCHRP survey of 49 U.S. state departments of transportation and 7 Canadian provincial ministries, only 6 states or provinces have an agency sustainability program in place [8]. Additionally, only 2 states or provinces use environmental performance for maintenance selections and only 1 uses sustainable maintenance specifications. Sustainable transportation may be described or defined in many ways that broadly address environmental, social and economic impacts, safety, affordability, and accessibility of transportation services. Transportation agencies address sustainability through a wide range of initiatives, such as ITS, livability, smart growth, recycling, planning and environment linkages, and addressing requirements of the National Environmental Policy Act (NEPA) [4].

Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) is a practical, web-based, collection of best practices that allow states to integrate sustainability into their transportation projects. INVEST is a collection of sustainability best practices, called criteria, intended to help transportation practitioners measure sustainability in highway projects. The purpose of this tool is to identify these criteria, to assist organizations in researching and applying those criteria, and to establish an evaluation method to measure the benefits and progress of sustainable highway projects [4]. There are a number of important goals associated with scoring projects, including to:

- Encourage more sustainable practices in roadway planning, design, and construction;
- Provide a standard quantitative means of roadway sustainability assessment;
- Provide a standard means of assessing the sustainability of an agency's Systems Planning and Operations programs;
- Allow informed decisions and trade-offs regarding roadway sustainability;
- Enable owner organizations to recognize the benefits of sustainable road projects.

III. SUSTAINABILITY MANAGEMENT IN PAVEMENT PROJECTS BY QUALITY ASSURANCE

Sustainability management is a way to measure and compare sustainability practices. This could be conducted by monitoring and controlling environmental impact, and use of natural resources. A major way to contribute to proper use of resources is to manage the quality in the construction projects. Performing high quality construction means maximizing the efficient life of the pavement and minimizing future rehabilitation and maintenance cost. Quality is defined as "(1) The degree of excellence of a product or service; (2) the degree to which a product or service satisfies the needs of a specific customer; or (3) the degree to which a product or service conforms to a given requirement." [9].

In practice, there are two terms associated with quality management in construction projects, quality control (QC) and quality assurance (QA). QC is the responsibility of the contractor while QA is conducted by the owner (agency). QC is actually included in QA. QA is defined as: "All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service." [9]. QC is defined as: "Those QA actions and considerations necessary to assess and adjust production and construction processes so as to control the level of quality being produced in the end product." [9]. In QC/QA certain quality characteristics are constantly monitored, such as asphalt content, pavement thickness, air void content, and aggregate gradation in hot mix asphalt projects. Quality characteristic is defined as: "That characteristic of a unit or product that is actually measured to determine conformance with a given requirement" [9].

To offer incentives for good quality and penalize bad quality performance, agencies apply pay factors and pay adjustments. Pay factor is "a multiplication factor, often expressed as a percentage, used to determine the contractor's payment for a unit of work, based on the estimated quality of work." [9]. Sustainability management in pavement construction could be conducted through controlling the quality of the project and ensuring that the resources are being used wisely. The tool for promoting quality (and therefore the use of resources) is the pay factor. Pay factors also have economic impacts, thus targeting two aspects of sustainability. Considering all these, pay factors are to be taken seriously in sustainability in construction. Fig. 2 represents the method proposed in this paper for implementation of sustainability in pavement projects.

A. Pay Factors: Incentives/Disincentive for Quality of Construction

Currently many agencies prefer to use a simple linear equation for calculating pay factor based on the percentage of the quality characteristic that is within the specifications (PWL). Eq. (1) is widely recognized by many highway agencies [9].

$$PF = 55 + 0.5 * PWL \quad (1)$$

This method of calculating pay factors is simple, but does not have a rational justification. Therefore, many researchers have tried improving it.

Schexnayder et al. [10] compared three HMA pavement specifications and how the PF is calculated in each one. Their study showed little or no consistency between what is considered as quality and how this quality is paid. This was a result of subjective preferences on what quality characteristic should be considered in payment calculation, undefined test method to determine them, and payments which are not based on proven performance relationships.

Lin et al. [11] developed a general approach to payment adjustment for flexible pavements. They considered three main issues: different measurement units for the distress indicators, possible correlation among them, and variation in each of them. They solved the first issue by normalizing each indicator to make it dimensionless, used principal components analysis to eliminate any possible correlation between indicators, and proposed a reliability analysis to determine the pay factor based on the ratio of the reliability of uncorrelated principal components of the as-built pavement over the as-designed one.

Weed [12] suggested a new pay schedule to provide more bonus for better quality and larger reduction for poor quality in which instead of basing the pay adjustment on individual quality measures, it would account for combined effect of deficient qualities. The quality measures were on smoothness, air voids, and thickness.

Choi and Bahia [13] developed a life cycle cost analysis embedded Monte Carlo approach for modeling pay adjustments, the basis of their method is similar to what is explained in the beginning of this introduction. They considered asphalt content (AC), air voids (AV), thickness (Th), and percent of aggregates passing sieve #200 as quality characteristics to develop a model that would include both the variability inherent in pay-factor items and also the interactions among individual pay adjustment schedules.

Burati [14] studied the risks involved in using multiple quality characteristics in determining pay factor, remove and replace provisions, and the effect on pay factor if these characteristics are correlated. His study showed for acceptance provisions that call for removal or replacement greater risks are imposed on contractor when multiple characteristics are used while correlation between variables does not affect pay factors in the long run.

Chou et al. [15] used artificial neural network modeling to develop time dependent roughness prediction models to overcome the subjectivity on the pay factors limits and to provide a rational method to assign those limits based on declining riding comfort of the highway.

Whiteley et al. [16] studied how the variability in the input parameters affects the pavement performance models for performance specifications, life cycle costs, and pay factors.

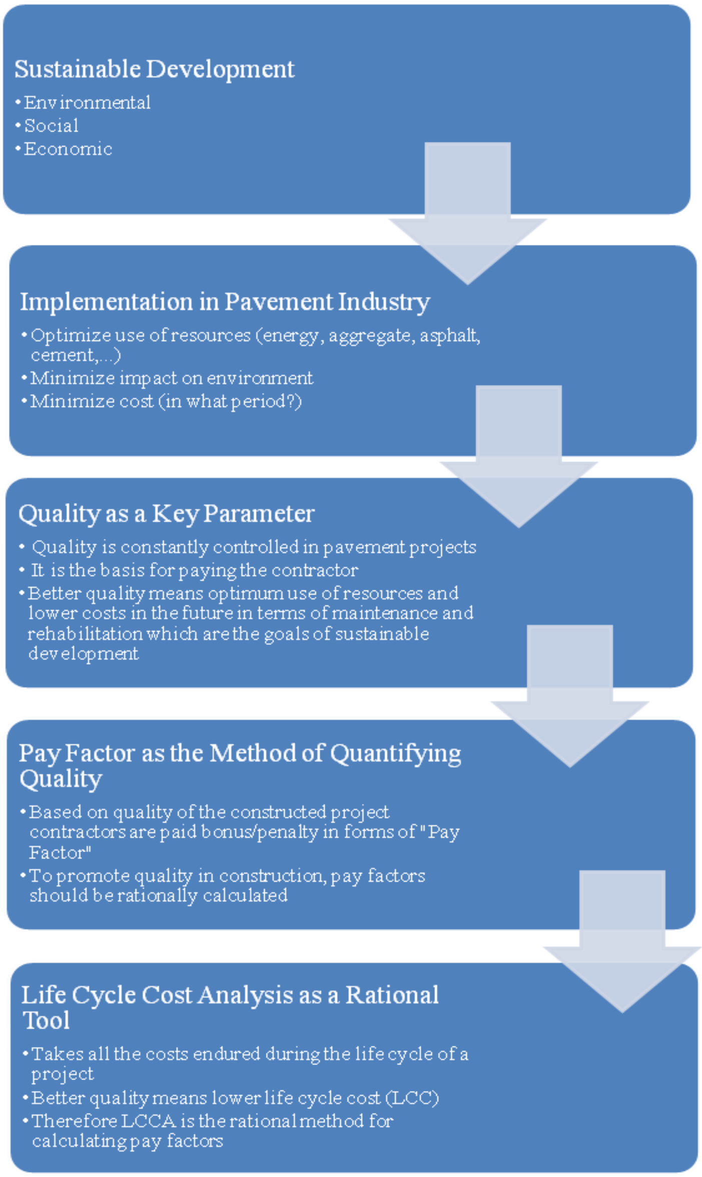

Fig. 2 The proposed method for effective and rational method of using quality assurance to promote sustainable development

B. Rational Model for Determination of Pay Factors

Pay adjustment is used to provide incentive/disincentive for the contractor based on the finished product. To make the pay adjustment fair and rational, the bonus/penalty should be proportional to the financial impact of the quality delivered by the contractor. How the quality is judged is based on the Quality Assurance Specification in use; currently Performance Related Specification (PRS) is most common. PRS is defined as a “quality assurance specifications that describe the desired levels of key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance” [9]. The costs of a pavement for the owner consist of construction costs plus the costs of keeping the pavement in service. This is the Maintenance and Rehabilitation (M&R) cost. If the contractor is to be awarded based on a delivered quality As Constructed (AC) better than what was required by the As Designed (AD) specification, the owner would pay this bonus in addition to the initial contract bid with the hope of saving money in the future by the better quality of the pavement, which is going to result in lower M&R expenses. What would make this extra payment rational is that it should be equal to or less than the resulting decrease in the Life Cycle Cost (LCC) of the pavement. Based on this, the rational way of computing pay factors consists of the following steps:

- Gathering the Quality Check (QC) data of the main quality characteristics that affect the performance for the constructed pavement, in addition to their AD values.
- Developing a Performance Model (PM) that would use the quality characteristics to predict the value of Performance Indices (PI) as a function of time. This model should be developed based on mechanistic empirical methods and should be verified by the available QC and PI data of previous projects.
- According to the owner policy, the M&R schedule would be developed based on the PI.
- A Life Cycle Cost Model (LCCM) is required to determine the LCC of AC and AD project. The input of this model would be the initial contract bid, M&R schedule and cost details of the region and other economic information such as inflation expected.
- The difference of LCC of AD and AC would be the incentive/disincentive, if positive the contractor would be awarded and if negative the difference would be subtracted from the initial contract bid.

The point to be noted is that the input for the first stage, that is the quality data, is not deterministic and has to be treated with their probability distribution. Therefore, inputs and outputs of each stage should be in form of probability distribution and based on Risk Management policy of the owner before the decisions are made.

IV. LIFE CYCLE COST ANALYSIS: RATIONAL TOOL FOR MEASURING PAY FACTORS AND COMPARING DECISION ALTERNATIVES

A. Introduction

Life cycle cost analysis (LCCA) is a powerful and rational tool for decision making and choosing among different alternatives. It provides the decision makers with better vision of the consequences of the choices they make. The main idea is to have a holistic view to different project alternatives and consider each one’s benefit and expenses through the whole life of the project in which it is in service; not only assessing the initial bid costs, but also being alert of future expenses that each alternative will impose. By estimating the costs in the future and having the initial cost for construction, the total cost of the option in present time can be estimated. By comparing the life cycle cost of all options the one with lowest cost would be the best choice, targeting the economic aspect of sustainability in the first place. However, environmental and social aspects also could be considered by quantifying those values through a process and considering them in the analysis (for more detail look for literature on Life Cycle Assessment).

An optimal solution to a LCCA would combine alternatives that are feasible based on a life-cycle assessment (LCA). Each alternative would meet a set of criteria that fulfill the environmental impacts of the project (minimizing the use of virgin materials by using recycled materials in pavement applications, for example) as well as social impacts (such as minimizing delays due to maintenance in pavement applications). After these alternatives are selected, the LCCA can determine the best alternative based on total project cost, while still meeting the standards or criteria found by the LCA. This thorough investigation would ensure that the project meets as many of the 3 portions of the sustainability paradigm as possible.

According to section 303 of NHS designation act of 1995, life cycle analysis is “a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment” [17]. Of course, this definition is tailored for pavement application. In fact, LCCA is a tool applicable in any field where selection between different alternatives would reach the same result.

LCCA is a subset of Benefit-Cost Analysis (BCA). In benefit per cost analysis the decision to do the project is still under investigation but in LCCA the construction of the project is already approved but the question is which alternative is the best. In BCA, besides costs, the user benefits resulting from the project and externalities are also considered but LCCA is mainly concerned with costs [18].

In this regard, project is a transportation investment that fulfills the agency’s requirement to provide a given level of service to the public. Therefore, the necessity of the service has already been verified through BCA. Now the choice between the alternatives is handled by LCCA. An alternative is a proposed means to provide the performance indicated in the project definition. Although alternatives have different methods, the results of them all are the same and will provide the user with the same level of comfort and service. Having this in mind, the only thing that would make an alternative best is the total costs endured in the whole life cycle of the project. To be able to make a sound comparison between alternatives, the costs associated with each alternative will be discounted to present value and then compared. The cheapest choice is the best [19]. Fig. 3 shows the concept of life cycle cost analysis tool in choosing between design parameters. In a survey conducted in 2001 Ozbay, et al. found state DOTs perform LCCA practices in 68% of design and research offices, 37.5% materials offices, and 37.5% pavement and management offices. All percentages are increased from a similar survey conducted in 1984 [18].

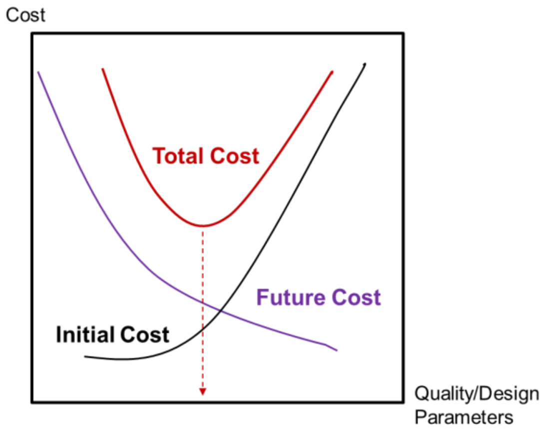

Fig. 3 Use of life cycle cost for choosing between design alternatives

B. Life Cycle Cost Analysis Steps

To have the lowest impact and cost, life cycle cost analysis should be used in evaluating the design alternatives. The steps needed for this are [19]:

- Establish design strategies alternatives
- Determine performance periods and activity timing
- Estimate agency costs
- Estimate user costs
- Develop expenditure stream diagrams
- Compute net present value (NPV)
- Analyze results
- Re-evaluate design strategy

After the project has been approved, the alternatives to reach the goal are suggested and based on each alternative's design. The agency's policy on maintenance and rehabilitation the M&R plan for each alternative is developed as well. The costs considered in LCCA can be categorized into agency costs and user costs. Agencies costs are:

- Design costs
- Construction costs
- Traffic control costs
- Maintenance costs
- Rehabilitation costs

User costs are:

- Normal operations versus work zones
- User cost rates, vehicle operating costs (VOC)
- Delay cost rates (value of time)
- Crash cost rates

Although these costs are not directly bared by the agency, they affect the agency's customers and their perception of the agency's performance. NCHRP 02-18(3), "Development of an Innovative Highway User-Cost Estimation Procedure" can be used for estimation of user cost.

After determining all the costs either by assumption, prediction, or based on previous data, cash flow diagrams are drawn and all costs in the future are discounted to the present time and added together to determine the Life Cycle Cost of each alternative. The present value of future expenses is:

$$\text{Present Value} = \text{Future Value} * 1/(1+r)^{n} \quad (2)$$

Where

r = real discount rate

n = number of years in the future when the cost will be incurred

Life cycle cost analysis is being widely used among States' Departments of Transportation for decision making purposes. Fig. 4 illustrates the distribution of DOTs using LCCA in their routines.

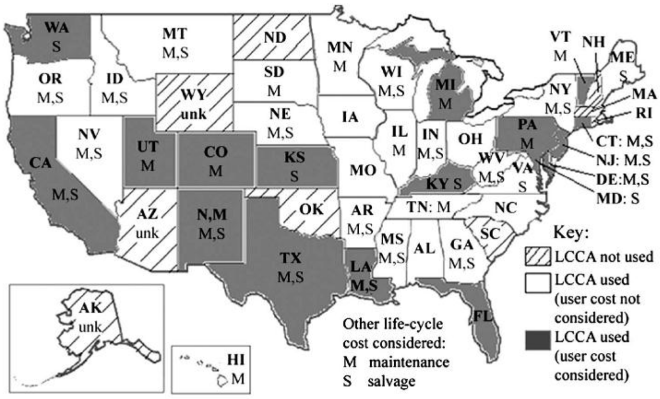

Fig. 4 Distribution of LCCA Use Among DOTs [20]

C. Advantages and Challenges

As discussed, LCCA is an important analytical tool applicable to a broad range of routine decisions. It provides a structured approach to evaluating design alternatives and it is rational, therefore decreases legal disputes for the agency. LCCA helps officials to demonstrate good stewardship of the public transportation assets. However, with all the advantages and rationality that LCCA brings to the decision making process, challenges still exist. The validity of any analysis is first dependent on the validity of its input values. For LCCA unfortunately, there is a significant source of uncertainty in input data. The data includes inflation rate, cost of activities in the future, user costs, traffic volume, activity timings, uncertain M&R plans, and the analyst cannot be 100% sure of the values that are put into the analysis. These values are either based on estimation, assumption, or viewpoint of experienced people in the field; and uncertainty exists for all values. To address this issue, probabilistic LCCA is used.

D. Probabilistic LCCA

In order to deal with the uncertainties in the input values, probabilistic LCCA is used. Deterministic approach assumes all the inputs as fixed known values and results in a single value as the LCC of each alternative. However, it does not provide the decision makers with any information regarding the possibility of occurrence of such value. In today's decision making sciences, it is of little value to have a single number as the value of a parameter that is not certain. In fact, decision makers who are engaging their capitals are interested to know what risks are involved and how confident they can be of the results of the analysis reported to them. In this regard, all the parameters used in analysis are considered as having probability distribution and the results are thus reported as probability distribution, as shown in Fig. 5. This allows the investor to fully understand the risks of his decisions. It would give a much better vision if the decision maker could know how much would be the possible variability in the total cost predicted for this investment through its life cycle. This is the whole idea behind probabilistic method in analysis; to perform risk analysis [20].

Net Present Value = Initial Costs + Σ Future Costs

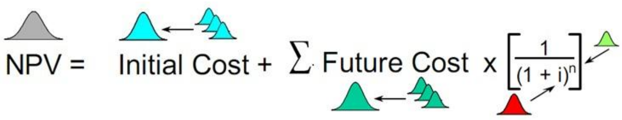

Fig. 5 Probabilistic LCCA [20]

E. Risk Analysis

The concept of risk comes from the uncertainty associated with future events, the inability to know what the future will bring in response to a given action today. Risk can be subjective or objective. Subjective risk is based on personal perception while objective risk is based on theory, experiment, or observation. Risk analysis is concerned with three basic questions about risk:

1) What can happen?

2) How likely is it to happen?

3) What are the consequences of its happening?

Risk analysis answers these questions by combining probabilistic descriptions of uncertain input parameters with computer simulation to characterize the risk associated with future outcomes.

The general approach for doing risk analysis consists of 5 steps [20]:

1. Identify structure and logic of problem.

2. Quantify uncertainty using probability.

3. Perform simulation.

4. Analyze and interpret results.

5. Make a consensus decision.

After identifying the structure of the problem by specifying the inputs to the model, the probability distribution of the input variables has to be determined to define how likely it is for each of them to have different values. This is either done based on the trend observed in the previous data of the agency, or if that is not available, its distribution is assumed by experts in the field. After that, simulation is done to get the probability distribution of the output. Simulations run the model many times by taking random values of each of input parameters based on their probability distribution, and will determine the value of the output. The values of the output gathered through these many iterations, which are usually in order of 10,000 or more, will form the probability distribution of the output. Then this output is analyzed to see the possibility of different values occurring. Based on the results, risk management policies, and tolerances of the agency, a consensus decision among decision makers will be made.

F. Selected Software for LCCA and PF Determination

1) Quality Related Specification Software (QRSS) – FHWA

The QRSS employs a database of pre-solved solutions of the MEPDG. The program is capable of conducting performance prediction for HMA pavements based on mix volumetric, binder, and aggregate properties of as-designed pavement and comparing them predicted performance of the actual constructed project (contractor's quality assurance data). This is achieved through putting input data into Witczak Predictive Equation to estimate values of the dynamic modulus (E*) that, in turn, are used to predict the development of rutting, fatigue cracking, and the pavement service life based on the development distresses over time. Finally, pay factor adjustment factors and payments (penalty/bonus) are derived from the predicted service life differences for each as-built lot or sub-lot. The distress predictions are probabilistic and are calculated using Monte Carlo procedure, which requires standard deviations of input values to account for variability [21].

2) PaveSpec 3.0 – FWHA

PaveSpec 3.0 is developed in an effort to implement performance related specifications (PRS) for jointed plain concrete pavements (JCPC). A main function of the software is to determine rational performance related pay-factors for JCPC pavements. A simulation engine is used to simulate pavement performance and life cycle costs of both as-design and as-constructed pavements are calculated. By comparing the as-design versus as-constructed life cycle costs, a rational pay adjustment could be calculated. The distress indicators that are predicted through the life of the project are: transverse slab cracking, transverse joint faulting, transverse joint spalling, and IRI. The input variables to PaveSpec are quality characteristics of the pavement; concrete strength, slab thickness, air content, initial smoothness, and percent consolidation around dowels [22].

3) BCA.NET – FHWA

BCA.Net is the Federal Highway Administration's (FHWA) web-based benefit-cost analysis tool to support the highway project decision-making process. The BCA.Net system enables users to manage the data for an analysis, select from a wide array of sample data values, develop cases corresponding to alternative strategies for improving and managing highway facilities, evaluate and compare the benefits and costs of the alternative strategies, and provide summary metrics to inform investment decisions. For a project evaluation, BCA.Net takes the capital costs, physical and performance characteristics, and forecast travel demand of the highway project as inputs. The user specifies strategies for improvements and maintenance, and builds a Base Case and an Alternate Case for evaluation. BCA.Net calculates the traffic impacts, the present values of agency and user costs, and benefits for each case. It compares results to arrive at measures including the net present value, benefit-cost ratio, and internal rate of return for the Alternate Case relative to the Base Case [23].

4) RealCost LCCA Package – FHWA

FHWA's RealCost software is based on a Microsoft Excel spreadsheet, and is obviously the most versatile package compared to the other existing LCCA packages. It has a detailed work-zone user costs computation. Unlike the Asphalt Pavement Alliance (APA) software, it does not update the values of travel time using the current CPI and the base CPI, and does not optimize work-zone timing to minimize user costs based on the hourly traffic distribution and work-zone duration. Such computations are left externally to the user. Shortcomings of the RealCost software include its limited analysis capacity, as only two alternatives can be analyzed at a time. Also, the RealCost software considers only time intervals of treatments (service lives) and, therefore, has no provision for the user to specify trigger values (an alternative to preset intervals) in the formulation of rehabilitation and maintenance strategies. The software requires the user to externally determine strategies for subsequent input in the software. Also, the software, in its present version, leaves the task of cost computation to the user. The estimated cost is then input by the user for the rest of the analysis. It would be useful for RealCost to be enhanced such that the user is provided with a drawdown list of alternative pavement design, rehabilitation, and maintenance strategies which may be adopted or modified as the user desires. Also, cost computation can be a burdensome task, and it would be useful for RealCost to include a mechanism to help users estimate pavement project costs [24].

5) DARWin – AASHTO

The DARWin Pavement Design System is a project level LCCA program that automates the AASHTO design equations. The life cycle cost module of DARWin considers project dimensions, initial construction costs, preprogrammed rehabilitation strategies (up to five), and the pavement salvage value at the end of its service life. DARWin then discounts all construction costs and salvage value to the present, and reports the net present value of the project. The program provides a life cycle cost analysis based on agency costs associated with specific projects and incorporates a database for managing materials, material properties, costs, and other aspects of pavement design and construction [25].

6) Pavement LCCA Package – Asphalt Pavement Alliance

The APA LCCA software is based on a Microsoft Excel spreadsheet, and generally seems to be more user friendly than most other LCCA software packages. Furthermore, it has an elaborate module for work-zone user costs computation, and updates the values of travel time using the current CPI and the base CPI. Furthermore, the APA LCCA software optimizes work-zone timing to minimize user costs based on the hourly traffic distribution and the work-zone duration. Shortcomings of the APA software include its limited analysis capacity, and that only four alternatives can be analyzed at a time, and only up to ten work-zone activities can be analyzed for each alternative. Also, user costs during normal operation of the pavement are not considered. Also, the APA software makes no provision for the user to specify trigger values (an alternative to preset intervals), in the formulation of rehabilitation and maintenance strategies. Finally, the software is not flexible to accommodate different analysis periods for different alternatives [26].

A study was conducted in Clemson University by contacting state DOTs and asking them about their approach toward LCCA [27]. Fig. 6 shows some of the results.

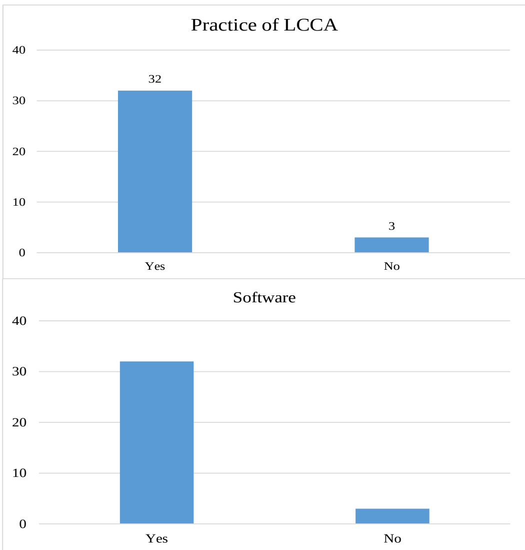

Fig. 6 Summary of the Clemson University Survey on LCCA [27]

V. NEW TECHNOLOGIES: WARM MIX ASPHALT

The NCHRP Survey showed that 41 states and provinces do not have sustainability programs in place as of 2009, but most do allow sustainable practices during the pavement life-span. 35 of the respondents allow the use of recycled materials and 29 allow alternative materials in their current designs programs [8]. The National Asphalt Pavement Association released the results of the Second Annual Asphalt Pavement Industry Survey in 2013, covering practices of states from 2009-2011. 49 states and Puerto Rico responded to the survey regarding usage of warm mix asphalt (WMA), reclaimed asphalt pavement (RAP), and reclaimed asphalt shingles (RAS). According to the survey, 68.7 million tons of warm-mix asphalt was used in 2011 [28]. The survey also indicates that 150 branches/companies reported using WMA and all 2011 statistics increased from 2010 [28].

Improving quality of the constructed pavement allows us to assure efficiency of the use of resources within the limits of conventional methods of construction, while new technologies for constructing pavements allows us to make major modifications in how we are using the resources. In other words, while quality control optimizes the resource utilization in a process and do not target the process itself, new technologies shoot for this shortcoming and try to improve the processes itself and invent new methods. A combination of the first and second approaches would allow the most rewarding approach toward sustainable development in pavement construction industry.

Warm mix asphalt (WMA) represents a group of technologies that allow production and placement of asphalt mixes at lower temperatures compared to hot mix asphalt (HMA). This is achieved through reducing the viscosity of asphalt and enabling complete coating of aggregate at lower temperature [29].

A. History

The first WMA pavements were constructed in Europe in 1995 by experimenting with Aspha-min zeolite. Shell Bitumen began experimenting with WAM (Warm Asphalt Mix) in Norway in 1996, which has now developed into WAM Foam. The first pavements with Sasobit were constructed in 1997 in Hamburg, Germany. In 2002, a National Asphalt Pavement Association (NAPA) study tour introduced WMA technology to the U.S. Later on in 2005, NAPA and Federal Highway Administration (FHWA) formed WMA Technical Working Group (WMA TWG). The primary goal of WMA TWG was to develop a data collection framework for WMA trials that agencies would use for their own evaluations on WMA technologies [30]. In 2008, the WMA TWG published a WMA Guide Specification for Highway Construction in AASHTO format. In 2012, NCHRP published NCHRP Report 714, Special Mixture Design Considerations and Methods for Warm Mix Asphalt: A Supplement to NCHRP Report 673: A Manual for Design of Hot Mix Asphalt with Commentary.

B. Advantages of WMA Compared to Hot Mix Asphalt (HMA)

WMA is typically produced at temperatures 35 to 100 ℉ lower than that for HMA. This characteristic of WMA provides higher workability at lower temperature and better compaction in the field. This results in less permeability and lower aging of the binder. The fact that WMA is softer than HMA is also an advantage in areas with low temperatures because the risk of thermal cracking is lower. Lower mixing and compaction temperatures also result in less fuel consumption and reduction in CO2 and fumes emission, which imposes less health risk on workers and shows better stewardship towards the environment. Considering paving benefits, there are several advantages to using WMA. The ability to pave in cooler temperatures, haul longer distances, compact mix with less effort, incorporate higher percentage of RAP, place thick lifts, and open roads to traffic in a shorter period of time are some of the benefits of using WMA [30].

C. WMA Technologies

WMA technologies could be categorized based on the temperature reduction that can be achieved by using them, but it is more common to classify them based on the method of production where WMA technologies are generally of three types: chemical additives, foaming processes, and organic additives.

Chemical additives cause mechanisms that help asphalt binder to have lower viscosity at lower temperature and, therefore, improve aggregate coating and improve compaction of WMA mixture. Chemical additives normally do not require much modification to the production line.

Foaming processes are based on the fact that water will expand by a factor of approximately 1700 when changed into steam at atmospheric pressure. Therefore, by adding small amount of water through a foaming nozzle or using damp aggregate, water steam is produced. This causes asphalt binder to go through the same expansion in volume and, therefore, increased coating. This also decreases the temperature for achieving such a level of coating.

Organic additives or waxes provide mechanisms for lowering the binder viscosity by melting, and cause binder to be more flowable and flexible at lower temperature compared to HMA. A key point is that melting point of the wax should be higher than the pavement service temperature, otherwise permanent deformation would occur [30].

D. WMA State of Practice in Cold Region States

In a study sponsored by North Dakota Department of Transportation (NDDOT), 22 states of cold regions in United States and Canada were contacted to collect information about their approach toward implementation of WMA in their paving projects as a sustainable substitute for HMA. The correspondents were asked about their experiences, amount of WMA production, modifications they have in specifications, and the performance of WMA compared to HMA [31].

Fig. 7 compares WMA production with HMA based on the responses collected through the survey. Fig. 8 illustrates the reduction in temperature achieved based on the DOTs experience in working with various types of WMA, as can be seen from the figure, reductions ranging from 20 to 60℉ have been achieved, which could result in great saving in fuel consumption and sustainability.

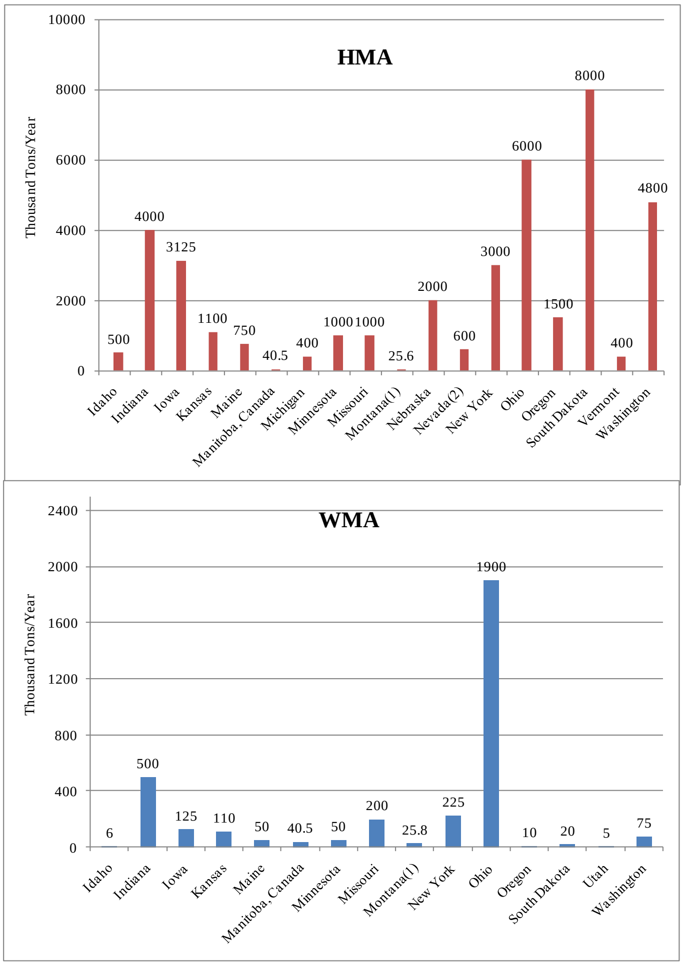

Fig. 7 Comparison of WMA production with HMA in cold region states [31]

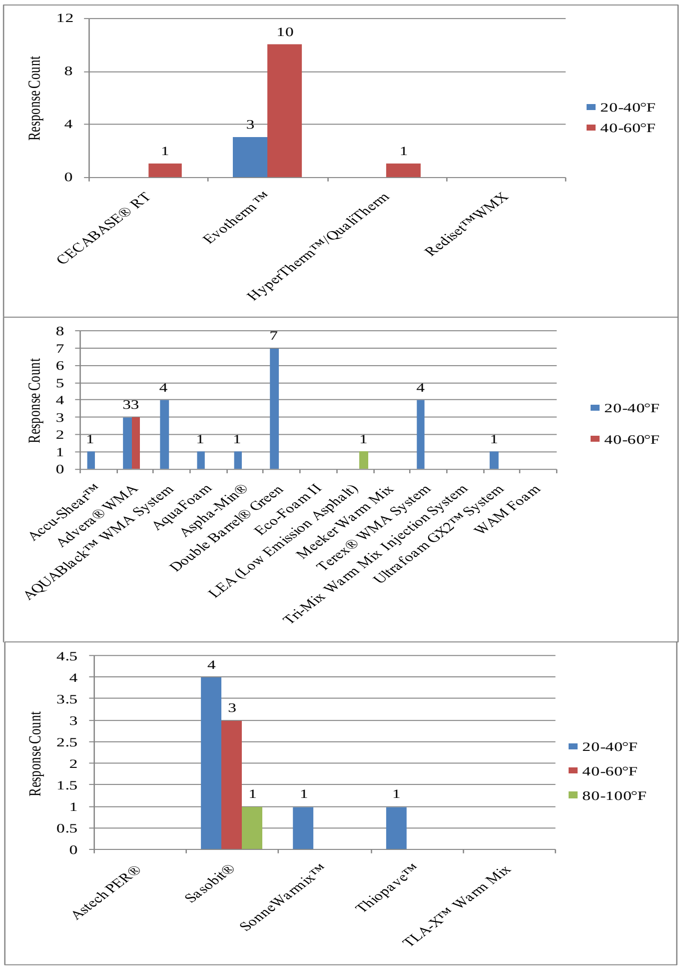

Fig. 8 Reduction in mixing temperatures achieved by using WMA compared to HMA [31]

VI. USE OF RECYCLED MATERIALS

A. Introduction

Recycling is processing used materials into new products to prevent waste of potentially useful materials, reduce the consumption of fresh raw materials, reduce energy usage, reduce air pollution (from incineration) and water pollution (from land filling) by reducing the need for "conventional" waste disposal, and lower greenhouse gas emissions as compared to virgin production [32]. According to the results of the Second Annual Asphalt Pavement Industry Survey in 2013, 66.7 million tons of reclaimed asphalt pavement and 1.2 million tons of reclaimed asphalt shingles were used in 2011. The survey also indicates that less than 1% of RAP and RAS were landfilled in 2009-2011. 198 and 81 branches/companies used RAP and RAS, respectively, in 2011 and all 2011 statistics increased from 2010 [28].

In addition to recycling old pavements, the benefits of reclaiming have impacts on the life-cycle environmental impacts. In an assessment of pavement practices, the Asphalt Pavement Association of Oregon used a life-cycle assessment software to compare different paving practices used within the state. They found the economic performances of Portland cement and asphalt cement concretes pavements were roughly equal, but the impact to the environment was significant for only the Portland cement and fly ash pavements [33]. Similar software analysis showed that the acquisition of materials produces more CO_2 than manufacturing, transportation and use of the pavements. Portland cement concrete pavements contribute about 11,200 g CO_2/unit, while 20% fly ash cements contribute about 9,000 g CO_2/unit. Asphalt pavements, on the other hand, only generate about 4,800 g CO_2/unit, with about half coming as a result of materials acquisition. The analysis shows that the use of asphalt pavements is better from a sustainability standpoint, and the materials acquisition is a major contributor to the CO_2 emissions. The use of recycled materials can reduce the materials acquisition through limiting the need for off-site virgin materials.

Recycling or reuse of pavement materials is a powerful concept. Because of the reuse of existing material, pavement geometrics and thickness can also be maintained during construction. In some cases, traffic disruption is less than that for other rehabilitation techniques. Literature lists the specific benefits of recycling as:

1. Reduced costs of construction

2. Conservation of aggregate and binders
3. Preservation of the existing pavement geometrics
4. Preservation of the environment
5. Conservation of energy
6. Less user delay

B. Implementation of Recycled Asphalt Pavement Materials into New Paving Projects

Use of recycled materials in new projects has the potential to impact all three phases of the sustainability paradigm through reuse of existing roadway materials. Recycled asphalt pavement (RAP) has been proven in lab studies to have performance capabilities equal to or better than traditional project materials as a base layer and surface layer material by means of resilient modulus or permanent deformation [34-38]. However, testing has shown mixed results due to the variability in RAP, RAP content, and variations to testing methods [34-38].

Most states and agencies have implemented RAP in new projects to some extent to date. Fig. 9 shows data collection statistics of studies conducted by the National Asphalt Pavement Association (NAPA), Federal Highway Administration (FHWA), and National Center for Asphalt Technology (NCAT) [28, 39-41]. The data presented shows the number of states or agencies using RAP at varying percentages, as indicated by multiple surveys since 2007. As shown, 20% is the most commonly utilized percentage of RAP for surface and non-surface layers. Most states and agencies surveyed use RAP between 10 and 30% in mixes, with very few mixes above 30%. Research indicates that high RAP content results in too much performance variability to be viable [34-38, 41].

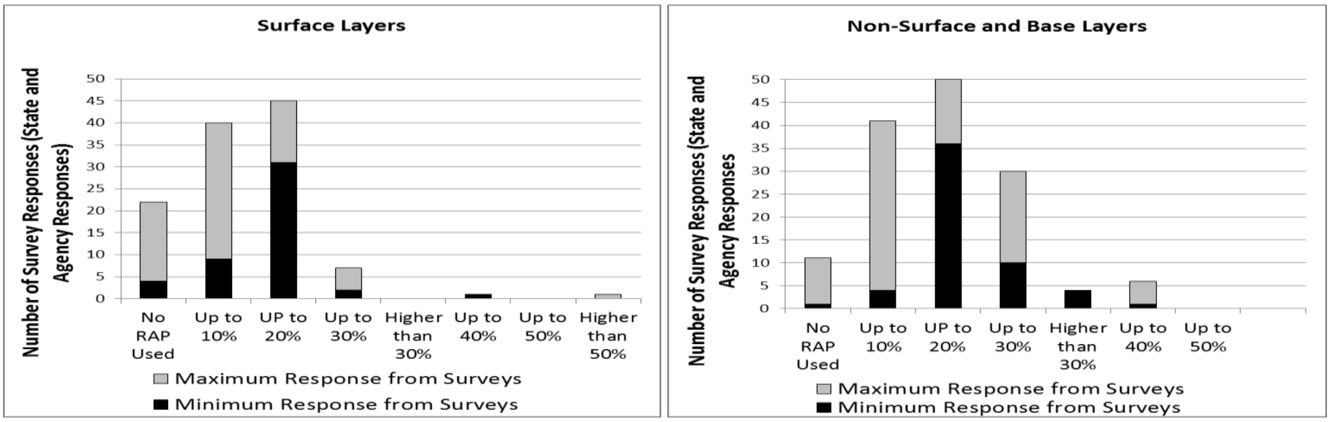

Fig. 9 States and agencies using RAP in surface and non-surface hot-mix asphalt pavement by percentage of RAP [39-41]

In addition to the use of RAP in existing projects, most agencies and states have set allowable limits for RAP percentages in HMA layers. Fig. 10 shows additional data collected by the survey about the number of states or agencies with maximum allowable RAP percentages in the surface, binder, and base layers of HMA Layers [28, 39-41]. As shown, 20% RAP is the most common amount for binder and surface courses; however base layer mixes are most commonly allowed to contain 30% RAP. Very few of the surveyed states and agencies allow more than 30% for any HMA pavement layer.

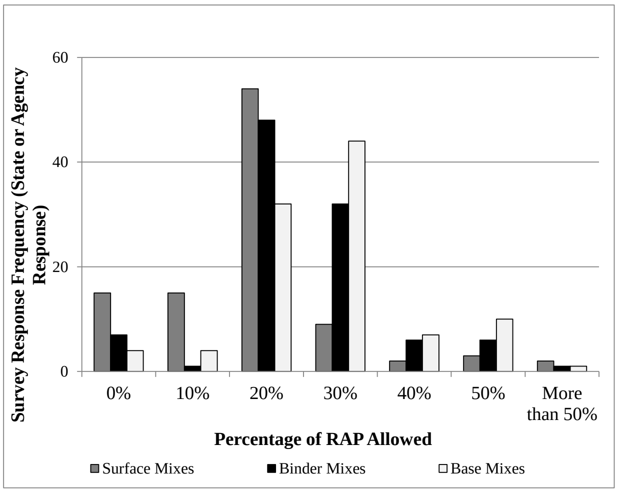

Fig. 10 Allowable percentages of RAP in HMA layers for states and agencies [39-41]

In order for RAP to be considered a sustainable option for future roadways, the performance of RAP-incorporated project must maintain adequate service and performance compared to the traditional virgin materials. The Long Term Pavement Performance program and NCAT have issued nation-wide surveys to assess the performance of RAP-incorporated projects in recent years [39-40]. Results of the surveys are shown in Fig. 11. Several distresses were utilized as performance indicators, including roughness, rutting, and fatigue cracking, and so on. Each project was assessed for the occurrence of the distresses and each state and agency compared the RAP projects to the virgin projects. Fig. 11 shows the percentage of projects where virgin material projects outperformed RAP, the percentage of RAP projects out performed virgin materials, and the percentage of projects where there was no significant difference between the two design methods. As shown, RAP projects generally have better performance or show no significance. This is an indication that RAP projects have the potential to improve, or at least maintain expected performance while utilizing a recycled material. However, the RAP projects also have a higher variability. The results from the surveys have a larger range between the maximum and minimum percentages reported for projects where RAP performed equal to or better than virgin materials.

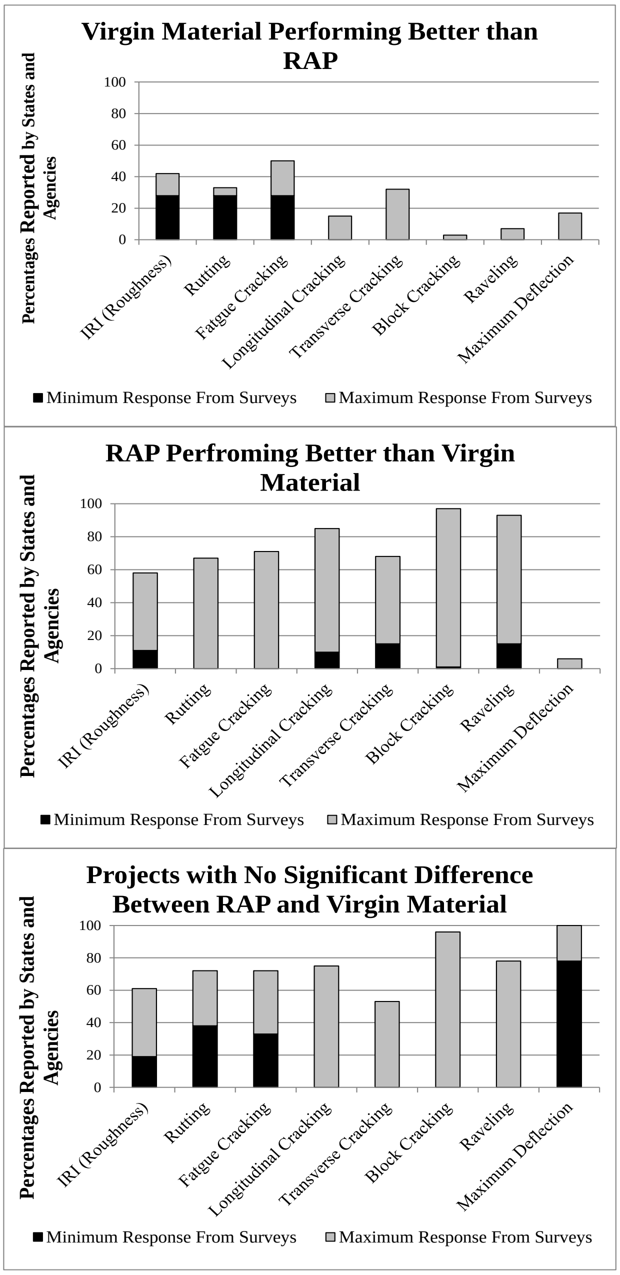

Fig. 11 Comparisons between RAP and virgin materials by specific distress measurements by percentage of projects [39-40]

C. *Crumb Rubber Modifier Use in Paving Projects*

Other materials can be used in new paving projects to increase pavement performance while utilizing recycled materials. Crumb rubber is most commonly produced through the grinding of previously used tires, of which about 25 million tires are annually recycled [32]. Like RAP, crumb rubber modified (CRM) asphalt must be proven in lab and field testing to have performance equal to or better than virgin materials in order to be considered viable and potentially sustainable. Using CRM asphalt in new projects has been in practice for decades and allowed for many years of improving the practice of CRM asphalt applications. For example, the FHWA published a state of the practice guide of design and construction using CRM materials in 1992, while newer improvements are summarized in current guides as published by the Rubber Pavements Association in 2011 [43, 44]. CRM practices have allowed the use of scrap tires in new paving projects, which has utilized a viable waste material, reduced the need for virgin asphalt binder, and improved performance aspects of roadways and rehabilitation strategies [43, 44].

1) Effectiveness of CRM in Asphalt Binder:

In general, research indicates that the use of CRM enhances the performance of typical asphalt by altering the properties of the binder to counteract the effects of pavement distresses like fatigue cracking, thermal cracking, and rutting [44-46]. The Superpave asphalt grading system is the common testing process for asphalt binder classification and much of the research of CRM asphalt mixes use the same standards as a means of direct comparison to known performance measures. In a study with road materials in Nebraska, the addition of 20% CRM, by weight of asphalt binder, was found to change the Superpave grading of PG 58-28 to PG 82-34, a change that indicates adequate performance at higher and lower temperatures [46].

2) Processing and Enhancement of CRM:

Developments in technology have shifted the current research towards optimizing the rubber-asphalt interaction through variation to CRM asphalt processing. Research has suggested the use of virgin polymers to further improve the effectiveness of CRM asphalts, primarily as a means to increase the material workability, enhance material properties, and optimize CRM [44-46]

3) Applicability of CRM:

Although lab performance is a key component to utilizing and optimizing CRM in field applications, cost implications will also be of concern to paving applications. The state of the practice lists chip seals and hot mix asphalt as the major uses of CRM asphalt, each having benefits with cost and performance [43]. The Arizona DOT cited lower cost associated with asphalt rubber pavements, as well as improved performance of long term applications with respect to cracking, rutting, roughness, skid resistance, and noise [43]. The Rubber Pavements Association analyzed the life-cycle cost of maintenance and rehabilitation practices using CRM asphalt by the highway agencies of Arizona, California, and Texas [47]. Using deterministic and probabilistic analysis methods, the analysis concluded that CRM would be a cost effective rehabilitation material for most applications and most cost-service life scenarios. However, a major conclusion of the research stated that the application of CRM techniques must be considered for each specific alternative, due to the fact that there are too many variables to consider; such as design life and specific costs associated with salvaging, construction/application, and designs [47].

D. Future Directions

There is a need to evaluate compliance and consistency of recycled material properties with respect to current specification requirements and to assess property-based requirements of recycled materials. Officials are receptive to pursuing changes in the way they specify recycled materials. It is agreed that current specifications are still outdated for virgin materials and do not reflect the current level of knowledge concerning desirable properties for pavement applications and do not provide all necessary property characterization to ensure field performance. Current procedures may or may not be the best testing to characterize the properties of recycled materials. There have been discussions regarding added testing procedures (to measure additional properties) in the current specifications to ensure the applicability of specifications on recycled materials. An example is asphalt-CRM binder stability. The concern regarding the relation between the suggested testing and performance has two aspects: If those relations are valid, then there is a need for a change in current specifications. If those relations do not exist, then marginal materials including local sources, that may be poor in properties, should be used successfully in most civil/construction applications [352].

VII. SUMMARY

Pavement industry consumes a significant amount of resources (materials and energy) and has a significant impact on the environment through fume emission in construction, and production of wastes, making it a very popular choice for implementation of sustainability practices. This is achieved in two areas: 1. Optimizing the current construction practices, and 2. Developing new technologies which are more sustainable.

To optimize the current practices, quality should be targeted, as the parameter constantly measured and controlled in construction. It could serve as a tool for assurance of efficient use of resources. Quality of the constructed sections is encouraged /penalized by Pay Factors in pavement industry. A rational method for calculation of pay factors using life cycle cost analysis is proposed, which eventually result in better quality of pavements. This equals more efficient way of using resources and that is the aim of sustainable development.

Developing new technologies that are more sustainable has attracted much attention within the last decade. For flexible pavements, Warm Mix Asphalt is gaining more popularity as a replacement for the traditional Hot Mix Asphalt. WMA technologies allow production at lower temperatures, which significantly reduces fuel consumption in pavement construction and helps minimizing fumes and CO_2 emissions. Furthermore, less heating the asphalt results in less aging and better performance of WMA compared to HMA in certain areas such as fatigue, thus not only new technologies are of interest due to cuts in resource usage, but also they can serve as a way to improve the performance of the final product which are the main ultimate goal of sustainable development. Implementation of recycled materials like RAP and crumb rubber (CRM asphalts) utilizes viable materials, reduces the need for virgin materials, and limits waste.

REFERENCES

[1] C. T. Onions, "The Shorter Oxford English Dictionary," Oxford, Clarendon Press, p. 2095, 1964.

[2] Agenda 21, "Declaration of the 1992 Rio Conference on Environment and Development," Retrieved 3.16.2009.

[3] H.E. Daly, "Toward some operational principles of sustainable development," Ecological Economics 2: 1–6, 1990.

[4] FHWA Sustainable Highways Self-Evaluation Tool Website: https://www.sustainablehighways.org/1/home.html, Retrieved 2.1.2012.

[5] "Report of the World Commission on Environment and Development: Our Common Future," United Nations General Assembly, 1990.

[6] http://www.who.int/hiv/universalaccess2010/worldsummit.pdf, 2005 World Summit Outcome Document, World Health Organization, Retrieved 2.1.2012.

[7] "Sustainability Accounting in UK Local Government," The Association of Chartered Certified Accountants, Retrieved 06.18.2008.

[8] NCHRP Research Results Digest 365: Sustainable Pavement Maintenance Practices, National Research Council, The National Academies Press, Washington, D.C., 2012.

[9] A. Patni, "Transportation research circular E-C137: Glossary of highway quality assurance terms," Transportation Research Board of the National Academies, Washington, DC, 2009.

[10] C. Schexnayder, and L. G. Ohrn, "Highway Specifications – Quality versus Pay," Journal of Construction Engineering and Management, American Society of Civil Engineers, vol. 123, no. 4, pp. 437-443, 2004.

[11] H. H. Lin, M. Solaimanian, and T. W. Kennedy, "General Approach to Payment Adjustments for Flexible Pavements," Journal of Transportation Engineering, American Society of Civil Engineers, vol. 127, no. 1, pp. 39-46, 2001.

[12] R.M., Weed, "New Jersey's Superpave Specification, the New Generation," Transportation Research Record: Journal of Transportation Research Board, National Research Council, Washington, D.C., no. 1761, pp. 10-14, 2001.

[13] J. H. Choi, and H. U. Bahia, "Life-Cycle Cost Analysis-Embedded Monte Carlo Approach for Modelling Pay Adjustments at State Departments of Transportation," Transportation Research Record: Journal of Transportation Research Board, National Research Council, Washington, D.C., no. 1900, pp. 86-93, 2004.

[14] J. L., Burati, "Risks with Multiple Pay Factor Acceptance Plans," Transportation Research Record: Journal of Transportation Research Board, National Research Council, Washington, D.C., no 1907, pp. 37-42, 2005.

[15] S. F. Chou, and T. K. Pellinen, "Assessment of Construction Smoothness Specification Pay Factor Limits Using Artificial Neural Network Modeling," Journal of Transportation Engineering, American Society of Civil Engineers, vol. 131, no. 7, pp. 563-570, 2005.

[16] L. W. Whiteley, S. Tighe, and Z. Zhang, "Incorporating Variability into Pavement Performance, Life-Cycle Cost Analysis, and Performance-Based Specification Pay Factors," Transportation Research Record: Journal of Transportation Research Board, National Research Council, Washington, D.C., no. 1940, pp. 13-20, 2005.

[17] NHS designation act of 1995: http://www.fhwa.dot.gov/legsregs/nhs_sec.html, Retrieved 2.20.12.

[18] K. Ozbay, D. Jawad, N. A. Parker, and S. Hussain, "Life-cycle cost analysis: State of the practice versus state of the art," Transportation Research Record: Journal of the Transportation Research Board, vol. 1864, no. 1, pp. 62-70, 2004.

[19] T. Beatty, "Life-Cycle Cost Analysis Primer," US Department of Transportation: Federal Highway Administration, 2002.

[20] M. Smith and F. R. Center, "Life-Cycle Cost Analysis in Pavement Design," Report No. FHWA-SA-98-079. FHWA, Washington, DC, 2002.

[21] J. Moulthrop and M. Witczak, "NCHRP Report 704: A Performance-Related Specification for Hot-Mix Asphalt," Transportation Research Board of the National Academies, Washington, DC, 2011.

[22] FHWA PaveSpce 3.0 Software: http://www.fhwa.dot.gov/pavement/pccp/pavespec/, Retrieved 2.12.12.

[23] Introduction to BCA.NET: http://www.fhwa.dot.gov/infrastructure/asstmgmt/bcanet.cfm, Retrieved 1.8.12.

[24] Life-Cycle Cost Analysis Software: http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm, Retrieved 1.8.12.

[25] DARWin Software: http://www.aashtoware.org/Pages/DARWin.aspx, Retrieved 1.8.12.

[26] APA LCCA: www.AsphaltRoads.org, Retrieved 1.8.12.

[27] P. R. Rangaraju, S. Amirkhanian, and Z. Guven, "Life Cycle Cost Analysis for Pavement Type Selection," Federal Highway Administration, Report FHWA-SC-08-01, 2008.

[28] K.R., Hansen and A. Copeland, "2nd Annual Asphalt Pavement Industry Survey on Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, and Warm-Mix Asphalt usage: 2009-2011," National Asphalt Pavement Association. IS-138, 2013.

[29] J.A., D'Angelo, E. E. Harm, et al., "Warm-Mix Asphalt: European Practice," Federal Highway Administration, 2008.

[30] B. D., Prowell, G. C. Hurley, et al., "Warm-Mix Asphalt: Best Practices, 2nd Edition," National Asphalt Pavement Association, 2011.

[31] A. Saboori, M. Abdelrahman, and M. E. Ragab, "Warm Mix Asphalt Processes Applicable to North Dakota," NDDOT Project Number: NDSU 11-01 - SPR-R033, North Dakota Department of Transportation, 2012.

[32] M. Abdelrahman and Arash Saboori, "Utilization of Waste Maetrials in Consruction," Encyclopedia of Sustainability Science and Technology, Springer, 2012.

[33] J. Huddleston, "Sustainable Pavement Management Practices," NWPMA Fall Conference. Asphalt Pavement Association of Oregon. Retrieved June 15, 2013, from http://nwpma-online.org/resources/08Fall_SustainMgtPracs_JimHuddleston.pdf.

[34] M. I. E. Attia, M. Abdelrahman,and T. Alam, "Investigation of Stripping in Minnesota Class 7 (RAP) and Full-Depth Reclamation Base Materials," Report No. MN/RC 2009-05, Minnesota Department of Transportation, St. Paul, Minnesota, 2009. Retrieved fromlinks in the references that http://www.lrrb.org/pdf/200905.pdf.

[35] M. I. E. Attia, "Characterization of the Structural Behavior of Reclaimed Asphalt Pavement as Pavement Base Layer," Doctoral Dissertation, North Dakota State University, Fargo, ND, 2010.

[36] E. J. Jeon, B. Steven, and J. T. Harvey, "Laboratory Testing and Performance Evaluation of Recycled Pulverized Hot-Mix Asphalt Material," Transportation Research Record, no. 2014, pp. 42-52, 2009.

[37] W. Kim and J. F. Labuz, "Resilient Modulus and Strength of Base Course with Recycled Bituminous Material," Report No. MN/RC-2007-05, Minnesota Department of Transportation, 2007. Retrieved from http://www.lrrb.org/pdf/200705.pdf.

[38] Y. Song and P. S. K. Ooi, "Interpretation of Shakedown Limit from Multistage Permanent Deformation Tests," Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the Academies, Washington, D.C., no. 2167, pp. 72-82, 2006.

[39] L. Wiser, "Statistical Analysis of Performance of Recycled Hot Mix Asphalt Overlays in Flexible Pavement Rehabilitation," Long-Term Pavement Performance Program, US Department of Transportation, Federal Highway Administration, No. FHWA-HRT-11-051, 2011.

[40] R. West, "Summary of NCAT survey on RAP management practices and RAP variability," Federal Highway Administration, Washington, DC, 2008. Obtained from: http://www. morerap. us/RAP% 20Resources/reports. html. Site last accessed January 2011.

[41] A. Copeland, "Reclaimed asphalt pavement in asphalt mixtures: state of the practice," Federal Highway Administration. No. FHWA-HRT-11-021, 2011.

[42] "State of the Practice: Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier Methods," FHWA-SA-92-022, 1992. http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=413.

[43] K. P. Biligiri, "Asphalt-Rubber Standard Practice Guide," 2011. http://www.rubberpavements.org/Library_Information/AR_Std_Practice_Guide_Second_Edition_20121001.pdf.

[44] S. J. Lee, C. K. Akisetty, and S. N. Amirkhanian, "The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements," Construction and Building Materials 22.7, pp. 1368-1376, 2008.

[45] M. Attia and M. Abdelrahman, "Enhancing the performance of crumb rubber-modified binders through varying the interaction conditions," *International Journal of Pavement Engineering*, vol. 10, no. 6, pp. 423-434, 2009.

[46] M. Abdelrahman, "Controlling performance of crumb rubber-modified binders through addition of polymer modifiers," Transportation Research Record: Journal of the Transportation Research Board, vol. 1962, no. 1, pp. 64-70, 2006.

[47] R. G. Hicks, J. R. Lundy, and J. A. Epps, "Life cycle costs for asphalt-rubber paving materials," Rubber Pavements Association, 1999.