A Method to Assess the Use of New and Recycled Materials in Pavements

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16. Abstract

This report includes the results of a research project aimed at developing a comprehensive analysis framework for evaluating new and recycled materials to be used in pavements in Michigan. Two basic components of the framework are: (i) Engineering performance evaluation and (ii) Sustainability evaluation. Engineering performance evaluation included several options for each kind of material used at different layers of pavements. For asphalt pavements, there are three options. First option is based on the field data to be supplied by the proposer of a new/recycled material. Second option is laboratory performance data such as the push pull fatigue, flow number and IDT strength. The third option involves prediction of performance using Level 1 inputs in Pavement ME Design software. For concrete pavements and unbound layers, there are two options. First option, similar to asphalt pavements, is the field data. The second option is analysis using the Pavement ME Design software. For other types of materials, field data is required. Once data for any option is presented to MDOT (by an entity), MDOT can input these data in the NewPave software developed as part of this project to calculate an Engineering Performance Score (PS^E). Second stage of the analysis framework presented in this report is the sustainability analysis. The sustainability analysis of a new material includes three basic components: (1) Environmental, (2) Economic and (3) Social analyses. At the end of analysis of each sustainability component, a performance score based on sustainability (PS^S) is computed. Then the sustainability and the engineering performance scores are combined to compute an overall Performance Score (PS). This final Performance Score (PS) will be used by MDOT to decide whether to try the proposed new/recycled material in MDOT-administered roadways.

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EXECUTIVE SUMMARY

Sustainable construction practices have been favored by Federal and State Departments of Transportation (DOTs) as well as industry. Example practices include Warm Mix Asphalt (WMA), reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), crumb rubber (CR) modified asphalt, fiber reinforced concrete, crushed glass reinforced concrete, subgrade stabilization using Lime Kiln Dust (LKD), etc. However, the impacts of using new and recycled materials in pavements - particularly on long-term pavement durability and performance - are often unknown. A comprehensive system for evaluating these "proposed materials" in terms of engineering performance and sustainability is very significant for making appropriate decisions on whether to use them for road construction in Michigan. This research resulted in an analysis framework and a software (called NewPave) that will help MDOT identify the impacts of new and recycled materials on pavement performance and environment. First task of this research included a thorough literature review on various methodologies used to comprehensively evaluate new and recycled materials. The evaluation strategies in terms of pavement durability, sustainability, life cycle cost, and carbon emissions were investigated. Second task included development of a methodology which was implemented (in Task 3) into a standalone software program (called NewPave) for use by MDOT as a tool for evaluation of a new or recycled material proposed by an entity (e.g., university, industry, etc.). In this framework, it is the responsibility of the proposer of the new/recycled material to provide data (e.g., from a field test section, laboratory test, etc.) needed by the software program. The NewPave software computes a Performance Score (PS), which is based on engineering performance and sustainability (considering life cycle cost, CO_2 emissions and social aspects). Fourth task included validation of the framework by performing example analyses using various new and recycled materials, whose performances are somewhat known in the literature.

The analysis framework included two basic components: (1) Engineering performance evaluation and (2) Sustainability evaluation. Engineering performance evaluation included several options for each kind of material used at different layers of pavements. For asphalt pavements, there are three options. First option is based on the field data that may be presented by the proposer of a new/recycled material. Second option is laboratory performance data such as the push pull fatigue, flow number and IDT strength. The third option involves prediction of performance using Level 1 inputs in Pavement ME Design software. For concrete pavements, there are two options. First option, similar to asphalt pavements, is based on field data. The second option for concrete pavements is analysis using Pavement ME Design software. For Unbound layers, similar to concrete pavements, there are two options; (i) field data and (ii) analysis using the Pavement ME Design software. For other types of materials, there is only one option, which is field performance data. Once data for any option is presented to MDOT (by an entity), MDOT can input these data in the NewPave software to calculate an Engineering Performance Score (PS^E). The PS^E represent the percent improvement of performance relative to a control material. For example, PS^E=0 means the new material is expected to perform as good as a control material. PS^E=10 means new material will perform 10% better than the control material (i.e., new material's life is 10% longer than the control) and PS^E=-10 means the new material will perform 10% worse than the control material.

Second stage of the analysis framework presented in this report is the sustainability analysis. The sustainability analysis of a new material includes three basic components: (1)

Environmental, (2) Economic and (3) Social analyses. At the end of the analysis of each component, a performance score based on sustainability (PS^S) is computed. It is worth noting here that the engineering performance score is used as an input to the analysis for the sustainability performance, in the environmental and economic analysis components. Once the engineering and sustainability performance scores are computed, they are combined to compute an overall performance score. Several example analyses presented in the report showed reasonable predictions of performance scores that indicate the relative performance of various kinds of new and recycled materials used/proposed in the past.

INTRODUCTION

The growing need for increased use of recycled as well as new materials in pavements has emerged due to the continuous decrease in natural resources and increased impact that the current state of practice has on the environment. Many transportation agencies are striving to make their practices and policies more ‘sustainable’. Sustainable development is typically defined as *“…the development that meets the needs of the present without compromising the ability of future generations to meet their own needs…*” (WCED, 1987). Sustainable construction practices have been favored by Federal and State Departments of Transportation (DOTs) as well as industry. Example practices include Warm Mix Asphalt (WMA), reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), crumb rubber (CR) modified asphalt, fiber reinforced concrete, crushed glass reinforced concrete, subgrade stabilization using Lime Kiln Dust (LKD), etc. However, the impacts of using new and recycled materials in pavements - particularly on long-term pavement durability and performance - are often unknown. MDOT does not have a system in place for evaluating any new or recycled materials as it relates to performance. This research resulted in an analysis framework that will help identify methodologies to effectively determine the impacts of new and recycled materials in pavement design and create a system for evaluating those materials.

Green and sustainable strategies are now being incorporated in many applications from foods to building cars and engineering structures (Louis 2010). Sustainability is a long-term approach that can enable environmental protection and process improvements. Thus, the application of sustainable practices for design and construction can enable environmentally responsible construction and effective use of resources. Increasing energy cost and environmental concerns have encouraged the development of using pollution-free, recyclable engineering materials that consume less energy to manufacture. The U.S. Department of Transportation is promoting sustainable practices in order to conserve energy and natural resources, decrease greenhouse gas (GHG) emissions, reduce pollution, enhance the workplace by minimizing hazardous materials and chemicals, and strengthen national interest by encouraging energy independence. As a result, new and recycled materials are increasingly being proposed in pavement applications. It is important that these materials perform as well as or better than the traditional counterparts in order not to compromise the long-term performance and durability of pavements. A comprehensive system for evaluating these “proposed materials” in terms of engineering performance and sustainability is very significant for making appropriate decisions on whether to use them for road construction in Michigan.

LITERATURE REVIEW

The literature review presented in this report is divided into two main categories:

1) Performance-based evaluation of new and recycled materials
2) Sustainability-based evaluation of new and recycled materials

Engineering Performance-Based Evaluation of Pavement Materials

In this section, the results of a literature review on the performance-based evaluation of pavement materials are presented. The first subsection highlights the state-of-the art methods for quantifying the engineering performance of new and recycled materials for use in asphalt (flexible) pavements. The second and third subsections summarize the findings of the literature review for concrete and unbound materials, respectively.

Asphalt Materials

In the area of asphalt pavements, numerous new and recycled materials have been proposed and tried over the last decade. These include Warm Mix Asphalt (WMA), Crumb Rubber Modified Asphalt, polyester fiber, bio-binder, etc. (Wu, Yue et al. 2009; Ozturk, Tascioglu et al. 2010; Fini, Al-Qadi et al. 2012; Kutay and Ozturk 2012). Researchers typically evaluated the engineering characteristics of these materials either through laboratory performance tests or accelerated pavement testing sections. The engineering evaluation of these materials typically included a traditional control asphalt mixture to be used as a benchmark. The following paragraphs describe major studies which included various methods to evaluate the engineering performance of materials such as rubberized asphalt, high amounts of recycled asphalt pavement, etc. The primary goal of presenting this literature is to assist in understanding the methods used by various investigators to evaluate new and recycled materials.

Xiao et al. (2007) investigated the rutting resistance characteristics of the rubberized asphalt mixtures containing Reclaimed Asphalt Pavement (RAP) through a laboratory testing program. The experimental design included the use of two rubber types (ambient and cryogenically produced), four rubber contents, and three crumb rubber sizes. In this study, the Asphalt Pavement Analyzer (APA) test was used for the evaluation of rutting resistance of all mixtures and the Indirect Tensile Strength (ITS) test was used as a measure of stiffness. The results of the experiments indicated that the use of RAP and crumb rubber in Hot Mix Asphalt (HMA) can effectively improve the rutting resistance of these mixes.

Mills-Beale, and You (2010) studied the mechanical properties of asphalt mixtures with Recycled Concrete Aggregates (RCA) for low volume roads. The RCA was substituted for Virgin Aggregates (VA) in a light traffic volume Hot Mix Asphalt (HMA) mixtures at the rate of 25, 35, 50 and 75% by weight of the aggregates. Various laboratory tests were conducted to evaluate the performance of the hybrid VA-RCA HMA. The Asphalt Pavement Analyzer (APA) was used to assess the rutting resistance of the mixture, the Dynamic Modulus ($|E^*|$) test was used as a measure of stiffness, Tensile Strength Ratio (TSR) test was used for moisture susceptibility evaluation, Indirect Tensile Test (IDT) resilient modulus (M_R) and the Construction Energy Index (CEI) were determined to evaluate the field performance suitability or otherwise of the mix. The findings of the study recommended that a certain amount of RCA in HMA is acceptable for low volume roads.

Apeagyei et al. (2011) presented the results of a study that investigated the rutting resistance of plant-produced asphalt concrete mixtures with Reclaimed Asphalt Pavement

(RAP) in the laboratory. A total of nineteen mixtures containing RAP amounts that ranged from 0% to 25% were used. Performance evaluation was conducted using the dynamic modulus (|E*|) test and the Flow Number (FN) test at 54°C to characterize stiffness and rutting resistance, respectively. Statistical analysis the authors presented illustrated that the RAP amount was the most significant factor affecting the rutting resistance. The study showed unexpected effects of RAP on FN. The rutting resistance decreased with increasing RAP percentages. Possible reasons might have been the use of softer asphalt binder in mixtures with higher RAP. It was concluded that more mechanistic studies are needed to characterize the rutting resistance of asphalt mixtures containing RAP.

Vargas-Nordcbeck and Timm (2013) evaluated physical and structural properties for different pavement sections including a Warm Mix Asphalt (WMA), several high RAP mixtures, and Permeable Friction Course (PFC) mixtures constructed at the National Center for Asphalt Technology (NCAT) Test Track. Various supplementary laboratory tests were conducted to evaluate the performance of these pavement sections and the asphalt binders used in the mix design of each pavement section. Asphalt binders were recovered from the plant produced mixtures and characterized using the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) tests to assess the effect of WMA technologies and addition of high RAP percentages on binder properties. Asphalt mixture characterization was conducted by the Confined and Unconfined Dynamic Modulus (|E*|) tests as a measure of stiffness. The rutting resistance of the asphalt mixtures was characterized using the Asphalt Pavement Analyzer (APA), the Flow Number (FN) test, and the Hamburg Wheel Tracking Device. The Hamburg Wheel Tracking Device was also used to evaluate the moisture damage of the mixtures along with the Tensile Strength Ratio (TSR) test. The Four Point

Bending Beam (FPBB) test was used to evaluate the fatigue resistance of the base mixes, and the Indirect Tension Test (IDT) was used to evaluate the thermal cracking resistance of the surface mixtures. The study concluded that the use of WMA technologies did not produce significant changes in mixture properties or performance. The main effect observed was the potential for higher permanent deformation as compared to the control. High RAP mixes were stiffer than the control, which suggests higher susceptibility to cracking, but higher rutting resistance. However, this was not reflected in some rutting tests or the Four Point Bending Beam (FPBB) test. High RAP mixes were also more resistant to moisture damage than the control and WMA mixes.

Apeagyei et al. (2013) investigated the performance of high RAP mixtures. Binders were extracted from mixtures and their dynamic shear moduli (|G*|) were measured. The rutting resistance of the asphalt mixtures was evaluated using the FN (Flow Number) test and the correlation between the |G*| of the extracted binder and FN was determined. The study concluded that the addition of high percentages of RAP to asphalt mixtures currently produced in Virginia has not resulted in excessively stiffened mixtures. The stiffness of high-RAP mixtures are primarily governed by the virgin binder stiffness.

Portland Cement Concrete Materials

In PCC pavements, numerous new/recycled materials were proposed to be used in the past. These included cement kiln dust, gypsum, railway ballast, plastics, and rubber. The laboratory test results showed that the engineering properties of specific secondary and recycled materials were advantageous for highways (Edwards 2003; Brosseaud, Gaudefroy et al. 2008). A clinker-free binder for making sustainable concrete was developed using cement kiln dust (CKD) and Class F fly ash. The CKD-activated fly ash binder developed a compressive strength of approximately 30 MPa after 48 hours of elevated temperature curing. Thermo-gravimetric and X-ray analysis helped determine the mineralogical composition of the developed clinker-free binder. The major contribution to strength development is attributed to the C-A-S-H gel, which was found extensively as a ground mass in the hardened CKD-activated fly ash system. An air-cleaning agent - titanium dioxide (TiO_2) - was used in concrete to make self-cleaning and air-purifying concrete pavements. The objective of the study was to evaluate the environmental and mix design parameters that may affect the effectiveness of the environmental performance of TiO_2 coating. The environmental efficiency of the samples to remove nitrogen oxides from the atmosphere was measured by using a newly developed laboratory setup (Taskiran, Taskiran et al. 1999). A study was conducted to ascertain the properties of low-carbon-content rice husk ash (RHA) and evaluate it as a supplementary cementing material. Specific tests that were conducted include pozzolanic reactivity and microstructure of RHA and other properties of cementitious pastes and mortars. These include flow, initial and final setting time, compressive strength, flexural strength, and split tensile strength. In addition, water absorption, effective porosity, and rapid chloride ion permeability were measured to ascertain the improvements offered by RHA in enhancing durability of cementitious mixes (Dongre, May et al. 2009).

Tangchirapat et al. (2013) studied the fresh and hardened properties of recycled aggregate concrete incorporating fly ash at different fineness levels. Two groups of recycled aggregate concretes were studied and compared with conventional concrete in which virgin aggregates (crushed limestone and local river sand) were used. The first group was prepared using 100% coarse recycled concrete aggregate, and local river sand; and the second group was prepared using 100% coarse and fine recycled concrete aggregates. The experimental program included tests such as the slump loss of fresh concrete, compressive strength testing, the splitting tensile strength, and the modulus of elasticity of all concretes. The results of this study concluded that incorporating fly ash with recycled aggregate concrete mixtures reduces the slump loss to lower than that of mixtures of recycled aggregate concrete without fly ash with increasing fly ash fineness. In addition, it was found that fly ash can be used to increase the compressive strength of recycled aggregate concrete, depending on its fineness and the degree of fly ash replacement. Fly ash with different fineness in recycled aggregate concrete had no significant effect on the splitting tensile strength and the modulus of elasticity of the recycled aggregate concrete.

Saravanakumar and Dhinakaran (2013) explored the strength characteristics of high-volume fly ash-based concrete with recycled aggregate. Virgin aggregates were replaced with recycled aggregates, and cement was replaced with fly ash in different percentages. Percentages of recycled aggregates replacing virgin materials were 25, 50, and 100%. Percentages of fly ash replacing virgin materials were 25, 50, and 100%. Compressive and tensile strength of characteristics of concrete were studied. The experiments were conducted at the ages of 7, 14, 28, and 56 days. They showed that an increase in the percentage of recycled aggregate reduces the compressive and tensile strength irrespective of the age of the concrete. They also observed that addition of fly ash shows a reduction in the strength of concrete. The study concluded that a 50% replacement of cement with fly ash and a 50% replacement of virgin aggregates with recycled aggregates is reasonable.

Moon C. Won (2001) evaluated the material properties of recycled concrete aggregate (RCA) used for reconstruction at a section of IH-10 (in Houston, TX). The pavement was constructed with Continuously Reinforced Concrete Pavement (CRCP) in 1995. The effect of

RCA on paving operations and in-situ concrete properties were investigated. In this project, crushed concrete was used as both coarse and fine aggregates in the new concrete and no virgin aggregates were used in the paving operation. The pavement age was 6 years at the time this study was conducted. Fifteen field cores were sampled and tested. The tests included compressive strength, indirect tensile strength, modulus of elasticity, thermal coefficient of expansion, chloride and sulfate, density, water absorption, permeability, and petrographic analysis (to identify the potential for distress due to chemical reactions in concrete). The study concluded that there is no significant difference in thermal coefficient of expansion and permeability between concrete with virgin aggregates and concrete with recycled aggregates. On the other hand, it was found that there are significant differences in modulus of elasticity, compressive and indirect tensile strength, and water absorption. It was reported that the overall performance of the reconstructed CRCP with RCA has been excellent, with tight crack widths and little spalling.

Unbound Materials

Several studies have emphasized the need to use more recycled and marginal materials in pavement foundations to encourage performance-based specifications. Such an approach needs data on the fundamental material parameters of stiffness. Several tests to characterize materials in the laboratory and field have been proposed to assess the mechanical properties of such materials (Lambert, Fleming et al. 2008). Arulrajah et al. (2011) presented the findings of a laboratory investigation of recycled crushed brick and an assessment of its performance as a pavement subbase material. The experimental program was extensive and included tests such as particle size distribution, modified proctor compaction, particle density, water absorption, California Bearing Ratio (CBR), Los Angeles abrasion loss, pH, organic content, static triaxial, and repeated load triaxial tests. The results presented in this paper indicated that crushed brick may have to be blended with other durable recycled aggregates to improve its durability and to enhance its performance in pavement subbase applications.

Gabr and Cameron (2012) presented a study of the performance and suitability of Recycled Concrete Aggregate (RCA) materials for use as unbound base course. Three South Australian base course products were investigated. The base course products included two RCA materials and a local virgin aggregate (quartzite). The resilient modulus (M_R) and permanent deformation behavior of RCA mixtures were investigated at different levels of moisture contents (90, 80, and 60% of optimum moisture content). In terms of both resilient modulus and accumulation of permanent deformation, the RCA material performed better than the quartzite aggregate.

NCHRP Project 04-31 was conducted to recommend procedures for performance-related testing and selection of recycled Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC) materials for use as aggregates in unbound pavement layers (NCHRP Report 598, Saeed 2008). The scope of the research included evaluating existing aggregate tests known to predict pavement performance for their applicability to RAP and Recycled Concrete Pavement (RCP) and to develop new tests or modify existing tests. It was concluded that the following tests relate to the performance of recycled materials used in unbound pavement layers: Screening tests for sieve analysis and the moisture-density relationship, the Micro-Deval test for toughness, Resilient Modulus (M_R) for stiffness, static triaxial and repeated load at Optimum Moisture Content (OMC) and saturated for shear strength, and the tube suction test for frost susceptibility.

Edil et al. (2012) evaluated the stiffness of RCA and RAP sources used as unbound base course without treatment and to determine the relationship between the Resilient Modulus (M_R) and physical properties (e.g., particle shape, binder type, aggregate mineralogy and contamination) of RCA and RAP through statistical correlations. The M_R of RAP and RCA measured in this study were compared to results from conventional base course. The study concluded that blending recycled materials with natural aggregates result in intermediate modulus between the moduli of the two materials. It was also observed that recycled materials had higher moduli then natural aggregate in this study.

Mengqi Wu (2011) investigated the potential use of high percentages of RAP as base course material without compromising the pavement performance in terms of excessive stiffening and permanent deformation, and permeability. The stiffness of base course material was characterized using the Resilient Modulus (M_R) test. In addition, repeated load triaxial tests were conducted to evaluate the effect of RAP percentages on permanent strain of the base course material. It was found that adding RAP to virgin aggregates increased the M_R of the blend, but decreased the rutting resistance under certain conditions.

Wu et al. (2012) evaluated the field performance of granulated ground blast furnace slag and fly ash stabilized Blended Calcium Sulfate (BCS) base materials as compared to a crushed stone base course under accelerated loading. The basic properties of BCS mixtures were determined through the gradation analysis, specific gravity test, and moisture-density compaction curves with various compaction energy. The strength properties of BCS were captured by unconfined compressive strength (UCS) tests. In addition, two repeated load triaxial tests were used to characterize the resilient and permanent deformation properties of different base materials considered in this study. The study concluded that the stabilized BCS materials evaluated are suitable for use in unbound layers in flexible pavements. It was also noted that when using a fly ash stabilized BCS base under a constantly wet environment caution should be made due to its possible moisture susceptibility problems.

Sustainability-Based Evaluation of Pavement Materials

Construction, rehabilitation, and maintenance of highway pavements require obtaining, processing, transporting, manufacturing, and placing large amounts of construction materials. These procedures use a significant amount of non-renewable materials and energy. The desire to minimize the impact of transportation projects on the environment and maximize the economic and social benefits has increased with the recent developments in the concept of sustainability. The growing concern for sustainable returns from transportation investments has made various agencies to incorporate the concept of sustainability in their vision. Some of the initiatives taken by various DOTS to incorporate concept of sustainability in transportation projects are as follows:

- *California DOT:* Initiated a project to develop a sustainability assessment framework. It recognizes the principle of triple bottom line, which encapsulates social, environmental and economic dimensions of sustainability. Defines various performance measures based on identified various smart mobility principles. (Caltrans 2010; CTC & Associates LLC 2013)
- *Illinois DOT:* Developed a comprehensive sustainability guide and rating system, “Livable and Sustainable Transportation” (I-Last). The tool is a joint effort by American Council of Engineering Companies-Illinois, Illinois DOT and Illinois Road and Transportation Builders Association. (I-LAST 2010)

- *New York DOT:* Applies sustainability practice at every level of a project using an indigenous developed rating system, "Green Leadership in Transportation and Environmental Sustainability" (GreenLITES). The program is aimed to promote sustainable practices within the agency. (NYSDOT 2010).
- *North Carolina DOT:* Developed an accountability framework, which is a set of objectives and performance measures developed in lines with the department's 2040 plan (NDOT 2011).
- *Oregon DOT:* Developing a series of documentation which will explain the ODOT's overall sustainability framework. Volume 1 in the series introduces ODOT's overall sustainability plan (ODOT 2008), Volume 2 focus on internal operations of ODOT (ODOT 2012) and Volume 3 (to be completed) would focus on the framework for management and operation of transportation system.
- *Pennsylvania DOT:* Initiated a "Smart Transportation Program" aimed at improving communities, environment, and economy integrating land use and transportation system (MacDonald et. al. 2011).
- *Texas DOT:* Developed a system called "Sustainability Enhancement Tool" (SET), which focuses on planning level corridor analysis. The tool addresses various sustainability related objectives which are rated through performance measured index for self-assessment of projects (Ramani 2011).
- *Washington DOT:* Produces annual sustainable transportation reports, detailing various sustainability efforts taken by the DOT (WDOT 2011).

Different DOTs define sustainability depending on the agency's need and priorities. Practices of sustainability in transportation systems may exhibit large diversity. Some of the components include (a) transportation and land use coordination such as regional commute trip reduction, (b) life cycle cost analysis, (c) environmental assessment, (d) various other activities such as LED highway lights, (e) bicycle and walkway friendly transportation system, (f) reliable and multi-modal transportation such as high capacity transportation etc. In general the DOTs recognize sustainability as an amalgam of measures that contributes to the following (Zietsman et al. 2011):

a) Development of the community and economical upliftment of the region.
b) Develop a quality environment and minimize impact of transportation investments on environment.
c) Minimal energy and resource consumption.
d) Maintain and provide a safe and aesthetical transportation system.
e) Encourage innovative sustainability approaches in transportation planning
f) Promote health and safety.
g) Efficient land use

Quantifying the design, implementation and performance of these measures are not easy and always felt as a barrier in implementing sustainability practice by DOTs. The scoring tools developed by some DOTs (NYSDOT 2010; I-LAST 2010) have circumvented this problem by adopting a scorecard system. Although these scoring tools are easy to implement, they are not quantified based on scientific measures, and hence cannot be used to compare different alternatives accurately (Tascioglu 2013). These tools essentially lump new or recycled materials under single category and cannot differentiate between different alternatives.

Scientific sustainability design is often based on quantifying environmental, economic and social evaluation which advocates use of life-cycle analysis of an entire system. The sustainability framework typically involve the following fundamental steps (Zietsman et al. 2011, Miller and Bahia 2009, Allen and Shonnard 2012):

Step 1: Defining scope and boundary of the problem

The level of accuracy and detailing is set in this step. As the choices at this stage define the scope and functional unit for future comparison of different alternatives, this step can significantly impact the results.

Step 2: Life-cycle inventory

This step is the most data intensive and time consuming. It involves listing all the input used and output generated from each process throughout the life cycle of the system. The major inputs are energy and raw materials and typical outputs are air borne emissions, water effluents and solid wastes.

Step 3: Life-cycle assessment (LCA)

The effects of the inputs and outputs are grouped into various classifications, which are then quantified using different indices.

Step 4: Evaluation of alternatives

The results are reported and uncertainties and opportunities are systematically evaluated.

The LCA-based methods are much more detailed and specific, and they are more situated when alternative materials need to be compared. A list of rating tools based on both the scorecard and LCA method is shown in Table 1. A comparison of the sustainability rating tools is presented in Table 2, a similar table was developed by Eisenmann (2012). Details of each rating system are given in the following subsections.

Table 1: Partial list of various sustainability based scoring tools for transportation system.

Agency	Year	Scoring tool	Type of Rating system
FHWA	2012	Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) V 1.0	Life-cycle analysis based self-evaluation
University of Washington and CH2M Hill	2011	Greenroads V1.5	Scorecard based third-party certification
University of Wisconsin	2010	BE^{2}ST	Life-cycle analysis based self-evaluation
Illinois DOT	2010	Livable and Sustainability Transportation (I-LAST) Version 1.0	Scorecard based self-evaluation
New York State DOT	2009	Leadership In Transportation and Environmental Sustainability (GreenLITES)	Scorecard based self-evaluation
University of California, Berkeley	2003	PaLATE	Life-cycle analysis based self-evaluation

Table 2: Comparison of several sustainability rating tools.

Categories	INVEST	I-LAST	Greenroads	BE^{2}ST	GreenLITES	PaLATE
Reuse materials	YES(1)	YES	YES	YES	YES	NO
Local material	NO	YES	YES	NO	YES	NO
Recycle materials	YES	YES	YES	YES	YES	NO
LCCA(2)	YES	NO	YES	YES	NO	YES
GHG	NO	NO	NO	YES	NO	YES
Air quality	YES	NO	YES	YES	NO	YES
Solid waste	YES	YES	YES	YES	NO	YES
Energy and Fuel	YES	YES	YES	YES	YES	YES
Water	YES	YES	YES	YES	YES	YES
Ecology	YES	YES	NO	NO	YES	NO
Social	YES	YES	YES	NO	YES	NO
Land use	YES	YES	YES	NO	YES	NO
Noise	YES	YES	YES	YES	YES	NO

Notes: (1) YES = Included in the analysis, NO = not included in the analysis. (2) LCCA is project requirement for certification; however, a lump sum score is gained for it.

Illinois: I-LAST

The guide and the rating system, I-LAST have been developed jointly by the American Council of Engineering Companies-Illinois, Illinois DOT and the Illinois Road and Transportation Builders Association. The main focus has been to keep the tool as simple as possible, preferably in a scorecard form. The scoring tool is essentially a comprehensive list of potential practices which can make highway projects more sustainable. The tool can collect a total of 233 points, on 153 items, under eight categories. The point system is based on scoring each action from 1 to 3, signifying the weightage of innovation, uniqueness and requirement of the action. The categories include planning, design, environmental, water quality, transportation, lighting, materials and innovation. The first six categories are typically good practices for highway projects and do not involve sustainability considerations related to materials. The materials and innovation categories promote recycled materials and new practices that can bring sustainability to projects. The material category has 33 specifications to promote use of local byproducts, recycled and salvaged materials with a maximum total possible score of 39 in the category. The innovation category promotes experimental features which can earn up to only 3 points. In the scoring tool, a total 42 points out of 233 points are dedicated to materials and innovation. Although the tool is comprehensive in enumerating possible practices it lacks scientific backing. Further the scoring card cannot distinctly distinguish the benefits gained using alternate materials and innovations in the project.

New York State DOT: GreenLITES

GreenLITES is an internal self-certification rating system (NYSDOT 2010), developed by NYDOT in 2008 to minimize impacts to the environment and promote sustainability practices at all levels of transportation projects. The program distinguishes projects based on sustainability performance. The projects are evaluated for over 175 possible sustainable practices and can earn up to 288 points in five categories. The categories include sustainable sites, water quality, material and resources, energy and atmosphere and innovation/unlisted. In the scoring tool, a maximum 66 points out of 288 points are dedicated to materials. The material and resources section involves items aimed to promote local materials, reuse of material, recycling of materials and minimization of natural resources and hazardous materials. The rating system can award four levels of certification, namely Certified (15-29 points), Silver (30-44), Gold (45-59 points) and Evergreen (60 points & up), which is based on the sustainable choices made and subsequent cumulative score of a project.

FHWA: INVEST

Infrastructure Voluntary Evaluation Sustainability Tool (INVEST V1.0) is a self-evaluating web-based tool developed by the Federal Highway Administration (FHWA) to evaluate and rate the infrastructure studies and highway projects in terms of sustainability (INVEST 2012). The most recent version of INVEST (Version 1.0) was released in 2012. The entire life cycle of a project can be evaluated over 68 criteria organized into three modules. The three modules include System Planning, Project Development and Operations & Maintenance. Each module can also be evaluated separately, independent of the other.

University of Washington & CH2M HILL: Greenroads

The Greenroads is a voluntary rating system used for highway design and construction, developed jointly by University of Washington & CH2M HILL (Greenroads 2011). It can be applied to both new and rehabilitation highway projects. The rating system has some minimum project requirements (total 11), as a minimum for the project to be considered for certification. Projects are evaluated over 37 voluntary credits (up to 108 points) and each action is scored from 1 to 5 points. An additional 10 points may be scored for project specific defined custom credits, subjected to approval of Greenroads. The rating system can award four levels of certification: Certified (32-42 points), Silver (43-54), Gold (55-63 points) and Evergreen (64 points & up), which is based on the sustainable choices made and subsequent cumulative score of a project.

University of Wisconsin: BE^{2}ST

BE^{2}ST is a self-certification rating system (BE^{2}ST 2010), developed by the University of Wisconsin for rating highway projects. The rating system is based on life cycle analysis and life cycle cost analysis using the Mechanistic Empirical Pavement Design Guide (MEPDG). Projects are evaluated over six main criteria (up to 12 points), scoring each of them equally. The criteria include greenhouse gas emissions, energy use, water consumption, material reuse, life cycle cost, human health and safety. Much of the environmental and economic rating in the tool is performed using LCA and LCCA respectively. Compared to the other existing rating systems, BE^{2}ST is much more equipped in sustainability rating of new and recycled materials.

University of California, Berkeley: PaLATE

PaLATE is an Excel based self-certification rating system, developed by University of California Berkley (Horvath 2003). The rating system is based on life cycle analysis and life cycle cost analysis used to evaluate the environmental and economic benefits of highway projects. The tool requires extensive user inputs about design, initial construction, maintenance, equipment use, etc. Output is categorized into two major sections: cost results and environmental results. Environmental results encompass various environmental impacts: energy consumption, CO_2 emissions, NO_x emissions, PM_{10} emission, SO_2 emission, CO emissions and Leachate information.

DEVELOPMENT OF A FRAMEWORK AND THE NEWPAVE SOFTWARE FOR EVALUATING NEW AND RECYCLED MATERIALS

The general framework developed as part of this project for evaluating new and recycled materials is illustrated in Figure 1. Once a new (or recycled) material is proposed, Stage I of the methodology is the evaluation of its engineering performance. This evaluation is performed based on the type of application, i.e., based on whether the material is proposed to be used in asphalt, concrete, or in unbound layers. The engineering performance evaluation will result in a score (PS^E) based on various criteria defined in a given application, e.g., asphalt layer (see different "Procedures" in Figure 2 through Figure 11).

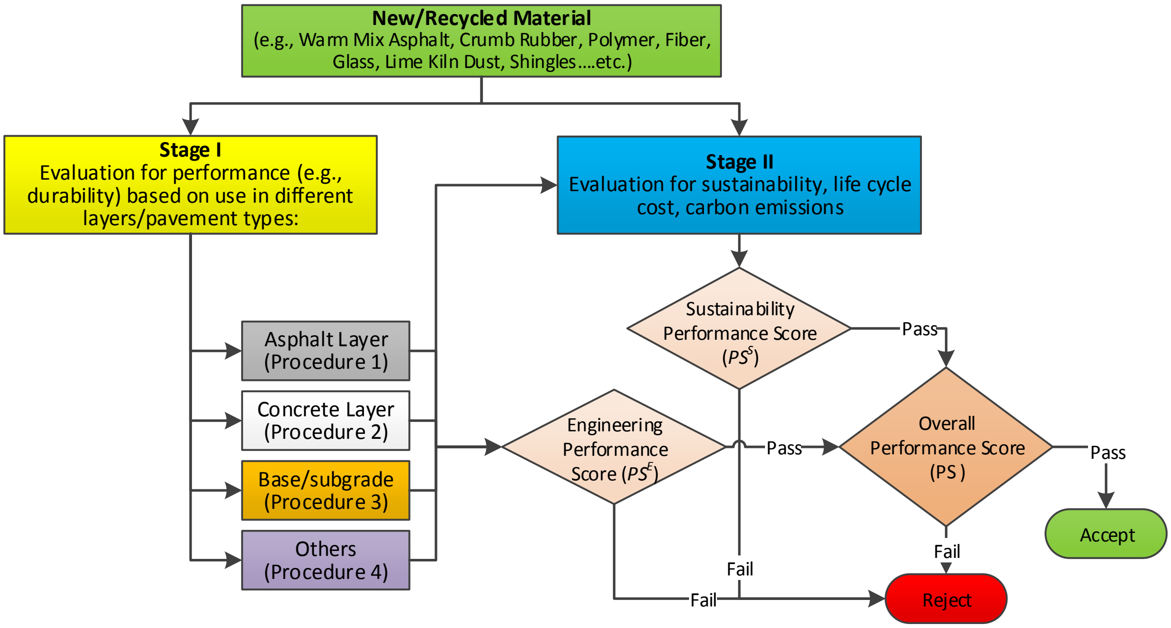


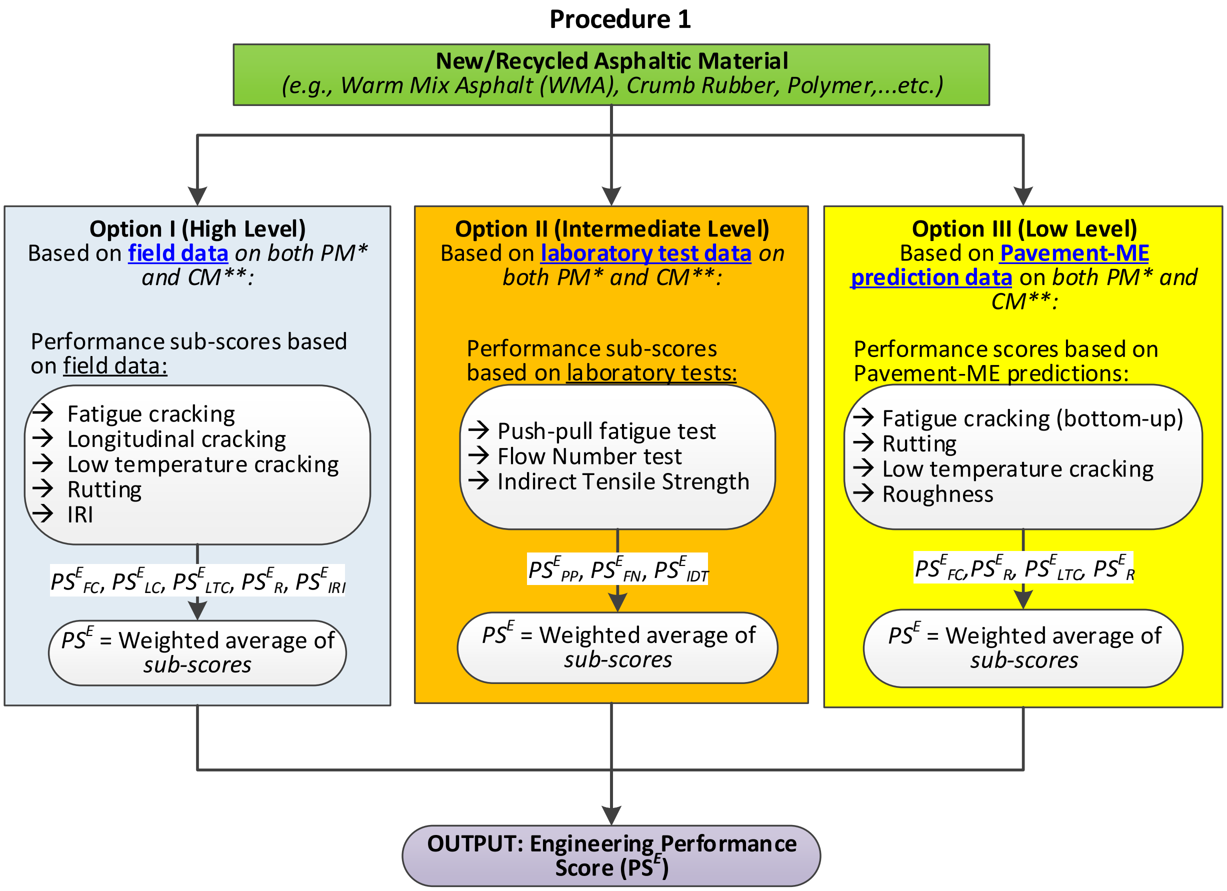
Figure 1: Overall approach for evaluation of a proposed new/recycled material

This score (PS^E) will be combined with the score based on sustainability (i.e., PS^S obtained in Stage II) to obtain an "overall score" (i.e., *PS*), which will be used to accept/reject the trial use of the material in MDOT-administered roads.

The proposed material may fail solely based on performance in Stage I, if it does not meet certain minimum requirements (i.e., if $PS^E <$ a threshold). In addition, there are sub-performance scores for each of the distresses of interest, which also serve as an "initial screening" tool. For example, if the new asphalt mixture type proposed does not meet the minimum performance criteria, a warning is displayed.

Stage I - Procedure 1: Performance Analysis of Asphaltic Layers in Pavements

Figure 2 shows Procedure 1 for the engineering evaluation and scoring of a proposed new or recycled material to be used in asphalt layers. In all options, the Proposed Material (herein called PM) and a Control Material (herein called CM) are tested and evaluated. For example, if a Warm Mix Asphalt (WMA) technology needs to be evaluated, a specific MDOT mix (e.g., 4E3 mixture that uses a PG70-22 asphalt binder) should be produced with this technology. In this particular case, the PM = 4E3-WMA, and the CM = 4E3-HMA, which is an equivalent 'typical' MDOT mix. The relative performance of the PM with respect to CM leads to an engineering performance score. As shown, there are three options for evaluation, with varying degrees of reliability.



Notes:
*PM = Proposed material *(e.g., 4E3&PG70-22 made with WMA)*
**CM = Equivalent 'control' material *(e.g., typical 4E3&PG70-22)*

Figure 2: Illustration of Procedure 1 for evaluation of new/recycled materials for use in asphaltic layers in pavements

Option I (high level)

Option I is the most reliable option because it is directly based on field performance data. Field data can be collected from trial test sections (constructed in Michigan or in other states). Accelerated Pavement Testing (APT) results on the proposed material could be another alternative to field data, provided that the APT conditions (such as environment and load level) simulate the conditions of Michigan. The field data needs to be collected on the proposed material (PM) and an equivalent control material (CM).

Option I Input Variables

Option I provide the opportunity to compare PM and CM over a list of performance data (shown in Table 3) collected from the field. Since, there is no unique practice for data collection and analysis, the procedure and unit of data collected from field may vary from agency to agency. Hence, in the present approach the collected data is first scaled to a single Performance Rating (PR) number before analysis. As the first step, the practical terminal damage value of each input variable should be identified, which is then used to calculate PR value using the following equation:

$$PR = 10\left(\frac{Damage\ Extent}{Terminal\ Damage}\right) \tag{1}$$

where, Damage Extent is the measured distress in field. From the equation it can be seen that, the PR value is scaled from 0 to 10, 0 being the best and 10 being the terminal damaged state (threshold). PR values lower than threshold value are assumed to be passing bear-minimum performance requirement. The software uses these PR values in calculating performance. These PR and engineering performance sub-scores are listed in Table 4.

Table 3: Field distresses and associated performance rating scale for asphalt pavements (for Option I)

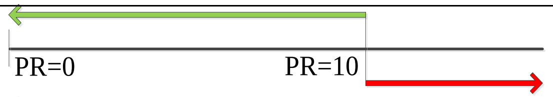
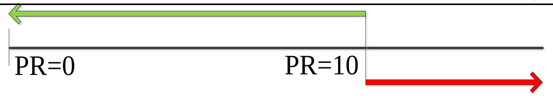
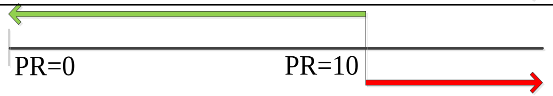
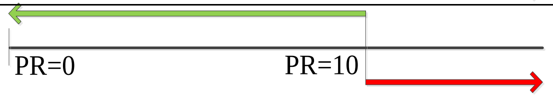
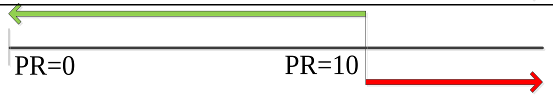
Performance Criteria	Scale
Fatigue Cracking	
Longitudinal Cracking	
Low Temperature Cracking	
Rutting	
IRI	

Table 4: Field distresses and associated engineering performance sub-scores for asphalt pavements (for Option I)

Performance Criteria	Step-1 (Calculate Performance Rating)	Step – 2 (Calculate Engineering Performance Sub-score)	Definitions**
Fatigue Cracking	$PR_{FC}^{PM} = \left(\frac{FC^{PM}}{FC^{TD}}\right)x10$ $PR_{FC}^{CM} = \left(\frac{FC^{CM}}{FC^{TD}}\right)x10$	$PS_{FC}^{E} = \frac{PR_{FC}^{CM} - PR_{FC}^{PM}}{TH}x100$	FC^{PM} , FC^{CM} = Fatigue cracking measured from field for PM and CM, respectively.
Rutting	$PR_{R}^{PM} = \left(\frac{R^{PM}}{R^{TD}}\right)x10$ $PR_{R}^{CM} = \left(\frac{R^{CM}}{R^{TD}}\right)x10$	$PS_{R}^{E} = \frac{PR_{R}^{CM} - PR_{R}^{PM}}{TH}x100$	R^{PM} , R^{CM} = Rutting measured from field for PM and CM, respectively.
Longitudinal Cracking	$PR_{LC}^{PM} = \left(\frac{LC^{PM}}{LC^{TD}}\right)x10$ $PR_{LC}^{CM} = \left(\frac{LC^{CM}}{LC^{TD}}\right)x10$	$PS_{LC}^{E} = \frac{PR_{LC}^{CM} - PR_{LC}^{PM}}{TH}x100$	LC^{PM} , LC^{CM} = Longitudinal cracking measured from field for PM and CM, respectively.
Low Temperature Cracking	$PR_{LTC}^{PM} = \left(\frac{LTC^{PM}}{LTC^{TD}}\right)x10$ $PR_{LTC}^{CM} = \left(\frac{LTC^{CM}}{LTC^{TD}}\right)x10$	$PS_{LTC}^{E} = \frac{PR_{LTC}^{CM} - PR_{LTC}^{PM}}{TH}x100$	LTC^{PM} , LTC^{CM} = Low temperature cracking measured from field for PM and CM, respectively.
Roughness (IRI)	$PR_{IRI}^{PM} = \left(\frac{IRI^{PM}}{IRI^{TD}}\right)x10$ $PR_{IRI}^{CM} = \left(\frac{IRI^{CM}}{IRI^{TD}}\right)x10$	$PS_{IRI}^{E} = \frac{PR_{IRI}^{CM} - PR_{IRI}^{PM}}{TH}x100$	IRI^{PM} , IRI^{CM} = Roughness measured from field for PM and CM, respectively.

**Note: PM = Proposed (new/recycled) Material, CM = Control Material, TH= is terminal damage threshold value which equal to 10.

Performance Score Computation (for Option I)

In option I the final performance score PS^E is a relative score which indicates field performance of the mix obtained using New/Recycled material as compared to the control mix. All the performance categories, for which data are collected, can be used in calculating PS^E. PS^E value is calculated using the following equation:

$$PS^E = 100\sum \delta_i w_i \left(\frac{PR_i^{CM} - PR_i^{PM}}{TH} \right) \quad (2)$$

where, i is performance criteria (i.e. fatigue cracking, longitudinal cracking etc), δ_i is Kronecker delta which takes value 0 or 1 depending on weather the i^{th} criteria is used in the score, w_i is weight given to the i^{th} performance criteria and TH is terminal damage threshold value which is equal to 10. The PR_i^{PM} is the performance rating value of the mix obtained for the Proposed (New/Recycled) Material and PR_i^{CM} is the performance rating value of the mix obtained for the Control Material. It should be noted that a positive PS^E value indicates a better performing New/Recycled mix as compared to the control mix. For example, $PS^E = 10$ means that the Proposed Material is 10% better than the Control Material, whereas $PS^E = -10$ means the Proposed Material is 10% worse than the Control Material.

Option II (intermediate level)

In Option II, the material is evaluated using state-of-the-art laboratory tests for each of the major distresses causing pavement failure. The proposer is asked to provide the laboratory data specified in Table 5, which are used as inputs in the NewPave software developed in this research. The NewPave software will compute an overall (weighted) average engineering performance score (PS^E), by giving different weights to different tests, based on the importance of corresponding distress in a given pavement application. For example, rutting (or plastic deformation/shearing) might be a concern for urban roads with many intersections. In this case, more weight could be given to flow number performance sub score (PS_{FN}^E in Table 5). As shown in Table 5, the laboratory tests used for characterizing asphalt materials are the Push-Pull Fatigue (PP) test, the Flow Number (FN) test for rutting/plastic deformation evaluation, and the Indirect Tensile Strength (IDT) test for low temperature cracking. The asphalt mixtures used in this study were collected from different locations covering the State of Michigan. As explained later, the mean value of the test results were used as a reference in calculating performance score.

Table 5: Laboratory tests and associated engineering performance sub-scores for asphalt pavements

Laboratory test	Distress	Engineering Performance Sub-score	Definitions**
Push-Pull Fatigue (PPF)	Fatigue Cracking	$PS_{FC}^{E} = \frac{\log\left(N_f^{PM}\right) - \log\left(N_f^{CM}\right)}{\log\left(N_f^{MDOT}\right)} x100$	N_f^{PM}, N_f^{CM} = No. of cycles to failure for PM and CM respectively (f=10Hz, T=20^{o}C).
Flow Number (Permanent micro-strain@ 1500 cycles)	Rutting (Plastic Deformation)	$PS_{FN}^{E} = \frac{\log\left(PD^{CM}\right) - \log\left(PD^{PM}\right)}{\log\left(PD^{MDOT}\right)} x100$	PD^{PM} PD^{CM} = Plastic deformation, micro-strain@ 1500 cycles for PM and CM, respectively (T=45^{o}C, 120psi deviator stress, unconfined test).
Indirect Tensile Strength (IDT)	Low Temperature Cracking	$PS_{IDT}^{E} = \frac{IDT^{PM} - IDT^{CM}}{IDT^{MDOT}} x100$	ITS^{PM}, ITS^{CM} = Indirect Tensile Strength for PM and CM, respectively (T=-10^{o}C).

**Note: PM = Proposed (new/recycled) Material, CM = Control Material, N_f^{MDOT}, FN^{MDOT}, IDT^{MDOT} are the laboratory obtained mean values for MDOT mixes.

Push-Pull Fatigue Test

Several tests exist for evaluating the fatigue life of an asphalt mixture. In this study, the cyclic push-pull (tension-compression) fatigue test (Kutay et al. 2008) was used for this purpose due to several advantages. First, the sample can be prepared using a gyratory compactor. Second, the testing equipment is relatively inexpensive. Third, since the stress is uniaxial, fundamental theories such as the Viscoelastic Continuum Damage Theory (VECD) can be applied to analyze the data. The VECD analysis provides fundamental fatigue properties of asphalt mixtures and can be used to simulate the fatigue performance of the material under any temperature, frequency, or strain level.

Several loose asphalt mixtures were collected from different paving jobs as part of a previous comprehensive research effort (Kutay and Jamrah 2013, MDOT Project RC 1593) to characterize 65 asphalt mixtures collected from locations covering the State of Michigan. In this study, a total of 16 different asphalt mixtures were characterized for fatigue life to serve as guidelines and thresholds for inputs in the developed NewPave software. Table 6 provides volumetric information and the corresponding layer of each asphalt mixture characterized in this study. Test samples were prepared in accordance with AASHTO PP60 "Preparation of Cylindrical Performance Test Specimens Using the SuperPave Gyratory Compactor (SGC)" to a height of 170 mm and then cut and cored to cylindrical specimens of 100 mm diameter and 150 mm height. In addition, the air void level of the tested specimens was within the 7.0±0.5%. Two replicates of each asphalt mixture were prepared and tested using a servo-hydraulic Material Testing System (MTS) unit in a strain controlled loading mode at 21°C and 5 Hz frequency. Three equally spaced Linear Variable Displacement Transducers (LVDTs) were mounted on the sides of each specimen, and the strain level at the actuator strain gauge was controlled such that the initial LVDT strain on the specimen was 300 microstrains for each mixture. Then, the viscoelastic continuum damage (VECD) analysis methodology described in Kutay et al. (2009) was applied on the collected data and the fatigue life (N_f) was predicted at a temperature of 20°C, a frequency of 10 Hz, and a microstrain level of 300. Figure 3 shows the VECD-simulated number of cycles to failure (N_f) for the asphalt mixtures tested, and is grouped based on the corresponding MDOT mix type.

Table 6: Volumetric information and corresponding layer of each asphalt mixture characterized for push-pull fatigue in this study.

Sample ID	MDOT mix type	Layer	PG	V_a (%)	V_{be} (%)	Passing #200	Cumulative Retained		
							#4	#3/8	# 3/4
2A	3E30	Base	64-22	7.38	10.45	5.0	25.0	10.7	0.0
18A	3E10	Base	58-22	7.37	10.67	5.2	24.0	11.1	0.0
21	5E10	Top	64-28	7.39	11.91	5.4	15.6	0.8	0.0
24B	5E10	Top	70-28	6.84	11.99	5.6	11.0	2.2	0.0
26C	3E3	Base	58-28	7.53	10.21	4.5	17.4	5.4	0.0
29A	5E3	Top	64-28	7.57	11.31	5.4	17.6	2.1	0.0
32A	5E3	Top	70-28	6.92	11.36	5.4	17.6	2.1	0.0
48	5E1	Top	64-28	7.24	11.62	6.1	16.4	0.3	0.0
65	5E3	Top	58-34	7.20	11.71	4.8	22.2	2.6	0.0
80	4E1	Leveling/Top	58-34	7.15	10.84	5.6	20.6	8.3	0.0
81	5E1	Top	58-34	8.03	11.61	5.8	22.2	2.6	0.0
105	4E10	Leveling/Top	70-22	6.84	10.90	5.5	25.3	11.0	0.0
202	5E10	Top	64-22	7.57	11.75	6.0	15.6	0.3	0.0
203	4E30	Leveling/Top	70-22	6.44	10.59	5.5	34.8	9.3	0.0
205	2E3	Base	58-28	6.74	9.84	4.4	12.3	3.8	10.0
206	5E1	Top	64-22	7.77	11.62	6.4	21.7	0.3	0.0

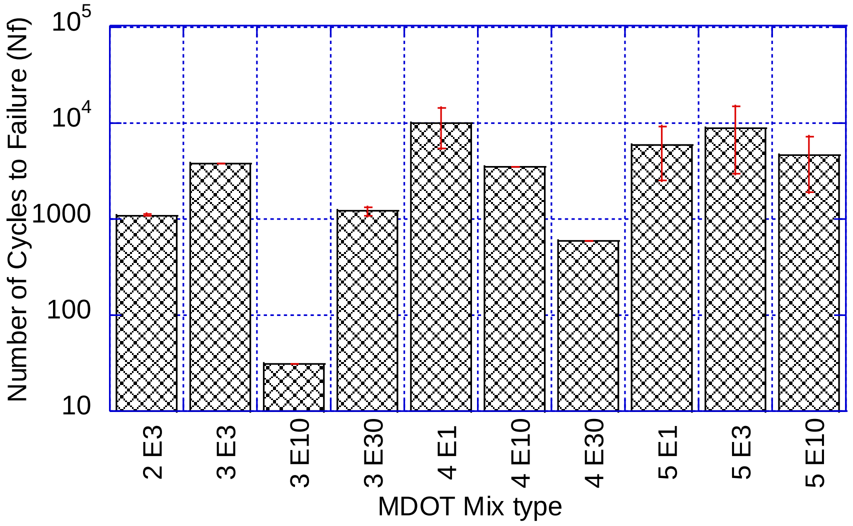


Figure 3: Number of cycles to Failure (N_f) for the asphalt mixtures tested, grouped based on the corresponding MDOT mix type. VECD simulation at 20°C, 10 Hz, and 300 micro-strain.

Flow Number Test

The flow number test was used in this study as a measure of the rutting/plastic deformation potential of asphalt mixtures. Several researchers reported the successful application of the flow number test on asphalt mixtures to characterize the rutting potential of conventional, as well as new asphalt mixtures (Apeagyei et al. 2011, Vargas-Nordbeck and Timm 2013, and Apeagyei et al. 2013). The flow number test is a dynamic creep test in which a haversine type of loading is applied on the test specimen with rest periods between loadings. The curve of accumulated strain versus the number of load cycles is the main output of the flow number test. The curve includes primary, secondary, and tertiary zones. Witczak et al. (2007) defined the flow number as the number of cycles that correspond to the minimum slope of the tertiary deformation.

The flow number test was conducted on 21 asphalt mixtures collected from various paving jobs in the State of Michigan (Kutay and Jamrah 2013, MDOT Project RC 1593) to serve as guidelines and thresholds for inputs in the developed software. Table 7 provides volumetric information and the corresponding layer of each asphalt mixture characterized in this study. Similar to the push-pull fatigue test, test samples were prepared in accordance with AASHTO PP60 “Preparation of Cylindrical Performance Test Specimens Using the SuperPave Gyratory Compactor (SGC)” to a height of 170 mm and then cut and cored to cylindrical specimens of 100 mm diameter and 150 mm height. In addition, the air void level of the tested specimens was within the 7.0±0.5%. Two replicates of each asphalt mixture were prepared and tested using an Asphalt Mixture Performance Testes (AMPT) machine. Based on the recommendations of NCHRP Project 9-19 (Witczak et al. 2007), the flow number tests of all mixtures characterized in this study were conducted at a test temperature of 46°C, with confining pressure (σ_3) of 5 psi, deviatoric stress ($\Delta\sigma_d$) of 120 psi, and the contact stress ($\sigma_{contact}$) was set to 4.35 psi.

Table 7: Volumetric information and corresponding layer of each asphalt mixture characterized for flow number in this study

Sample ID	MDOT mix type	Layer	PG	V_a (%)	V_{be} (%)	Passing #200	Cumulative Retained		
							#4	#3/8	# 3/4
4	4E30	Leveling/Top	70-28	6.95	10.71	4.9	15.4	10.2	0.0
18B	3E10	Base	58-22	7.00	10.09	4.4	18.5	4.5	1.9
20C	4E10	Leveling/Top	64-28	7.53	10.86	4.6	15.1	4.6	0.0
26A	3E3	Base	58-22	7.06	10.71	5.2	25.8	9.7	0.0
28A	4E3	Leveling/Top	64-28	6.70	10.44	5.4	18.1	9.3	0.0
31A	4E3	Leveling/Top	70-28	7.49	10.85	4.7	15.8	6.1	0.0
31B	4E3	Leveling/Top	70-28	7.53	10.31	5.4	18.1	9.3	0.0
49A	GGSP	Leveling/Top	70-28	7.03	13.17	8.2	43.4	24.6	0.0
51B	LVSP	Leveling/Top	58-28	7.44	10.76	5.2	12.4	7.1	0.0
62	3E3	Base	58-28	6.70	10.75	3.5	19.2	10.4	0.0
67	4E3	Leveling/Top	64-34	7.21	10.99	5.0	19.5	11.6	0.0
85	4E1	Leveling/Top	64-34	7.47	11.22	5.4	18.0	9.3	0.0
102	4E10	Leveling/Top	64-22	7.80	10.53	5.6	23.5	9.9	0.0
103	5E10	Top	64-22	7.22	11.66	6.0	24.0	0.1	0.0
108	4E3	Leveling/Top	64-22	7.50	10.65	5.7	22.2	11.4	0.0
112	5E3	Top	70-22	7.45	11.94	6.1	24.1	0.1	0.0
127	LVSP	Leveling/Top	58-22	7.50	10.82	5.6	7.6	5.7	0.0
200	3E10	Base	58-28	7.25	10.24	5.1	17.6	6.3	0.1
204	5E30	Top	70-22	6.86	11.42	6.1	23.3	0.3	0.0
205	2E3	Base	58-28	6.74	9.84	4.4	12.3	3.8	10.0
207	5E1	Top	64-22	7.60	11.58	5.3	12.3	1.8	0.0

Some of the mixtures did not exhibit any tertiary flow within the 10,000 recommended cycle count, and therefore the parameter used for quantifying the rutting/plastic deformation potential of the asphalt mixtures investigated in this study was the plastic micro-strain ($\mu\varepsilon_p$) or permanent deformation corresponding to cycle number 1,500. In addition, two test replicates were used to generate the data of the rutting potential of each mixture. Tests were conducted in accordance with AASHTO TP79 "Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)". Figure 4 shows the plastic micro-strain at cycle 1,500 developed in the asphalt mixtures investigated, and is grouped based on the corresponding MDOT mix type.

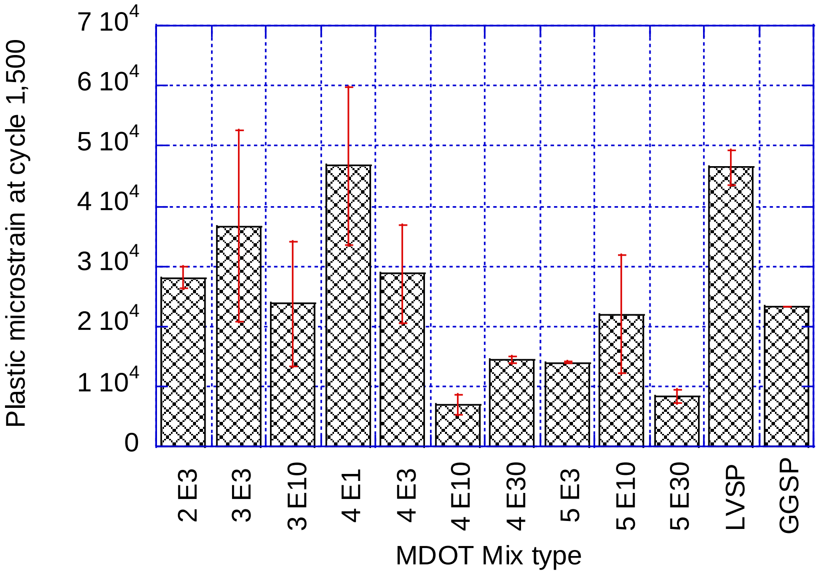


Figure 4: Plastic microstrain at cycle 1,500 developed in the asphalt mixtures investigated; grouped based on the corresponding MDOT mix type.

Indirect Tensile Strength Test

The low temperature Indirect Tensile (IDT) strength test is a measure of an asphalt mixtures resistance to thermal cracking and is currently the most widely used thermal cracking mixture characterization method. The IDT strength test is conducted by applying a strain controlled loading mode along the vertical diametrical axis of a cylindrical specimen until failure. The stress level reached at failure corresponds to the low temperature IDT strength and is directly related to the expected thermal cracking pavement performance in the field.

In a previous MDOT project, the IDT strength test was conducted on 65 asphalt mixtures collected from various paving jobs in the State of Michigan (Kutay and Jamrah 2013). This data served as guidelines and thresholds for inputs in the developed software. Similar to the push-pull fatigue test, test samples were prepared in accordance with AASHTO PP60 “Preparation of Cylindrical Performance Test Specimens Using the SuperPave Gyratory Compactor (SGC)”. The gyratory compacted specimens are then cut to a height of 38 mm and diameter of 150 mm. In addition, the air void level of the tested specimens was controlled and maintained within the 7.0±0.5% range. Three replicates of each asphalt mixture were prepared and tested using an Indirect Tensile Test System which consists of an axial loading device, environmental chamber, and a control and data acquisition system. Tests were conducted in accordance with AASHTO T322 “Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device”. The ITS tests were conducted at a test temperature of -10°C by applying a load to the specimen inside a loading frame at a rate of 12.5 mm of ram vertical movement per minute. While the load is being applied on the material, the vertical and horizontal deformations are monitored and recorded using two LVDTs on each specimen face. In addition, the loading magnitude is recorded as well. Details and volumetric information of each asphalt mixture investigated are presented elsewhere (Kutay and Jamrah 2013, MDOT Project RC 1593) and will not be shown here for brevity.

Figure 5 shows the IDT strengths of the asphalt mixtures investigated, grouped based on the corresponding MDOT mix type.

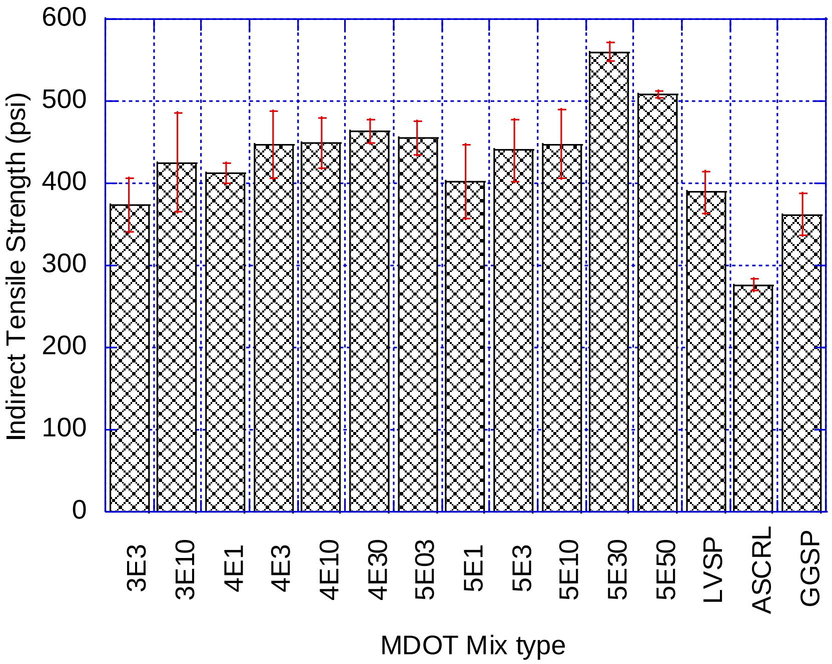


Figure 5: IDT strengths of asphalt mixtures investigated; grouped based on the corresponding MDOT mix type.

Consideration of Statistical Variability in Option II Input Parameters

The parameters obtained from the laboratory tests may show variability, which can be because of sample-to-sample variations or other reasons. In order to account for statistical variability, a reliability-based performance evaluation approach is proposed. As explained earlier, in the first step, the practical performance value of each input variable for a typical MDOT mix type were obtained in the laboratory. The proposed software uses these values in calculating performance. The option requires laboratory test data on both PM and CM. These tests and engineering performance sub-scores are as listed in Table 5. To obtain these scores, a normal distribution is assumed for each input variable, using the laboratory obtained mean and standard deviation. PS^E value in Option II is defined as the mean of the normalized difference between the two distributions, calculated using equation

$$f\left(\mu_i^{PS}, \sigma_i^{PS}\right) = \left(\frac{f\left(\mu_i^{PM}, \sigma_i^{PM}\right) - f\left(\mu_i^{CM}, \sigma_i^{CM}\right)}{\mu_i^{MDOT}}\right) 100 \tag{3}$$

where, f is normal distribution, i is performance criteria (i.e. push-pull, plastic strain obtained from flow number test and indirect tensile strength), μ^{PM} and μ^{CM} are laboratory obtained mean values for PM and CM; σ^{PM} and σ^{CM} are laboratory obtained standard deviation values for PM and CM; μ^{PS} and σ^{PS} are mean and standard deviation of the performance score distribution, μ^{MDOT} is the laboratory obtained mean values for MDOT mixes. Assuming that the laboratory test data $f(\mu^{PM}, \sigma^{PM})$ and $f(\mu^{CM}, \sigma^{CM})$ as uncorrelated and normally distributed, it can be shown that $f(\mu^{PS}, \sigma^{PS})$ is also normally distributed with mean and standard deviation as follows:

$$\mu^{PS} = \left(\frac{\mu^{PM} - \mu^{CM}}{\mu^{MDOT}}\right) 100 \qquad (4)$$

$$\sigma^{PS} = \frac{\sqrt{(\sigma^{PM})^2 + \left(\sigma^{CM}\right)^2}}{\mu^{MDOT}} 100 \qquad (5)$$

Figure 6 illustrates the concept of the performance evaluation in Option II. The distributions provide information about the reliability level of the performance score. To determine the reliability, the area under the curve is obtained. Thus, the reliability may be expressed as:

$$R = P(f(\mu^{PS}, \sigma^{PS}) > 0) \qquad (6)$$

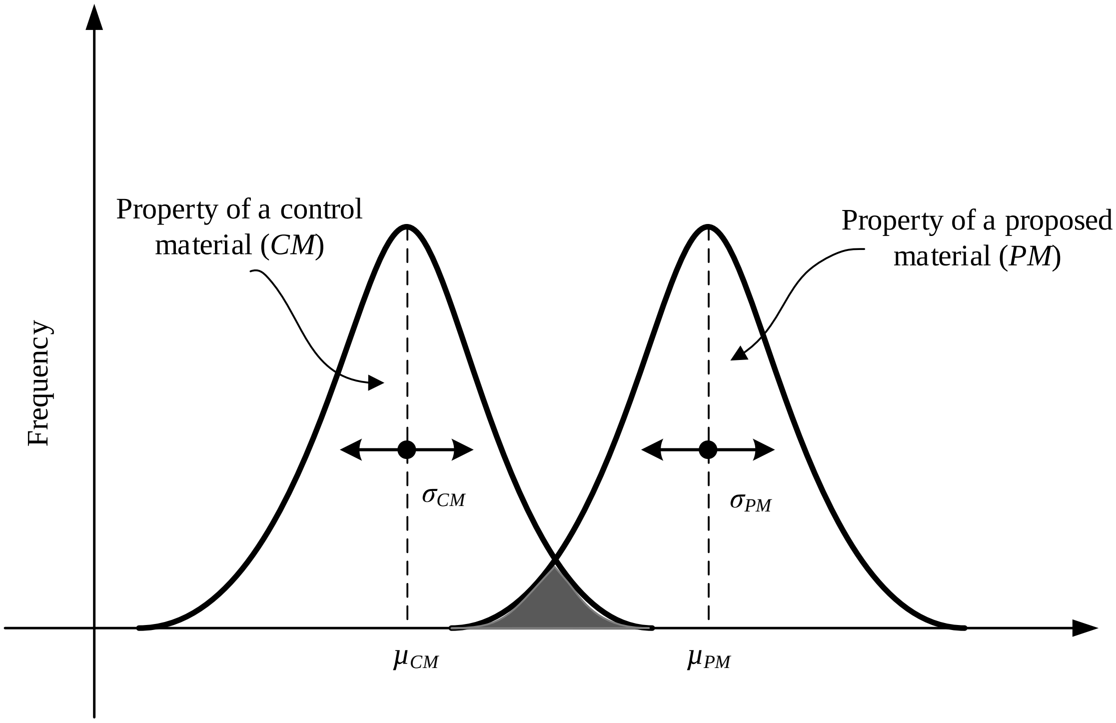


Figure 6: Illustration of reliability concept used for evaluation of new/recycled materials in Procedure-1, Option-2.

Performance Score Computation (for Option II)

Similar to Option I, the performance score in Option II PS^E is also a relative score which indicates laboratory performance of a mix obtained using a New/Recycled material as compared to the control mix. All the performance categories, for which data is collected, can be used to develop an overall performance distribution $PS^E(\mu, \sigma)$ using equation

$$PS^E(\mu^{PS}, \sigma^{PS}) = 100 \sum \delta_i w_i \left(\frac{f(\mu_i^{PM}, \sigma_i^{PM}) - f(\mu_i^{CM}, \sigma_i^{CM})}{\mu_i^{MDOT}} \right) \quad (7)$$

where, i is the performance criteria (i.e. push-pull, flow number and indirect tensile strength), δ_i is the Kronecker delta, which takes a value of 0 or 1 depending on weather the i^{th} criteria is used in the score, and w_i is weight given to the i^{th} performance criteria. By default the weights in the software are assumed to be 1. It should be noted that a positive PS^E value indicates a better performing New/Recycled mix compared to the control mix. Assuming that the laboratory test data $f(\mu^{PM}, \sigma^{PM})$ and $f(\mu^{CM}, \sigma^{CM})$ is uncorrelated and normally distributed, it can be shown that $PS^{E}(\mu, \sigma)$ is also normally distributed. PS^{E} value in Option II is defined as the mean of the distribution $PS^{E}(\mu^{PS}, \sigma^{PS})$ and reliability is defined as the probability $PS^{E}(\mu^{PS}, \sigma^{PS}) > 0$.

Option III (low level)

In this option, the material is evaluated based on its performance predicted using the Pavement ME Design software. Using the Pavement ME Design software, the fatigue cracking (bottom-up), rutting, low temperature cracking, and roughness will be predicted for both PM and CM. The |E*| master curve, D(t) and IDT strength of the asphalt mixture, and |G*| master curve of the asphalt binder will be measured (by the proposer) for both PM and CM and input to Pavement ME Design software as Level 1 material inputs. It should be noted that a proposed material will be evaluated at the mixture level. Even though the proposed material could be a binder additive or some kind of aggregate, the actual asphalt mixture made from this material will be tested and evaluated. This is important because testing just the binder or just the aggregate can be misleading. The compatibility between aggregates and binder as well as the overall aggregate skeleton after compaction is much more important as far as the long-term performance is concerned.

Option III Input Variables and Performance Score Computation

Level 1 Pavement ME Design software distress outputs for both PM and CM are used as inputs in the NewPave software. It should be noted that the analysis using the Pavement ME Design software would involve two major inputs:

(1) Climate condition: Climate file for a Michigan region would be used.

(2) Material properties: Level 1 inputs, |E*| master curve, D(t) and IDT strength of the asphalt mixture, and |G*| master curve of the asphalt binder will be measured (by the proposer) for both PM and CM.

Once the distresses are predicted for both PM and CM, the performance sub-scores are computed as percent improvement in performance with respect to the distress values (computed by the Pavement ME Design software) for MDOT mixes:

$$PS_i^E = \left(\frac{Distress_i^{CM} - Distress_i^{PM}}{Distress_i^{MDOT}} \right) x100 \tag{8}$$

where, $Distress_i^{PM}$ and $Distress_i^{CM}$ are the Level 1 Pavement ME Design software distress outputs for distress type i (i.e. fatigue cracking, rutting, low temperature cracking and roughness) for PM and CM; $Distress_i^{MDOT}$ is the mean MEPDG distress values for MDOT mixes. These engineering performance sub-scores are listed in Table 8. Then these performance sub-scores will be used to calculate the overall engineering performance score (PS^E) based on a weighted average formulation

$$PS^E = 100 \sum \delta_i w_i \left(\frac{Distress_i^{CM} - Distress_i^{PM}}{Distress_i^{MDOT}} \right) \tag{9}$$

where, $Distress_i^{PM}$ and $Distress_i^{CM}$ are the Level 1 Pavement ME Design software distress outputs for distress type i (i.e. fatigue cracking, rutting, low temperature cracking and roughness) for PM and CM; and $Distress_i^{MDOT}$ is the mean MEPDG distress values for MDOT mixes , δ_i is the Kronecker delta, which takes a value of 0 or 1 depending on weather the i^{th} distress is used in the score, w_i is the weight given to the i^{th} performance criteria.

Table 8: The distresses predicted by the Pavement ME Design software and associated engineering performance sub-scores for asphalt pavements

Predicted Distress	Engineering Performance Sub-score	Definitions**
Bottom-up Fatigue Cracking	$PS_{FC}^{E} = \frac{FC^{PM} - FC^{CM}}{FC^{MDOT}} x100$	FC^{PM} , FC^{CM} = Percent fatigue cracking (bottom-up) at the end of the design period for PM and CM, respectively.
Rutting	$PS_{R}^{E} = \frac{R^{PM} - R^{CM}}{R^{MDOT}} x100$	R^{PM} , R^{CM} = Rutting at the end of the design period for PM and CM, respectively.
Low Temperature Cracking	$PS_{LC}^{E} = \frac{LC^{PM} - LC^{CM}}{LC^{MDOT}} x100$	LC^{PM} , LC^{CM} = Percent low temperature cracking at the end of the design period for PM and CM, respectively.
Roughness (IRI)	$PS_{IRI}^{E} = \frac{IRI^{PM} - IRI^{CM}}{IRI^{MDOT}} x100$	IRI^{PM} , IRI^{CM} = Roughness at the end of the design period for PM and CM, respectively.
**Note: PM = Proposed (new/recycled) Material, CM = Control Material, FC^{MDOT} (Fatigue Cracking) , R^{MDOT} (Rutting), LC^{MDOT} (Low Temperature Cracking) and IRI^{MDOT} (International Roughness Index) are the mean MEPDG distress values for MDOT mixes.		

It should be noted that FC^{MDOT} , R^{MDOT}, LC^{MDOT} *and* IRI^{MDOT} are the mean MEPDG distress values for MDOT mixes.

Pavement ME Design Software Runs to Develop Limiting Distresses for Michigan Mixtures

In order to develop reference and limiting values for performance parameters obtained from the Pavement ME Design software, several asphalt mixtures commonly used in the State of Michigan were analyzed. The analyses were conducted using a Pavement ME Design software Level 1 analysis. The pavement cross section considered in the analyses, as well as the required inputs for each layer, are shown in Figure 7. The total number of mixtures investigated was 44 asphalt mixtures corresponding to a wide range of MDOT mix types and regions. The volumetric information of each asphalt mixture is presented elsewhere

(Kutay and Jamrah 2013, MDOT Project RC 1593) and is not shown here for brevity. However, the following table shows the number of unique mixtures analyzed of each MDOT mix type.

Cross-section

Required inputs for each layer

AADT: 5000

Default asphalt concrete layer:
1. Thickness: 4 inches.
2. Dynamic modulus: Level 1 input.
3. Asphalt binder: Level 1 – SuperPave.
4. IDT Strength.
5. D(t)

Non-stabilized Base: A-1-a material:
1. Thickness: 6 inches.
2. Poisson’s ratio: 0.4
3. Resilient modulus: 20,000 psi.

Subgrade: A-6 material:
1. Thickness: semi-infinite.
2. Poisson’s ratio: 0.4
3. Resilient modulus: 13,500 psi.

Figure 7: Pavement cross section considered in the Pavement ME analysis and required inputs for each layer.

Table 9: Number of unique asphalt mixtures corresponding to each MDOT mix type investigated.

MDOT mix type	Number of corresponding mixtures	MDOT mix type	Number of corresponding mixtures
5 E03	1	4 E30	2
5 E1	5	3 E3	3
5 E3	6	3 E10	2
5 E10	4	3 E30	1
5 E30	1	2 E3	1
4 E1	4	GGSP	1
4 E3	6	LVSP	4
4 E10	3		
		Total	44

Figure 8 shows distress predictions for typical MDOT mixtures analyzed using Pavement ME Design software. As shown in the figure, variability is observed in the performance. Therefore, multiple replicates for each input are required by the NewPave software.

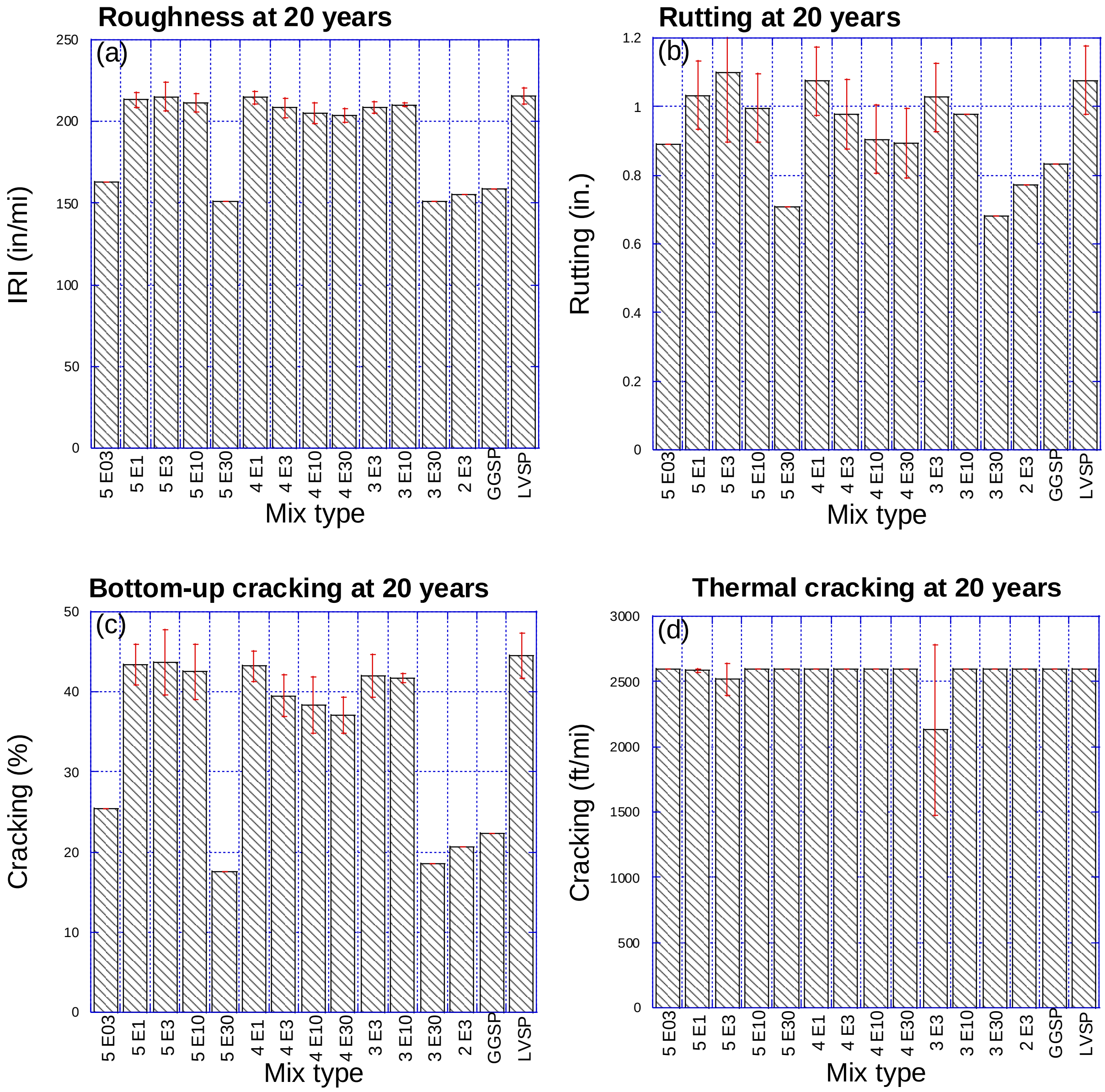


Figure 8: Performance prediction results obtained from Pavement ME Design software for typical MDOT mixtures: (a) Roughness, (b) Rutting, (c) Bottom-up fatigue cracking, (d) Thermal cracking

Stage I - Procedure 2: Performance Analysis of Portland Cement Concrete Layers in Pavements

As shown in Figure 9, Procedure 2 consists of two options. Option I and Option II in Procedure 2 are very similar to Option I and Option III in Procedure 1 described for asphalt mixtures. However, the differences are in the engineering properties for concrete materials and the performance measures for rigid pavement systems (for options I and II). For example, the distresses that are determinant of performance for concrete materials include cracking, joint faulting, and IRI. Equations for the performance sub-scores for concrete are not presented for brevity; however, they are very similar to those presented for asphalt (see Equation 2). Similar to Option I, in Option II, the relative performance of the PM with respect to CM will lead to an engineering performance score.

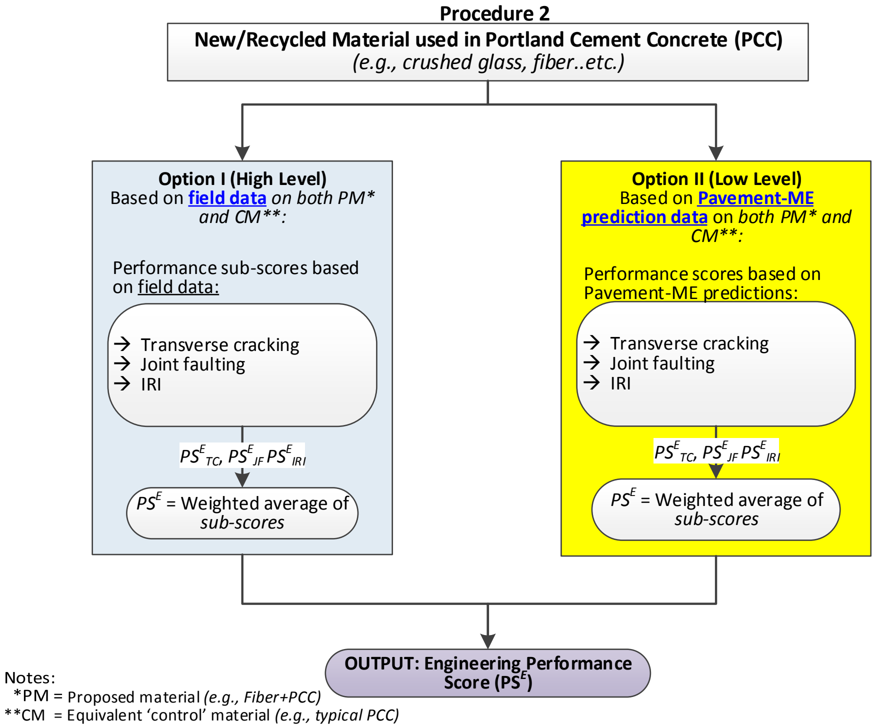


Figure 9: Illustration of Procedure 2 for evaluation of new/recycled materials for use in Portland cement concrete layer

Option I (high level):

In this option, the field data needs to be collected on the proposed material (PM) and an equivalent control material (CM). As the first step, the collected field data is scaled to a single Performance Rating (PR) number before analysis, using the same procedure used in Procedure 1. These PR and engineering performance sub-scores are listed in Table 10. The NewPave software uses these PR values in calculating PS^E using the same equation used in Procedure 1, Option 1 (Equation 2).

Table 10: Field distresses and associated engineering performance sub-scores for concrete pavements (for Option I)

Predicted Distress	Performance Rating	Engineering Performance Sub-score	Definitions**
Transverse Cracking	$PR_{TC}^{PM} = \left(\frac{TC^{PM}}{TC^{TD}}\right)x10$ $PR_{TC}^{CM} = \left(\frac{TC^{CM}}{TC^{TD}}\right)x10$	$PS_{TC}^{E} = \frac{PR_{TC}^{CM} - PR_{TC}^{PM}}{TH}x100$	TC^{PM}, TC^{CM} = Transverse cracking measured from the field for PM and CM, respectively.
Joint Faulting	$PR_{JF}^{PM} = \left(\frac{JF^{PM}}{JF^{TD}}\right)x10$ $PR_{JF}^{CM} = \left(\frac{LC^{CM}}{JF^{TD}}\right)x10$	$PS_{JF}^{E} = \frac{PR_{JF}^{CM} - PR_{JF}^{PM}}{TH}x100$	JF^{PM}, JF^{CM} = Joint faulting measured from the field for PM and CM, respectively.
Roughness (IRI)	$PR_{IRI}^{PM} = \left(\frac{IRI^{PM}}{IRI^{TD}}\right)x10$ $PR_{IRI}^{CM} = \left(\frac{IRI^{CM}}{IRI^{TD}}\right)x10$	$PS_{IRI}^{E} = \frac{PR_{IRI}^{CM} - PR_{IRI}^{PM}}{TH}x100$	IRI^{PM}, IRI^{CM} = Roughness measured from the field for PM and CM, respectively.

**Note: PM = Proposed (new/recycled) Material, CM = Control Material, TH= is terminal damage threshold value which equal to 10.

Option II (intermediate/low level):

Option II in Procedure 2 is similar to Option III in Procedure 1. In this option, the material is evaluated based on its performance, predicted using the Pavement ME Design software (a.k.a. MEPDG). In a Pavement ME Design software Level 1 analysis, the transverse cracking, joint faulting, and roughness will be predicted for both PM and CM. The PC modulus of elasticity (E), modulus of rupture (MOR) and indirect tensile strength at various ages will be measured (by the proposer) for both the PM and CM and input into Pavement ME Design software as Level 1 material inputs. Once the distresses are predicted for both the PM and CM, the performance sub-scores will be computed as percent improvement in performance with respect to typical MEPDG distress values in Michigan for rigid pavements. These engineering performance sub-scores are listed in Table 11. The expression used in calculating the sub-scores, and the overall engineering performance score, were the same as Equation 8 and Equation 9 respectively. It should be noted that TC^{MDOT}, JF^{MDOT} and IRI^{MDOT} shown in Table 11 are the mean MEPDG distress values used as reference values in the software. These values were obtained by running MEPDG using inputs obtained from a previous research project sponsored by MDOT (Buch et al. 2008 – MDOT RC 1516).

Table 11 Distresses predicted by the Pavement ME Design software and associated engineering performance sub-scores for concrete pavements (for Option II)

Predicted Distress	Engineering Performance Sub-score	Definitions**
Transverse Cracking (% slab cracked)	$PS_{TC}^{E} = \frac{TC^{PM} - TC^{CM}}{TC^{MDOT}} x100$	TC^{PM}, TC^{CM} = Percent transverse cracking at the end of the design period for PM and CM, respectively.
Joint Faulting (in)	$PS_{JF}^{E} = \frac{JF^{PM} - JF^{CM}}{JF^{MDOT}} x100$	JF^{PM}, JF^{CM} = Joint faulting at the end of the design period for PM and CM, respectively.
Roughness IRI (in/mi)	$PS_{IRI}^{E} = \frac{IRI^{PM} - IRI^{CM}}{IRI^{MDOT}} x100$	IRI^{PM}, IRI^{CM} = Roughness at the end of the design period for PM and CM, respectively.

**Note: PM = Proposed (new/recycled) Material, CM = Control Material, TC^{MDOT}, JF^{MDOT}, IRI^{MDOT} are the mean MEPDG distress values in Michigan.

Buch et al. (2008) conducted a comprehensive evaluation of the NCHRP 1-37A design process of new and rehabilitated rigid and flexible pavements. The research team evaluated the MEPDG rigid pavement design procedure for local Michigan materials and conditions. In addition, the relationship between measured and predicted pavement performance for selected sections in Michigan was verified, and the performance models were locally calibrated. The research team also conducted an extensive sensitivity analysis on inputs needed for the MEPDG to identify significant input variables. The results showed that PCC slab thickness and edge support had a significant effect on performance, while CTE, MOR, base type and subgrade played an important role among material properties. To effectively capture the interaction effects between variables, the research team designed and analyzed a full factorial experiment and then performed statistical analyses to identify significant main and interaction effects of input variables. Based on the findings of the research project, recommendations/ limiting values for several inputs pertaining to the concrete material are summarized in Table 12.

Stage I - Procedure 3: Performance analysis of unbound layers in pavements

The basic procedure for assessing new or recycled materials in the unbound layers is shown in Figure 10. Similar to Procedure 2, there are two options for evaluating such materials. Since such materials can be used in both flexible and rigid pavements, the impacts of their engineering properties should be determined based on the performance of both pavement types. Such performance evaluations can be easily achieved by field test as in Option I or using the Pavement ME Design software in Option II.

Table 12: Recommended inputs for Level 1 Analysis of rigid pavements (Buch et al. 2008)

Input	Software range	Unit	Recommended values
Thermal			
Unit weight	120 to 160	lb./ft^3	145
Poisson's ratio	0.1 to 0.45	-	0.2
PCC coefficient of thermal expansion	2 to 8	(in./in./°F)×10^{-6}	4.5 to 5.8
PCC thermal conductivity	0.2 to 2	BTU/hr-ft-°F	1.25
PCC heat capacity	0.1 to 0.5	BTU/lb-°F	0.28
Mix			
Cement type	-	-	Type I
Cementitious material content	400 to 800	lb./yd^3	500
Water to cement ratio	0.3 to 0.7	-	0.42
Aggregate type	-	-	Limestone
Strength*			
Elastic modulus	1 to 7×10^6	psi	3.8×10^6
Modulus of rupture	300 to 1000	psi	662
Elastic modulus 14 days	1 to 7×10^6	psi	4×10^6
Modulus of rupture 14 days	300 to 1000	psi	663
Elastic modulus 28 days	1 to 7×10^6	psi	5.1×10^6
Modulus of rupture 28 days	300 to 1000	psi	632
Elastic modulus 90 days	1 to 7×10^6	psi	5.2×10^6
Modulus of rupture 90 days	300 to 1000	psi	650
Ratio 20 Year/28 Day	0 to 10	-	1.2

* Level 1 Analysis

Option I (high level):

Similar to the previous procedures (for concrete and asphalt pavements), Option I for Procedure 3 involves field data collection. In Procedure 3, which is for the unbound layers, the software lists performance criteria both from Procedure 1 (asphalt) and Procedure 2 (concrete). Depending on weather the material is used in a flexible or a rigid pavement, the corresponding performance criteria can be selected. As the first step, the collected field data is scaled to a single Performance Rating (PR) number before analysis, using the same procedure as discussed in Procedure 1 and Procedure 2. These PR and engineering performance sub-scores are the same as listed in Table 4 for asphalt pavements and Table 10 for concrete pavements. The software uses these PR values in calculating PS^E using the same equation used in Option I (Equation 2).

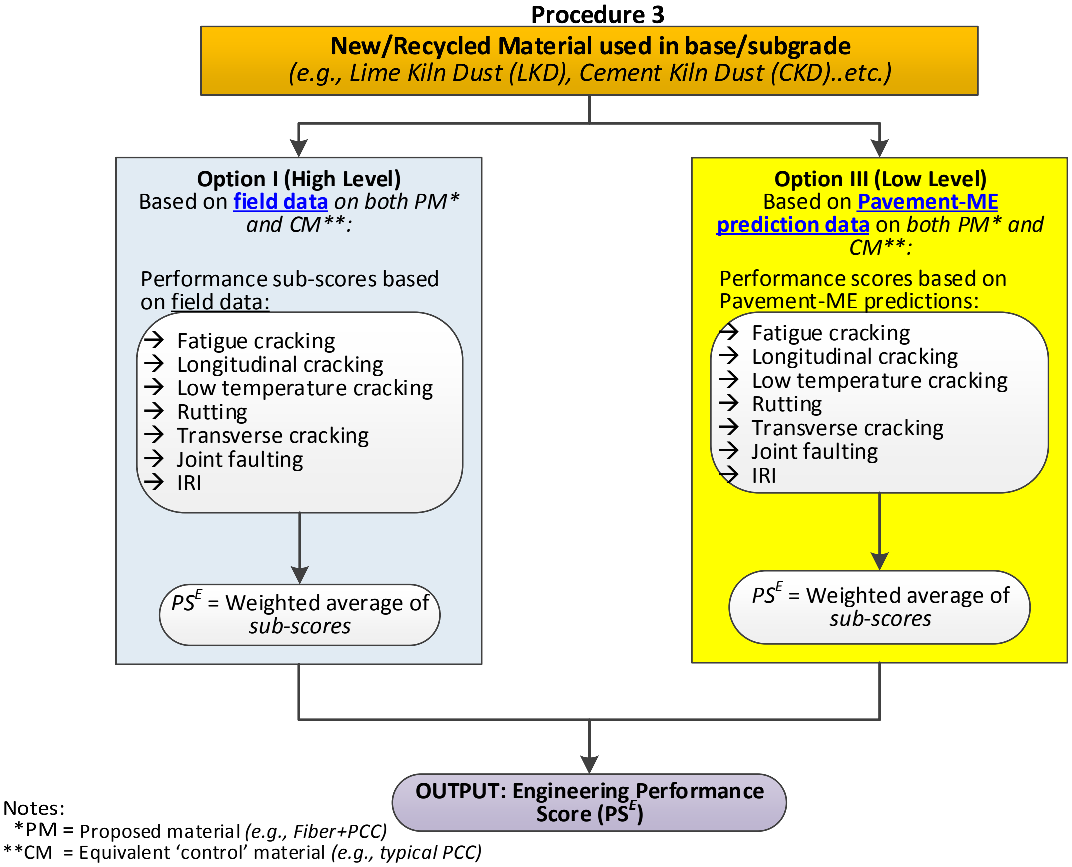


Figure 10: Illustration of Procedure 3 for evaluation of new/recycled materials for use in base/subgrade layers

Option II (Intermediate/Low level):

Option II in Procedure 3 is similar to Option II in Procedure 2. In this option, the material is evaluated based on its performance, predicted using the Pavement ME Design software. Regardless of whether the material is used in a flexible or rigid pavement, the Level 1 option is chosen in the Pavement ME Design software. When the proposed material is used in a flexible pavement, the fatigue cracking (both top-down and bottom-up), rutting, low temperature cracking, and roughness will be predicted using the Pavement ME Design software for both PM and CM. When the proposed material is used in a rigid pavement, the transverse cracking, joint faulting, and roughness will be predicted for both PM and CM. It should be noted that any innovative material in the unbound layers will have unique mechanical properties such as resilient modulus or CBR which can be conveniently determined in the laboratory. These properties can be used for the pavement layer(s) containing such unique materials to evaluate their impact on the expected pavement performance. The resilient modulus (M_R), Poisson's ratio (ν), unbound material gradation and plasticity will be measured (by the proposer) for both the PM and CM and input into Pavement ME Design software as Level 1 material inputs. Once the distresses are predicted for both the PM and CM, the performance sub-scores will be computed as percent improvement in performance with respect to the reference distress values for flexible/rigid pavements. As explained in Procedure 1 and Procedure 2, these PR and engineering performance sub-scores are the same as those listed in Table 8 and Table 11. The expressions used in calculating sub-scores and the overall engineering performance score were the same as Equation 8 and Equation 9 respectively.

As part of a previous research project sponsored by MDOT (Baladi et al. 2011 – MDOT RC 1548), Baladi et al. (2011) conducted an extensive research study on the characterization of unbound granular layer moduli for multiple pavement structures in Michigan. In this study, deflection data measured using the Falling Weight Deflectometer

(FWD) was used to backcalculate the various pavement layers moduli and roadbed soils. Then, the backcalculated values were compared to default values provided in the Pavement ME Design software and subjected to statistical analyses to determine the most reliable input values to be used in the pavement design process for Michigan materials and conditions.

The following tables highlight the findings and recommendations of the research study for layer moduli inputs in a Level 1 analysis of Pavement ME Design software. Table 13 shows the recommended range of granular layer and roadbed moduli for rigid pavements.

Table 13: Recommended range of unbound material moduli for <u>rigid</u> pavements (Baladi et al. 2011).

Statistics	Backcalculated layer moduli (psi)	
	Granular layer	Roadbed
Average	38,440	23,490
Maximum	150,000	62,370
Minimum	10,000	6,550

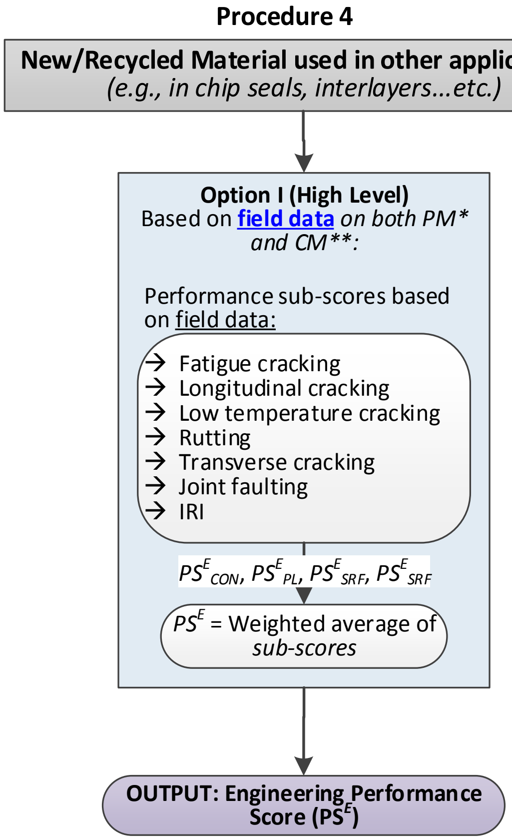
In addition, Table 14 shows the recommended range of granular layer and roadbed moduli for two layer flexible pavements, and the recommended range for roadbed, subbase and base layers for three layer flexible pavements. It should be noted that these values were used in determining reference MEPDG distress values in the software.

Table 14: Recommended range of unbound material moduli for <u>flexible</u> pavements (Baladi et al. 2011).

Statistics	Backcalculated layer moduli (psi)				
	Two layer analysis		Three layer analysis		
	Granular layer	Roadbed	Roadbed	Subbase layer	Base layer
Average	34,000	25,950	26,100	28,770	63,490
Maximum	94,230	67,790	67,840	78,540	388,120
Minimum	11,120	7,090	7,340	8,340	16,940

Stage I - Procedure 4: Performance analysis of other applications in pavements (e.g., chip seal, interlayer systems, etc.)

This procedure is for analyzing new and recycled materials that are proposed to be used in other applications in pavements; such as pavement preservation treatments (e.g., chip seal) and interlayers (e.g., stress absorbing membrane interlayer (SAMI) systems). For such applications, an analysis using the Pavement ME Design software is not possible. The analysis will be based on field data (Option I) as shown in Figure 11.



Notes:
*PM = Proposed material *(e.g., a pavement with SAMI)*
**CM = Equivalent 'control' material *(e.g., similar pavement with no SAMI)*

Figure 11: Illustration of Procedure 4 for evaluation of new/recycled materials other than asphalt, concrete and unbound layers.

Similar to other field test evaluation options, the field data needs to be collected on the proposed material (PM) and an equivalent control material (CM). In Procedure 4, the software lists performance criteria both from Procedure 1 and Procedure 2. Depending on weather the material is used in a flexible or rigid pavement, the performance criteria from Procedure 1 or Procedure 2 can be selected. As the first step, the collected field data is scaled to a single Performance Rating (PR) number before analysis, using the same procedure as used in Procedure 1 and Procedure 2. These PR and engineering performance sub-scores are the same as listed in Table 4 for flexible pavements and Table 10 for rigid pavements respectively. The software uses these PR values in calculating PS^E using the same equation used in Option I (Equation 2).

Stage II Sustainability Assessment and Life Cycle Analysis

Once the Stage I analysis is performed successfully, the NewPave software prompts the user to move to Stage II of the analysis. Stage II of the methodology is the sustainability evaluation of the new or recycled material. Components of Stage II in the NewPave software are shown in Figure 12. This evaluation is independent of the type of application, i.e., whether the material is proposed to be used in asphalt, concrete, unbound layers or in other applications.

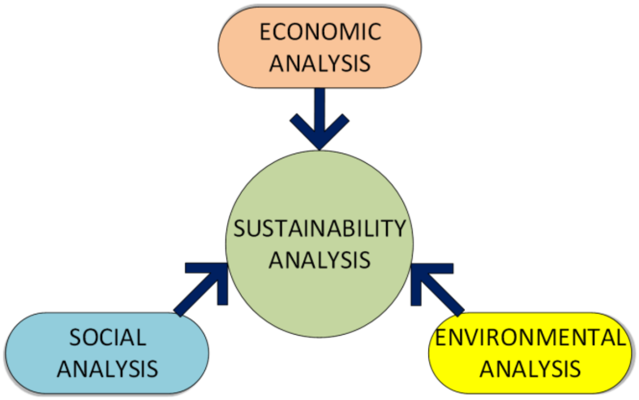


Figure 12: The sustainability framework addressed in the software

The sustainable development concept as defined by the World Commission on Environmental and Development (1987) is “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Such a development requires comprehensive study, involving potential environmental, economic and social impact of an intended project. An activity in pavements (design, construction and maintenance) involves a large capital investment apart from huge energy consumptions and greenhouse gas emissions. Due to the inherent material and resource intensive activities, sustainable design in the pavement industry caters to the potential to reduce the environmental and economic impact, improving social life of future generations.

In a typical pavement system evaluation, user cost is primarily considered as a decisive indicator. However, researchers have shown that for a sustainable development, environmental and social impact indicators need to be considered in the decision making process. In addition to the basic concept of sustainability, Figure 12 also shows the sustainability issues addressed in the NewPave software.

Assessing risk or impact over a single event may often be misleading. This is because the approach in such an analysis gets localized, rather than considering the whole system. As an example, the use of polymer modified binders may increase initial cost, increased production energy and higher greenhouse gas emission. However, due to improved performance and less maintenance activities, it may be more economical and less environmentally strenuous over time. Analysis over the entire life cycle (cradle-to-grave) is the most comprehensive scientific technique to assess each and every impact associated with all the stages of a project. Such an analysis is important in determining the sustainability of the system constituting new and recycled materials. The following analysis or tools can be used to achieve sustainable development:

1. Life cycle cost analysis (LCCA)
2. Life cycle assessment (LCA)

In the NewPave software, life cycle study refers to both the Life Cycle Cost Analysis (LCCA) and Life Cycle Analysis (LCA). These tools are used to develop a methodology which results in an increased service life of the highway, reduced life cycle cost and minimum impacts on the environment. Therefore, a general framework for highway life cycle needs to be designed which comprises the process of service life design, economic evaluation, environmental evaluation and social benefit evaluation.

In the NewPave software, based on relevant existing models, a procedure with cost analysis, life cycle assessment and social sustainability assessment is developed for the comparison and evaluation of the new/recycled materials in pavements. It should be noted that while providing information in the software, the proposer should include all the significant life-cycle stages covering; (i) obtaining and processing raw materials, (ii) production (plant manufacturing), (iii) assembly (placement and compaction of the material on the road), (iv) service life (maintenance and rehabilitation) and (v) end life value (recycling potential). In these stages, transport distances, fuel efficiency, energy consumption, environmental effects and associated costs should be considered. In Figure 13, the sustainability assessment processing tool is sketched, showing an integrated circulation based approach. In this diagram, sustainability assessment and the development of sustainability performance scores are detailed. The parameters effecting the sustainability assessment such as service life, placement, production and raw material extraction are given as process components in the life cycle. Based on these, the sustainability analysis will result in a score (PS^S). This score (PS^S) will be combined with the score based on sustainability (i.e., PS^E obtained in Stage I) to obtain an "overall score" (i.e., PS), which will be used to accept/reject the trial use of the New/Recycled material in MDOT-administered roads.

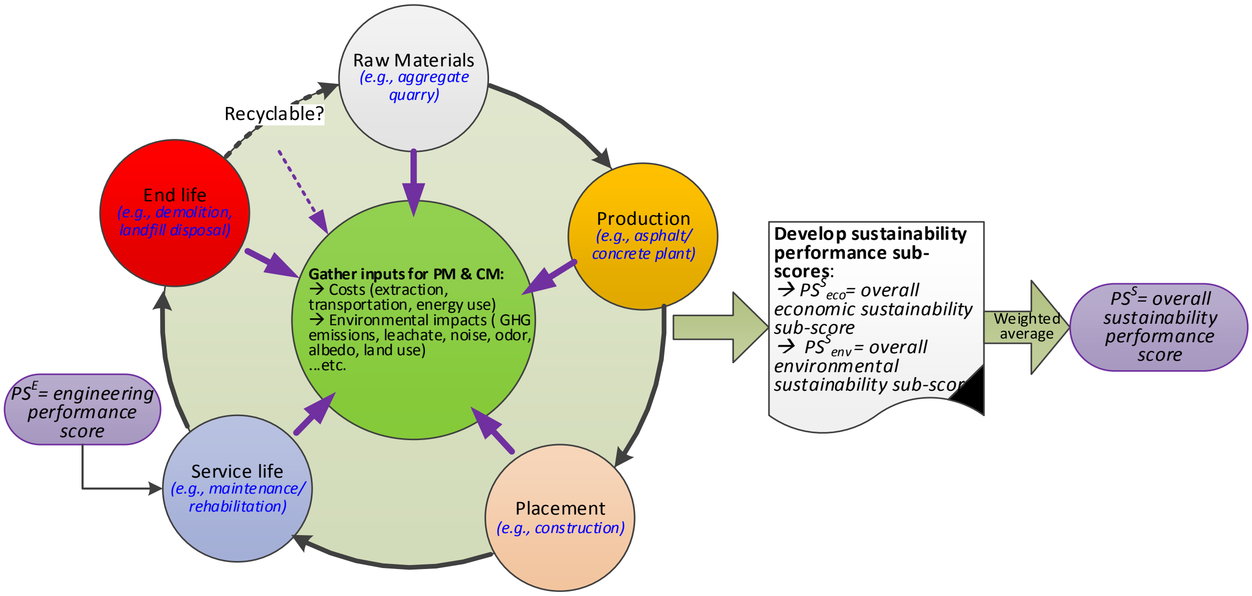


Figure 13: Life cycle analysis framework

Economic analysis

In the NewPave software, an LCCA model has been implemented to compare the monetary value of pavements constructed with Control Material (CM) and Proposed Material (PM). The LCCA model computes the net present value from the costs incurred over the design life, then converts this to value per year. Figure 14 illustrates typical timelines of life cycles of CM and PM. It is assumed that, at the end of initial life, pavement is reconstructed with the same material, and the cost (or the value) of the construction remains the same. It is also assumed that each reconstruction would restore the pavement to its original condition.

It is expected that the proposer will provide following information to MDOT:

(i) The value (i.e., cost) of the construction/reconstruction for the CM: V_{CM}

(ii) The value (i.e., cost) of the construction/reconstruction for the PM: V_{PM}

(iii) Expected life of constructed/reconstructed pavement made with the CM: Δt_{CM}

(iv) The reduced rate of interest: r

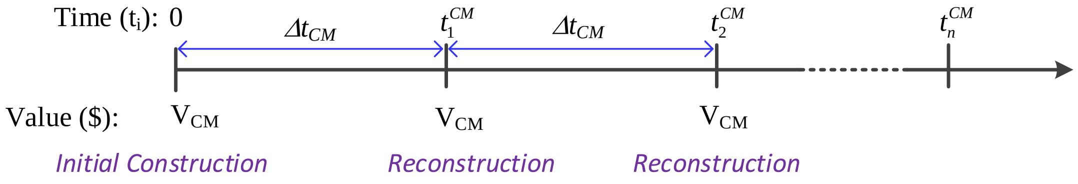
(v) Estimated number of reconstructions for the CM: n

LCCA model first calculates the analysis period of the CM using the following formula:

$$t_n^{CM} = (n+1)\Delta t_{CM} \tag{1}$$

where t_n^{CM} = the analysis period for the CM (years), Δt_{CM} = expected life of the CM (years), and n = number of reconstructions for the CM.

(a) Control Material (CM)



(b) Proposed Material (PM)

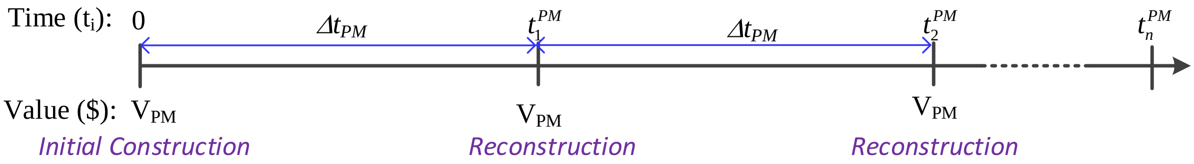


Figure 14: Illustration of timeline of the life cycle analysis

Then the expected life of constructed/reconstructed pavement made with the PM (i.e., Δt_{CM}) is computed from the engineering performance score (PS^E) obtained in Stage I of the analysis as follows:

$$\Delta t_{PM} = \Delta t_{CM}(1 + PS^E) \tag{2}$$

where Δt_{PM} = expected life of constructed/reconstructed pavement made with the PM, Δt_{CM} = expected life of constructed/reconstructed pavement made with the CM, and PS^E=engineering performance score. Then, the analysis period of the PM is calculated using the following formula:

$$t_n^{PM} = (n+1)\Delta t_{PM} \tag{3}$$

The software uses this information to calculate the expected present value of the pavements made with CM and PM using the following equations:

$$PV^{CM} = V_{CM} + \sum_{i=1}^{n} \left(\frac{V_{CM}}{\left(1+\frac{r}{100}\right)^{t_i^{CM}}} \right) \tag{4}$$

$$PV^{PM} = \mathrm{V}_{\mathrm{PM}} + \sum_{i=1}^{n}\left(\frac{\mathrm{V}_{\mathrm{PM}}}{\left(1+\frac{r}{100}\right)^{t_i^{PM}}}\right) \tag{5}$$

where, r is the reduced rate of interest, t_i^{CM} is the (cumulative) time of i^{th} reconstruction of the CM (years), t_i^{PM} is the (cumulative) time of i^{th} reconstruction of the PM (years), V_{CM} is the value of construction/reconstruction of the CM (\$), V_{PM} is the value of construction/reconstruction (\$) of the PM and n is the total number of constructions during the life cycle of the pavements made with the *CM* and *PM* (see Figure 14).

Since the analysis period of the CM and PM are different, the net present values PV^{CM} and PV^{PM} cannot be directly compared. Therefore, they are converted to the cost incurred per year using the following formula:

$$V_{year}^{CM} = PV^{CM}\,\frac{\left(\left(1+r\right)^{t_n^{CM}}-1\right)}{r\left(1+r\right)^{t_n^{CM}}} \tag{6}$$

$$V_{year}^{PM} = PV^{PM}\,\frac{\left(\left(1+r\right)^{t_n^{PM}}-1\right)}{r\left(1+r\right)^{t_n^{PM}}} \tag{7}$$

where, V_{year}^{CM} is the cost incurred per year for CM, V_{year}^{PM} is the cost incurred per year for PM, PV^{CM} is the net present value for CM, PV^{CM} is the net present value for PM, *r* is the reduced rate of interest, t_n^{CM} and t_n^{PM} are the analysis periods of CM and PM, respectively.

Once the cost incurred per year are predicted for both PM and CM, the economic performance sub-score (PS_{eco}^{S}) is computed using the following formula:

$$PS_{eco}^{S} = \left(\frac{V_{year}^{CM} - V_{year}^{PM}}{V_{year}^{CM}} \right) x100 \tag{15}$$

where, V_{year}^{CM} and V_{year}^{PM} are the cost incurred per year for CM and PM.

Environmental analysis

Life cycle assessment is a technique to evaluate the environmental impacts of a product or process over its entire life cycle. In the developed software, the LCA tool is used to compare the environmental impact of the pavement systems with respect to PM and CM. The model is based on equivalent CO_2 emissions in new construction and in maintenance cycles of the pavement. The LCA would include all the emissions which will be directly emitted due to MDOT construction activities, over the life cycle of the pavement system. It should be noted that, as in LCCA, for comparison purpose, the same treatment is performed at every reconstruction, which is, employing full-depth reconstruction. It is assumed that each reconstruction would restore the pavement to its original condition. Therefore, in the developed software, the LCA model incorporates the rehabilitation strategy of the life cycle LCCA model. Hence the total CO_2 emissions over the entire life cycle is calculated as the sum of fixed CO_2 emissions incurred at equal intervals. To calculate the fixed CO_2 emissions, which is incurred at every reconstruction, the software allows the proposer to develop a list of materials and equipment used over the entire life cycle. Finally, the software uses the CO_2 conversion factors from a previous MDOT study to calculate CO_2 emissions.

The major steps followed in the LCA analysis are:

Step 1. The first step is to establish the scope and boundaries of the system. The system boundaries are determined based on the limits in data collection. The outcome of life cycle analysis results are strongly influenced by the boundary of the system chosen. As an example, use of certain industrial wastes in pavement may save landfilling. However, when the pavement reaches the end of its life, maintenance or recycling of the modified pavement might have much more significant environmental concerns. Hence, in such cases, the system boundary in the LCA for pavements must involve maintenance and recycling. As illustrated in the example, diluting the life cycle boundaries may lead to loss of critical features in the pavement system. In the present work, the system boundary starts at the procurement and material selection to the maintenance and recycling of the pavement system.

Figure 15 shows the main processes within the system boundaries for the asphalt pavement life cycle analysis. These processes can be used as a guideline by the new material proposer in compiling life cycle inventory information in step 2, as explained later.

Step 2. The second step is to inventory the inputs and outputs that occur during the life cycle. The life cycle analysis inventory (LCAI) inputs in the software are classified as material level and equipment level. The proposer will provide the LCAI for both PM and CM, which can be prepared from the list of typical materials and equipment provided in the software. The output in the software is considered as CO_2 equivalent greenhouse gas emissions.

$$CO_2\ emission = \sum_{i=1}^{NM} (MF_m)_i (QTY)_i + \sum_{j=1}^{NE} (MF_e)_j (No)_j (hr)_j \tag{16}$$

where, MF_m is carbon emission multiplying factor for material i (CO_2 emitted per unit material), MF_e is carbon emission multiplying factor for equipment, j (CO_2 emitted per equipment per hour), No is number of equipment type j, hr is number of hours each equipment is used, NM and NE are the number of material and equipment used, respectively.

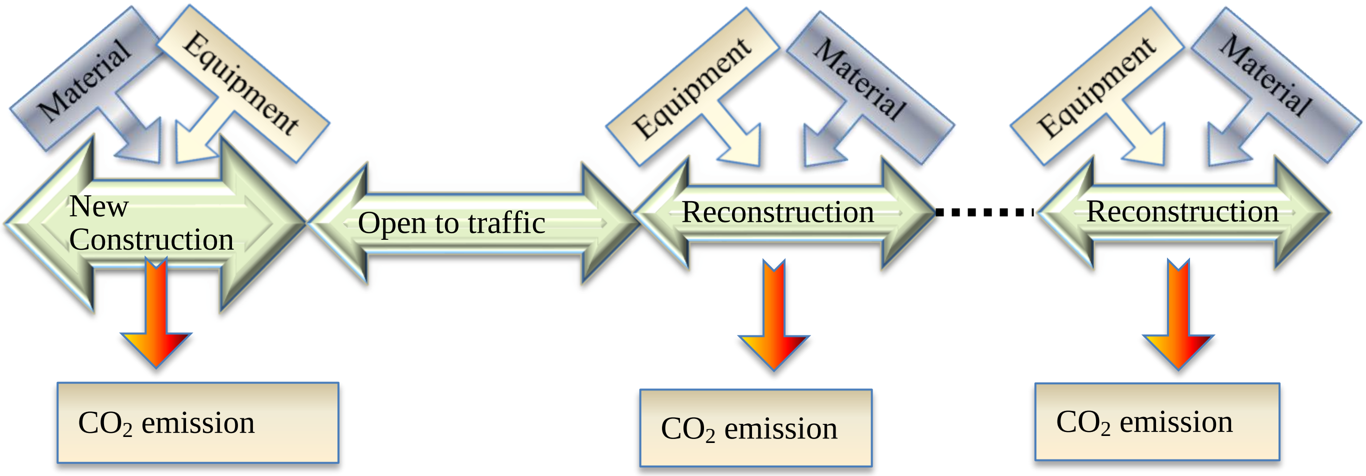


Figure 15: Illustration of maintenance cycles in LCA for environmental analysis

Step 3. The third step in LCA is to assess the environmental impact of the various inputs and outputs in the inventory. In the software, this is done by quantifying the total equivalent CO_2 greenhouse gas emission over the entire life cycle of the pavement system.

$$\begin{aligned}Total\ CO_2\ emission = {} & (number\ of\ constructions\ in\ LCA)\, x \\ & (CO_2\ emission\ during\ each\ construction)\end{aligned} \tag{17}$$

where, the number of constructions in LCA for CM and PM are *n* and *m* respectively, as obtained in the LCCA. However, it should be noted that, as discussed earlier, the CO_2 emissions calculated in Equation 17 may not be over the same life cycle duration for both CM and PM. Hence, the total CO_2 emission values calculated for CM and PM using Equation 17, may not be directly compared. These cost components need to be converted to emissions incurred per year for comparison purpose, as shown in the following equation:

$$CO_2\ emission\ per\ year = \frac{Total\ CO_2\ emission}{Life\,cycle\ period\ in\ years} \tag{18}$$

Once the emissions incurred per year are predicted for both the Proposed Material PM and the Control Material CM, the environmental performance scores will be computed as percent improvement in emission per year. Once the emission incurred per year are predicted for both PM and CM, the environmental performance sub-score (PS_{env}^{S}) is computed using the following formula:

$$PS_{env}^{S} = \left(\frac{CO_{2_{year}}^{CM} - CO_{2_{year}}^{PM}}{CO_{2_{year}}^{CM}} \right) x100 \tag{15}$$

where, $CO_{2_{year}}^{CM}$ and $CO_{2_{year}}^{PM}$ are the emissions incurred per year for CM and PM.

Social analysis

The goal of this component in the software is to provide some information on the social aspects to decision makers alongside the economic and environmental life cycle analysis. Social impact assessment is not mandatory to complete the evaluation; however, it may be used when the social impact of a project is appropriate and relevant. The main challenge in a social analysis is to identify the set of social indicators and develop an appropriate evaluation scale. The software uses five categories of social impacts as listed in Table 15.

This option requires a performance rating (PR) on both the PM and CM. The inputted social performance PR value is selected over a scale from 0 to 10, 0 being the best and 10 being the worst, based on the discretion of the agencies. These PR and engineering performance sub-scores are listed in Table 15. The final performance score PS_{soc}^{S} is a relative score which indicates social performance using a New/Recycled material compared to the control material. The software uses these PR values in calculating PS_{soc}^{S} as follows:

$$PS_{soc}^{S} = 100\sum \delta_i w_i \left(\frac{PR_{soci}^{\ PM} - PR_{soci}^{\ CM}}{TH} \right) \tag{19}$$

where, i is the performance criteria, δ_i is the Kronecker delta which takes a value of 0 or 1 depending on weather the i^{th} criteria is used in the score, w_i is the weight given to the i^{th} performance criteria and TH is the terminal damage threshold value which equal to 10. By default, the weights in the software are assumed to be 1. PR_i^{PM} is the performance rating value obtained for the New/Recycled material and PR_i^{CM} is the performance rating value obtained for the control material.

Table 15: Social impact factors and associated performance sub-scores

Social impact category	Social Performance Sub-score	Definitions**
Skid Resistance	$PS_{SR}^{S} = \frac{PR_{SR}^{PM} - PR_{SR}^{CM}}{TH} x100$	PR_{SR}^{PM} and PR_{SR}^{CM} = Skid resistance rating for PM and CM, respectively.
Visibility/Marking	$PS_{VM}^{E} = \frac{PR_{VM}^{PM} - PR_{VM}^{CM}}{TH} x100$	PR_{VM}^{PM} and PR_{VM}^{CM} = Visibility/Marking rating for PM and CM, respectively.
Land Filling	$PS_{LF}^{E} = \frac{PR_{LF}^{PM} - PR_{LF}^{CM}}{TH} x100$	PR_{LF}^{PM} and PR_{LF}^{CM} = Land filling rating for PM and CM, respectively.
Noise	$PS_{N}^{E} = \frac{PR_{N}^{PM} - PR_{N}^{CM}}{TH} x100$	PR_{N}^{PM} and PR_{N}^{CM} =Noise rating for PM and CM, respectively.
Aesthetic	$PS_{A}^{E} = \frac{PR_{A}^{PM} - PR_{A}^{CM}}{TH} x100$	PR_{A}^{PM} and PR_{A}^{CM} = Aesthetic rating for PM and CM, respectively.

**Note: PM = Proposed (new/recycled) Material, CM = Control Material, TH=10.

EXAMPLE ANALYSES AND VALIDATION OF THE NEW/RECYCLED MATERIAL EVALUATION FRAMEWORK

In this section, actual field distress data and laboratory measured material properties were used to present example applications of the analysis framework. The first subsection presents an example for asphalt pavements. The second and third subsections present examples for concrete and unbound materials respectively.

Asphalt Pavements (Procedure 1)

In this section, actual field distress data for flexible pavements, and laboratory measured asphalt mixture properties were used in Procedure 1 in the software.

Option I (high level)

The Option I procedure in the software has been validated using FHWA accelerated pavement testing (APT) data (Gibson et al. 2012). The term validation herein is used when the outcome of the NewPave software (i.e., the performance scores) were logical as compared to the actual field data observed. The FHWA's APT data was chosen for initial validation of the NewPave software since the data collected were known to be well controlled and accurate. At FHWA's APT experiment conducted as part of the Transportation Pooled Fund (TPF) study TPF-5(019), there were 12 different pavement sections constructed side by side and tested for rutting and fatigue cracking. All sections had the same mixture design and structure. The only difference was the type of asphalt binder used, which included several kinds of polymer modified and crumb rubber modified binders. The field data was collected on both the modified new material (PM) and control material (CM); and fatigue cracking at a reference load cycle was compared. Two examples have been presented (1) comparison of control mix with CRTB (crumb rubber terminal blend) mix and (2) comparison of control mix with Terpolymer mix. It should be noted that the examples presented here are for fatigue cracking, however, depending on the availability of data, the same exercise can be repeated for the other distresses (Rutting, IRI and Longitudinal cracking).

Example-1: Comparison of control mix with CRTB terminal blend mix: Field test

In this example, Option I of the developed software was used to compare fatigue cracking field performance data from APT. The details of the verification procedure are given below:

Step-1: Collect and review field data

The collected field data was carefully plotted (Figure 16) and a reference load cycle was used to extract damage extent for each mix type. It is suggested to use the load cycle corresponding to terminal damage in the control mix as the reference. As shown in Figure 16 the percentage area cracked observed at 100,000 load cycles was selected as a reference. It should be noted that 100,000 cycles correspond to 100% cracking for the control mix, which was assumed as terminal damage in the example.

Step-2: Calculate performance rating

As shown in Table 16, the damage extents and terminal damage extracted from Figure 16 was scaled to a single Performance Rating (PR).

Step-3: Calculate Engineering Performance Score (PS^E)

In the example, the Engineering Performance Score (PS^E) is a relative score which indicates performance of the mix obtained using CRTB terminal blend compared to the control mix.

$$PS^E = 100\left(\frac{10-4}{10}\right) = 60$$

It should be noted that a positive value PS^E = 60 indicates a 60 percent better performing CRTB terminal blend compared to the control mix.

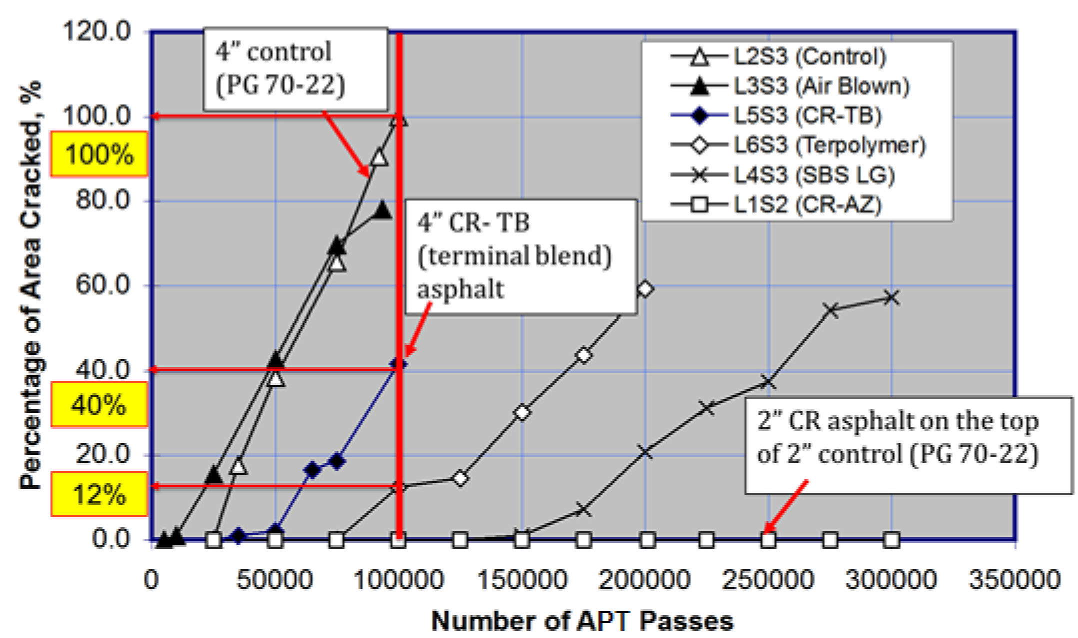


Figure 16: Comparison of field distress data measure in FHWA APT facility

Table 16: Example 1-Field distress and performance rating inputs in Option I

Mixture	Rutting (in)		Performance Rating
	Damage Extent	Terminal Damage	$PR = 10\left(\frac{Damage\ Extent}{Terminal\ Damage}\right)$
New mix: CRTB terminal blend	40%	100%	4
Control mix: PG 70-22	100 %		10

<u>Example-2: Comparison of control mix with Terpolymer mix: Field test</u>

Step-1: Collect and review field data

The step involves same procedure as explained in Example-1. As shown in Figure 16 the percentage area cracked observed at 100,000 load cycle was selected as a reference.

Step-2: Calculate Engineering Performance Score (PS^E)

The step involves same procedure as explained in Example-1. As shown in Table 17, the damage extents and terminal damage extracted from Figure 16 was scaled to a single Performance Rating (PR).

Table 17: Example 2-Field distress and performance rating inputs in Option I

Mixture	Rutting (in)		Performance Rating
	Damage Extent	Terminal Damage	$PR = 10\left(\frac{Damage\ Extent}{Terminal\ Damage}\right)$
New mix: Terpolymer	12%	100%	12
Control mix: PG 70-22	100 %		10

Step-3: Calculate Engineering Performance Score (PS^E)

$$PS^E = 100\left(\frac{10-1.2}{10}\right) = 88\%$$

It should be noted that a positive value PS^E = 88 indicates a 88 percent better performing Terpolymer mix compared to the control mix. Therefore, Example-1 and Example-2 clearly show that the performance of APT Terpolymer mixture and APT CRTB are superior to APT Control mix.

Option II (intermediate level)

The Option II procedure in the software has been verified using laboratory obtained MDOT mixture test data. This option requires laboratory test data on both PM and CM. Laboratory data for push-pull, flow number and IDT tests were obtained for 5E3 (32A) MDOT control mix (CM). Three MDOT mixes, CRTB, GTR, and LVSP were used as proposed materials (PM) for comparison. One of the primary reasons for verifying Option II with three different PM was to show different possible performance (PS^E) outcome examples.

Example-3: Comparison of control mix with CRTB terminal blend mix: Push-pull

In this example, Option II of the developed software was used to obtain engineering performance using push-pull data from the laboratory. The details of the verification procedure are given below:

Step-1: Collect and review laboratory data

The laboratory obtained push-pull data was processed using a VECD analysis and the fatigue life (N_f) was predicted at a temperature of 20°C, a frequency of 10 Hz, and a microstrain level of 300 using the N_f equation proposed by Kutay et al. 2009. The processed N_f data for Control 5E3 and CRTB mixtures are shown in Table 18.

Table 18: Example 3-Push-pull test inputs in Option II

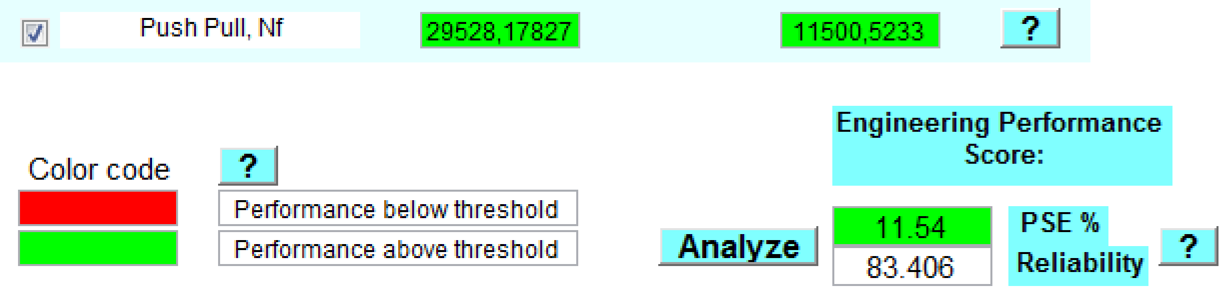
Mixture	Temperature (^oC)	Micro-strain ($\mu\varepsilon$)	No of cycles to failure N_f (mean, standard deviation)
Control: 5E3 (32A)	20	300	11500, 5233
CRTB	20	300	29528, 17827

Step-2: Calculate Engineering Performance Score (PS^E)

Performance score in Option II (PS^E) is also a relative score which indicates laboratory performance of a mix using a New/Recycled material compared to the control mix. In the example, PS^E is a relative score which indicates performance of CRTB compared to the control mix 5E3.

$$PS_{FC}^{E} = \frac{\log\left(N_f^{PM}\right) - \log\left(N_f^{CM}\right)}{\log\left(N_f^{MDOT}\right)} x100 = \frac{\log(29528) - \log(11500)}{3.55} x100$$
$$= 11.54\%$$

Figure 17 shows a snapshot of the NewPave software input panel and the PSE (engineering performance score) computation. Reliability computed by the software is 83.41%. It is noted that a positive value PS^E = 11.54 indicates 11.54 percent better performing CRTB mix compared to the 5E3 control mix. Further, a reliability of 83.41% indicates that the probability CRTB mix will perform better than the control mix is equal to 0.83.



☑ Push Pull, Nf 29528,17827 11500,5233

Color code
🟥 Performance below threshold
🟩 Performance above threshold

Engineering Performance Score:
PSE % 11.54
Reliability 83.406

Figure 17 Snapshot of the NewPave software input panel and the PSE (engineering performance score) computation.

Example-4: Comparison of control mix with CRTB terminal blend mix: Flow number

In this example, Option II of the developed software was used to obtain engineering performance using flow number test data from the laboratory. The details of the verification procedure are given below:

Step-1: Collect and review laboratory data

The flow number tests of all mixtures characterized in this study were conducted at a test temperature of 46°C, with confining pressure (σ_3) of 5 psi, deviatoric stress ($\Delta\sigma_d$) of 120 psi, and the contact stress ($\sigma_{contact}$) was set to 4.35 psi. It should be noted that not all mixtures would exhibit tertiary flow within the 10,000 recommended cycle count, and therefore the parameter used for quantifying the rutting/plastic deformation potential of the asphalt mixtures investigated in this study was the plastic micro-strain ($\mu\varepsilon_p$) or permanent deformation corresponding to cycle number 1,500. So, the laboratory obtained flow number data was processed and the plastic micro-strain was obtained at 1500 cycles as shown in Table 19.

Table 19: Example 4- Flow number test inputs in Option II

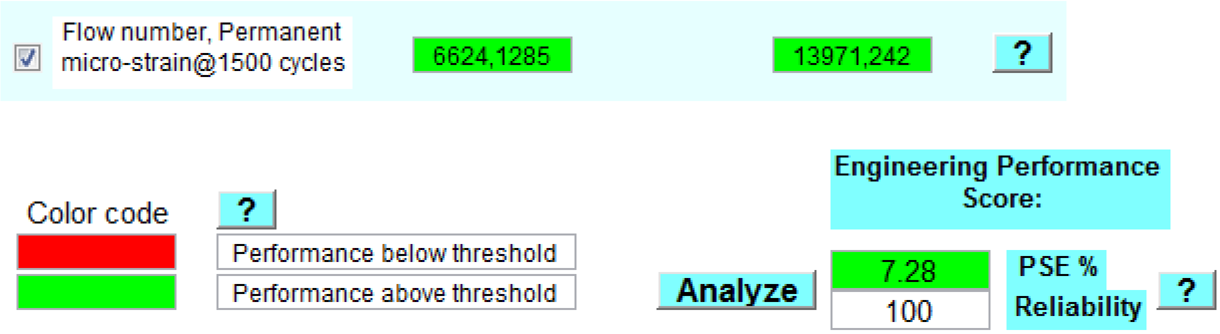
Mixture	Temperature (^{o}C)	Deviator stress (psi)	Confining stress (psi)	Plastic micro-strain ($\mu\varepsilon_p$) (mean, standard deviation)
Control: 5E3 (32A)	45	482	69	13971, 242
CRTB	45	482	69	6624, 1285

Step-2: Calculate Engineering Performance Score (PS^{E})

The PS^{E} is calculated as

$$PS_{FN}^{E}=\frac{\log\left(PD^{CM}\right)-\log\left(PD^{PM}\right)}{\log\left(PD^{MDOT}\right)}x100=\frac{\log(13971)-\log(6624)}{4.45}x100=7.28\%$$

Figure 18 shows a snapshot of the NewPave software input panel and the PSE (engineering performance score) computation. It is noted that a positive value PS^{E} = 7.28 indicates a 7.28 percent better performing CRTB mix compared to the 5E3 control mix. Further, a reliability of 100% indicates that the probability CRTB mix will perform better than the control mix is equal to 1.



☑ Flow number, Permanent micro-strain@1500 cycles 6624,1285 13971,242

Color code
🟥 Performance below threshold
🟩 Performance above threshold

Engineering Performance Score:
PSE % 7.28
Reliability 100

Figure 18 Snapshot of the NewPave software

Example-5: Comparison of control mix with GTR terminal blend mix: Flow number

Step-1: Collect and review laboratory data

The step involves same procedure as explained in Example-4. The laboratory obtained plastic microstrain at 1500 cycles for the control and GTR mixes are shown in Table 20.

Table 20: Example 5- Flow number test inputs in Option II

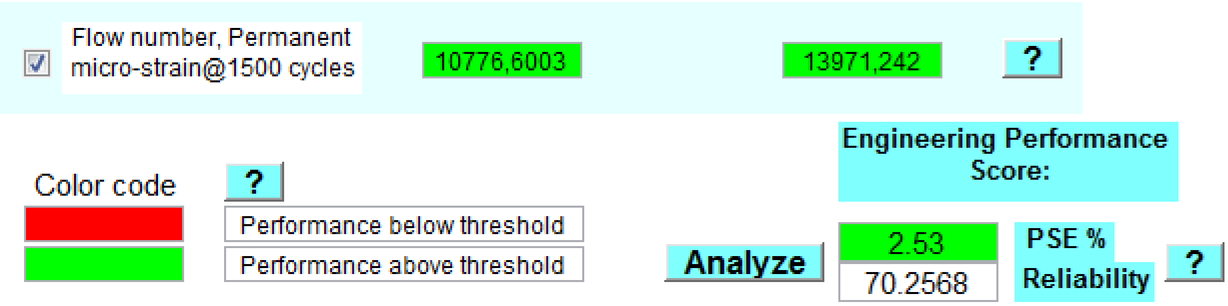
Mixture	Temperature (^oC)	Deviatory stress (psi)	Confining stress (psi)	Plastic micro-strain ($\mu\varepsilon_p$) (mean, standard deviation)
Control: 5E3 (32A)	45	482	69	13971, 242
GTR	45	482	69	10776, 6003

Step-2: Calculate Engineering Performance Score (PS^E)

$$PS^E_{FN} = \frac{\log\left(PD^{CM}\right) - \log\left(PD^{PM}\right)}{\log\left(PD^{MDOT}\right)} x100 = \frac{\log(13971) - \log(10776)}{4.45} x100 = 2.53\%$$

Reliability=70.26%

Figure 19 shows a snapshot of the NewPave software. As mentioned earlier, a positive value PS^E = 2.53 indicates a 2.53 percent better performing GTR mix compared to the 5E3 control mix. Further, a reliability of 70.26% indicates that the probability GTR mix will perform better than the control mix is equal to 0.70.



☑ Flow number, Permanent micro-strain@1500 cycles 10776,6003 13971,242

Engineering Performance Score:

PSE % 2.53

Reliability 70.2568

Figure 19 Snapshot of the NewPave software

Example-6: Comparison of control mix with LVSP mix: Flow number

Step-1: Collect and review laboratory data

The step involves same procedure as explained in Example-4. The laboratory obtained plastic microstrain at 1500 cycles for control and GTR mixes are shown in Table 21.

Table 21: Example 6- Flow number test inputs in Option II

Mixture	Temperature (^{o}C)	Deviatory stress (psi)	Confining stress (psi)	Plastic micro-strain ($\mu\varepsilon_p$) (mean, standard deviation)
Control: 5E3(32A)	45	482	69	13971,242
LVSP	45	482	69	14566,1094

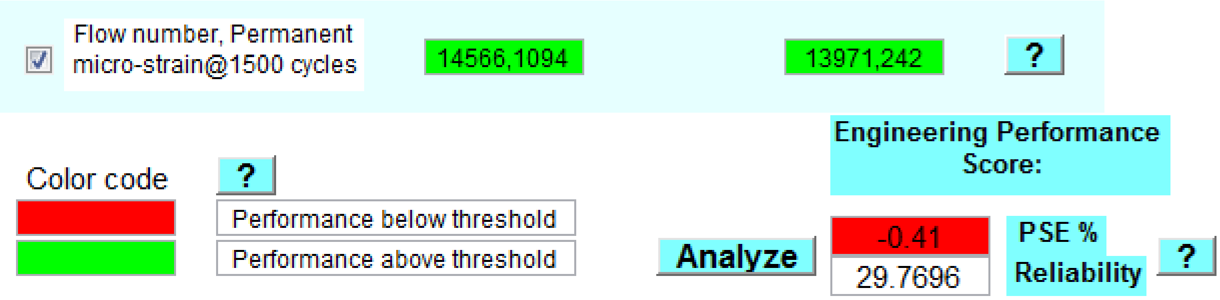
Step-2: Calculate Engineering Performance Score (PS^E)

$$PS_{FN}^{E} = \frac{\log(PD^{CM}) - \log(PD^{PM})}{\log(PD^{MDOT})} x100 = \frac{\log(13971) - \log(14566)}{4.45} x100 = -0.41\%$$

Reliability=29.77%

Figure 20 shows a snapshot of the NewPave software. As mentioned earlier, a negative value PS^E = -0.41 indicates a 0.41 percent poor performing LVSP mix compared to the 5E3 control mix. Further, a reliability of 29.77% indicates that the probability LVSP mix will perform better than the control mix is equal to 0.30.

Example-4 through Example-6 shows that the performance score based on flow number test is highest for CRTB followed by GTR, Control 5E3 and LVSP.


☑ Flow number, Permanent micro-strain@1500 cycles 14566,1094 13971,242

Engineering Performance Score: -0.41

PSE % Reliability 29.7696

Figure 20 Snapshot of the NewPave software

Example-7: Comparison of control mix with LVSP mix: IDT strength, psi

Step-1: Collect and review laboratory data of asphalt mixtures investigated.

Table 22 shows the IDT of the Control 5E3 and LVSP MDOT asphalt mixtures investigated.

Table 22: Example 2- IDT test inputs in Option II

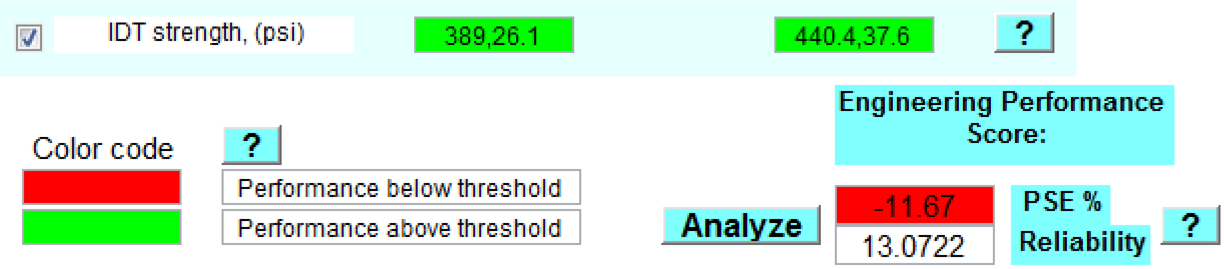
Mixture	Temperature (°C)	IDT strength (psi) (mean, standard deviation)
Control: 5E3 (32A)	10	440.4, 37.6
LVSP	10	389, 26.1

Step-2: Calculate Engineering Performance Score (PS^E)

$$PS^{E}_{IDT} = \frac{IDT^{PM} - IDT^{CM}}{IDT^{MDOT}} x100 = \frac{389 - 440.4}{440.4} x100 = -11.67\%$$

Reliability=13.07%

Figure 21 shows a snapshot of the NewPave software. As mentioned earlier, a negative value PS^E = -11.67 indicates 11.67 percent poor performing LVSP mix compared to the 5E3 control mix. Further, a reliability of 13.07% indicates that the probability LVSP mix will perform better than the control mix is equal to 0.13.



☑ IDT strength, (psi) 389,26.1 440.4,37.6

Color code

🟥 Performance below threshold

🟩 Performance above threshold

Engineering Performance Score:

-11.67

13.0722

PSE %

Reliability

Figure 21 Snapshot of the NewPave software

Option III (low level)

Option III in the software requires MEPDG Level 1 distress data on both the PM and CM as inputs. The procedure in the software has been verified using laboratory obtained MEPDG Level 1 inputs for MDOT mixtures.

Example-8: Comparison of control mix with High RAP CRTB mix: MEPDG Level 1

Step-1: Run the laboratory tests needed by the Pavement ME Design software for Level 1 analysis

The |E*| master curve, D(t) and IDT strength of the asphalt mixture, and |G*| master curve of the asphalt binder were measured for both the Control (4E1) and High RAP CRTB mixtures and input into Pavement ME Design software as Level 1 material inputs. Table 23 shows predicted fatigue cracking (both top-down and bottom-up), rutting, low temperature cracking, and roughness of the Control 4E1 and High RAP CRTB MDOT asphalt mixtures.

Table 23: Example 8 inputs in Option III (which are outputs of the the Pavement ME Design software)

Distress Type	Mixture	
	Control: 4E1(44)	New: High RAP CRTB
Terminal IRI (in./mile)	219.64	189.75
Permanent deformation - total pavement (in.)	1.21	0.81
AC bottom-up fatigue cracking (%)	76.21	49.71
AC thermal cracking (ft/mile)	27.17	27.17

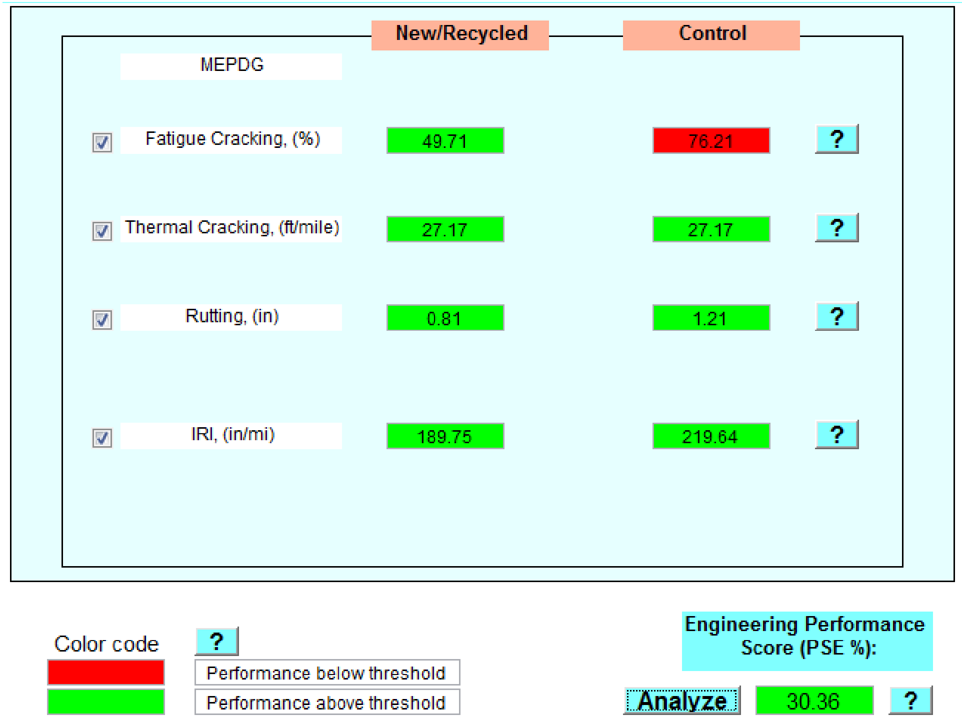
Step-2: Calculate Engineering Performance Score (PS^E)

$$PS^E = 100 \sum \delta_i w_i \left(\frac{Distress_i^{CM} - Distress_i^{PM}}{Distress_i^{MDOT}} \right)$$

$$= \left[\frac{1}{4} \left(\frac{219.64 - 189.75}{208.3} \right) + \frac{1}{4} \left(\frac{1.21 - 0.81}{1} \right) + \frac{1}{4} \left(\frac{76.21 - 49.71}{39.5} \right) + \frac{1}{4} \left(\frac{27.17 - 27.17}{2592.7} \right) \right] 100$$

$$= 30.36\%$$

Figure 22 shows the software output for Procedure-1 Option III. It should be noted that a positive value $PS^E = 30.36$ indicates 30.36 percent better performing GTR mix compared to the 5E3 control mix.



MEPDG	New/Recycled	Control	
☑ Fatigue Cracking, (%)	🟩 49.71	🟥 76.21	?
☑ Thermal Cracking, (ft/mile)	🟩 27.17	🟩 27.17	?
☑ Rutting, (in)	🟩 0.81	🟩 1.21	?
☑ IRI, (in/mi)	🟩 189.75	🟩 219.64	?

Color code ?

🟥 Performance below threshold

🟩 Performance above threshold

Engineering Performance Score (PSE %): 30.36

Figure 22: Software output for Procedure-1 Option III

Concrete Pavements (Procedure-2)

Option II

Option II for concrete pavements in the software is similar to Option III for asphalt pavements. Option II for concrete pavements requires MEPDG Level 1 distress data on both the PM and the CM as inputs. The procedure in the software has been verified using MEPDG Level 1 inputs recommended in a previous research project sponsored by MDOT (Buch et al. 2008 – MDOT RC 1516), Buch et al. (2008), referred to as the control mix.

Example-9: Comparison of control mix with 20AF mix: MEPDG Level 1

Step-1: Run the laboratory tests needed by the Pavement ME Design software for Level 1 analysis

Table 24 shows the Pavement ME Design predicted transverse cracking, joint faulting, and roughness of the Control and 20AF concrete mixtures.

Table 24: Example 9- MEPDG distress inputs in Option II

Distress Type	Mixture (JPCP)	
	Control	New: 20AF
Terminal IRI (in./mile)	210.19	208.37
Mean joint faulting (in.)	0.15	0.15
JPCP transverse cracking (percent slabs)	16.51	12.96

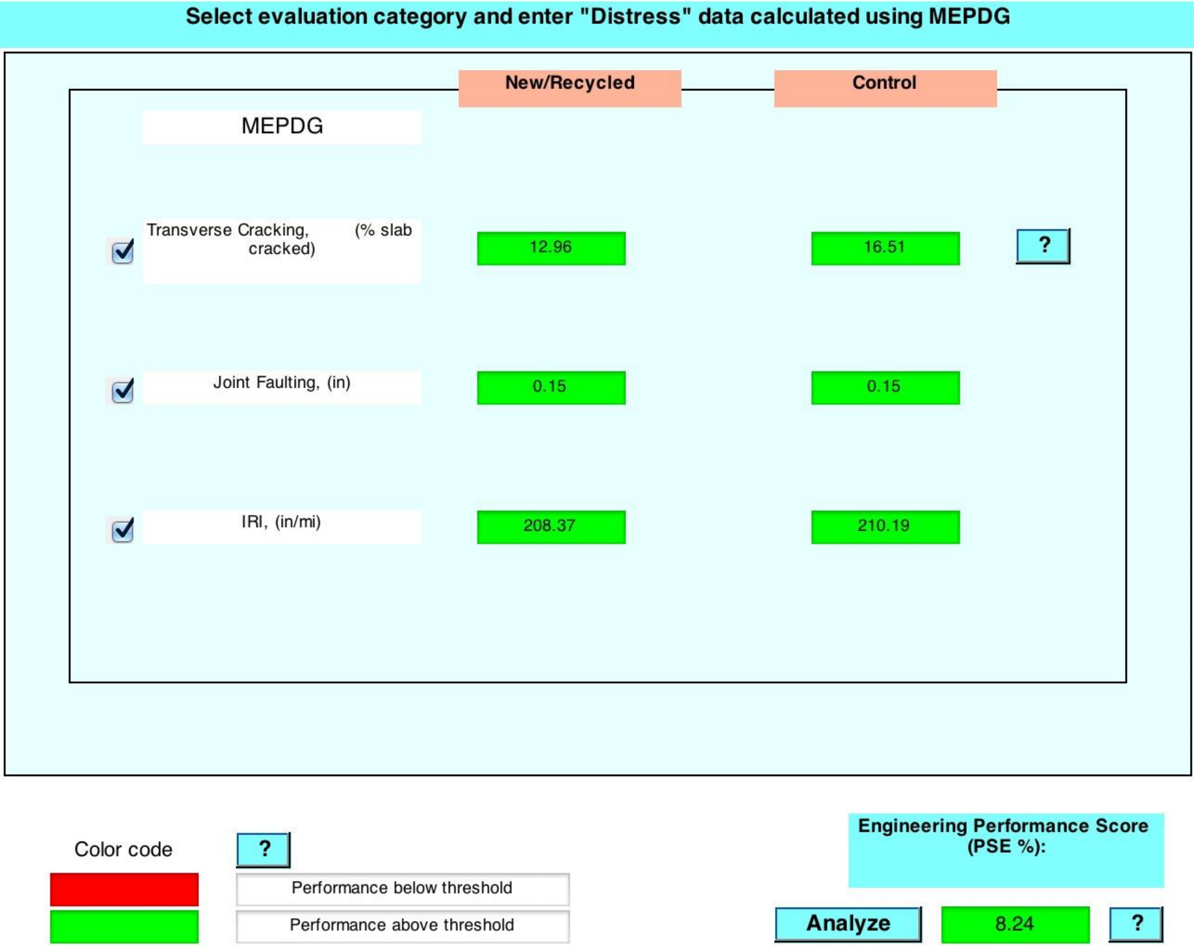
Step-2: Calculate Engineering Performance Score (PS^E)

$$PS^E = 100\sum \delta_i w_i \left(\frac{Distress_i^{CM} - Distress_i^{PM}}{Distress_i^{MDOT}}\right)$$

$$= \left[\frac{1}{3}\left(\frac{210.19 - 208.37}{172}\right) + \frac{1}{3}\left(\frac{0.15 - 0.15}{0.12}\right) + \frac{1}{3}\left(\frac{16.51 - 12.96}{15}\right)\right] 100$$

$$= 8.24\%$$

Figure 23 shows the software output for Procedure-2 Option II. It should be noted that a positive value PS^E = 8.24 indicates 8.24 percent better performing 20AF mix compared to the control mix.



Select evaluation category and enter "Distress" data calculated using MEPDG

MEPDG	New/Recycled	Control
☑ Transverse Cracking, (% slab cracked)	12.96	16.51
☑ Joint Faulting, (in)	0.15	0.15
☑ IRI, (in/mi)	208.37	210.19

Color code

🟥	Performance below threshold
🟩	Performance above threshold

Engineering Performance Score (PSE %): 8.24

Figure 23: Software output for Procedure-2 Option II

Base/subgrade (Procedure-3)

Option II

Option II in Base/Subgrade is similar to Option II in concrete pavements and Option III in asphalt pavements. In this option, the material is evaluated based on its performance, predicted using the Pavement ME Design software (a.k.a. MEPDG). Depending on whether the material is used in a flexible or rigid pavement, the appropriate MEPDG Level 1 option is chosen.

Example-10: Comparison of Class 5 aggregates with RAP blend Class 5 aggregates: MEPDG Level 1

The procedure in the software has been verified using Class 5 aggregates as CM and RAP blended Class 5 aggregates as PM in a flexible pavement. The specifications for the Class 5 aggregates and RAP blend for the base course were as per MDOT specifications.

Step-1: Run the laboratory tests needed by the Pavement ME Design software for Level 1 analysis

Table 25 shows the Pavement ME Design predicted fatigue cracking (both top-down and bottom-up), rutting, low temperature cracking, and roughness of the Class 5 aggregates and RAP blend.

Table 25: Example 10- Pavement ME Design software distress used as inputs in Option II

Distress Type	Mixture	
	Control: Class 5 aggregates	New: RAP
AC bottom-up fatigue cracking (percent)	55.11	46.81
AC thermal cracking (ft/mile)	27.17	27.17
Permanent deformation - total pavement (in.)	0.89	0.81
Terminal IRI (in./mile)	194.65	186.71

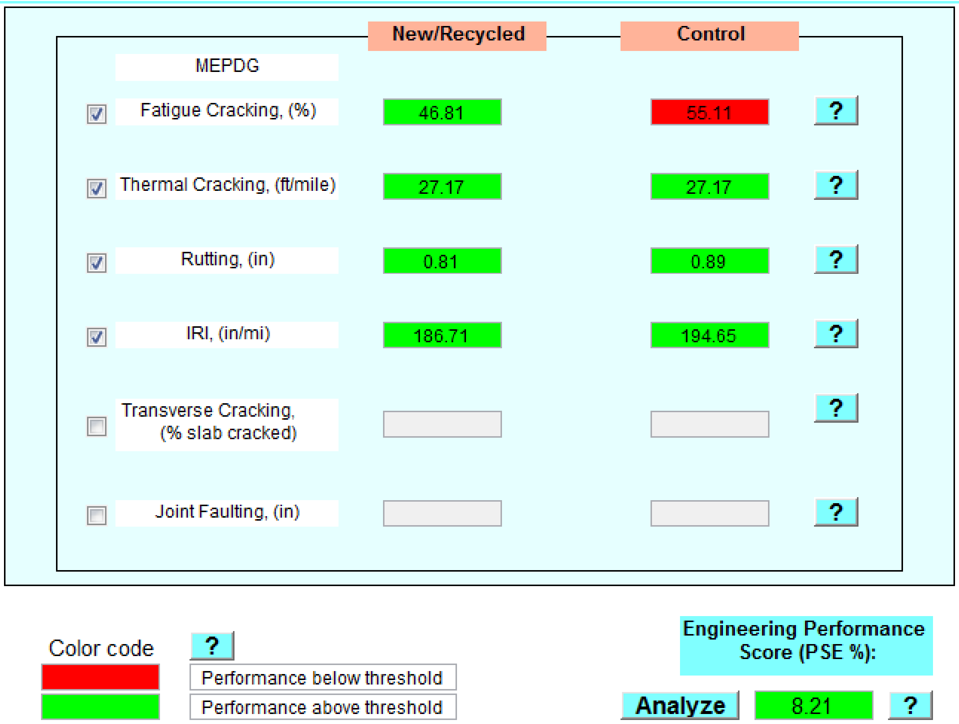
Step-2: Calculate Engineering Performance Score (PS^E)

$$PS^E = 100 \sum \delta_i w_i \left(\frac{Distress_i^{CM} - Distress_i^{PM}}{Distress_i^{MDOT}} \right)$$

$$= \left[\frac{1}{4}\left(\frac{194.65-186.71}{208.3}\right)+\frac{1}{4}\left(\frac{0.89-0.81}{1}\right)+\frac{1}{4}\left(\frac{55.11-46.81}{39.5}\right)+\frac{1}{4}\left(\frac{27.17-27.17}{2592.7}\right)\right]100$$

$$= 8.21\%$$

Figure 24 shows the software output for Procedure-3 Option II. It should be noted that a positive value $PS^E = 8.21$ indicates 8.21% better performing RAP mix compared to the control mix.



	MEPDG	New/Recycled	Control	
☑	Fatigue Cracking, (%)	🟩 46.81	🟥 55.11	?
☑	Thermal Cracking, (ft/mile)	🟩 27.17	🟩 27.17	?
☑	Rutting, (in)	🟩 0.81	🟩 0.89	?
☑	IRI, (in/mi)	🟩 186.71	🟩 194.65	?
☐	Transverse Cracking, (% slab cracked)			?
☐	Joint Faulting, (in)			?

Color code ?
🟥 Performance below threshold
🟩 Performance above threshold

Engineering Performance Score (PSE %): 8.21

Figure 24: Software output for Procedure-3 Option II

Stage II: Sustainability evaluation

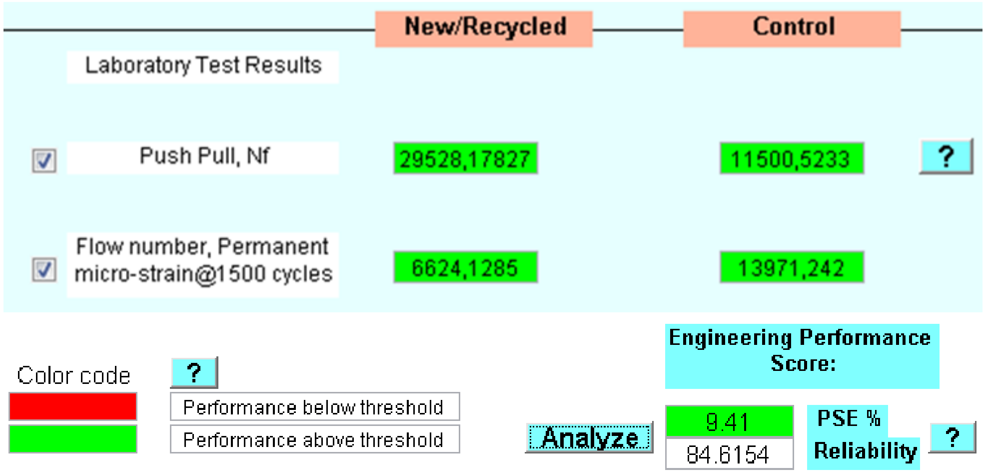
In this section, an example is presented to illustrate Stage II sustainability analysis in the NewPave software. In stage II analysis, proposed material is evaluated under three criteria: (a) economic analysis (b) environmental analysis and (c) social analysis.

Example-11: Comparison of control mix with CRTB mix

In this example, CRTB and a control mixture 5E3 are compared. The details of the verification procedure are given below:

Step-1: Perform Stage I analysis.

Stage II analysis in the software requires engineering performance results from Stage I as an input. Therefore, Stage I analysis is mandatory before running Stage II. In this example push-pull and FN test results measured from laboratory were used in Stage I (Option II) analysis. Figure 25 shows a snapshot of the NewPave software input panel and the PSE (engineering performance score) computation. Reliability computed by the software is 84.62%. It is noted that a positive value $PS^E = 9.41$ indicates 9.41 percent better performing CRTB mix compared to the 5E3 control mix. Further, a reliability of 84.62% indicates that the probability CRTB mix will perform better than the control mix is equal to 0.846.



	Laboratory Test Results	New/Recycled	Control
☑	Push Pull, Nf	29528,17827	11500,5233
☑	Flow number, Permanent micro-strain@1500 cycles	6624,1285	13971,242

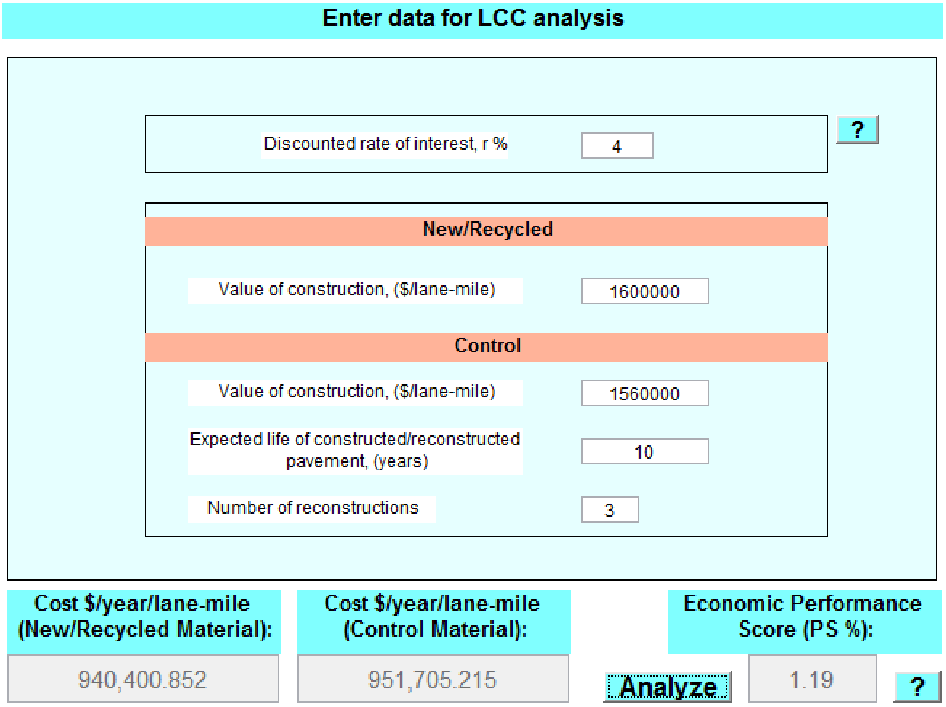
Color code
🟥 Performance below threshold
🟩 Performance above threshold

Engineering Performance Score:
PSE %: 9.41
Reliability: 84.6154

Figure 25 Snapshot of the NewPave software: Stage I, Option II

Step-2: Perform economic analysis.

After the Stage I analysis is successfully completed, first, economic analysis is performed as part of Stage II. Figure 26 shows the software input and output screen for economic analysis. As an input, the software requires expected life of pavement reconstructed/constructed using proposed material and number of reconstructions expected during the analysis period. Expected life of pavement constructed using proposed material is then calculated by the software based on engineering performance (obtained from Stage I). Note that a positive value PS = 1.19% indicates a 1.19 percent reduction in cost if the proposed material is used.



Enter data for LCC analysis

Discounted rate of interest, r %: 4

New/Recycled

Value of construction, ($/lane-mile): 1600000

Control

Value of construction, ($/lane-mile): 1560000

Expected life of constructed/reconstructed pavement, (years): 10

Number of reconstructions: 3

Cost $/year/lane-mile (New/Recycled Material): 940,400.852

Cost $/year/lane-mile (Control Material): 951,705.215

Economic Performance Score (PS %): 1.19

Figure 26 Snapshot of the NewPave software: Stage II, environmental analysis.

Step-3: Perform environmental analysis.

After the economic analysis is successfully completed, environmental analysis module is activated. In environmental analysis LCA is used to compare a proposed and control mix. As shown in Figure 27, this requires developing an inventory of material and an inventory of equipment for both the proposed and control mix construction.

Figure 27 shows per year metric ton CO2 emission expected over the design period. It should be noted that a positive value PSE = 9.73 indicates 9.73% reduction in CO2 emissions when CRTB is used.

Step-4: The last module in sustainability analysis is social analysis. In social analysis, each parameter in the module can be scored over a scale 0-10, 0 being the best and 10 being the best. It is well known that rubber modified pavement have benefits such as: noise reduction, and land fill save. However, the importance of parameters in the social analysis typically varies from project to project. In this example it was assumed that the proposed material improves the landfill condition by 10% and reduces noise by 20%.

New Construction

List of materials

Item	Mult	Unit	QTY
Aggregates 21A	0.0061	Ton	98106
Natural Aggregates	0.0061	Ton	68115
Asphalt Binder PG 5...	0.1569	Ton	5191
Recycled Tires	0.1100	Ton	519

List of equipments

Item	Mult	Unit	No	hrs
Air Compressor	0.0173	No	3	8
Rollers	0.0182	No	316	5
Paver	0.0188	No	77	6
Tractor	0.0203	No	173	8

CO2 emission (Ton/year) (New/Recycled):

59.454

New Construction

List of materials

Item	Mult	Unit	QTY
Aggregates 21A	0.0061	Ton	98106
Natural Aggregates	0.0061	Ton	68115
Asphalt Binder PG 5...	0.1569	Ton	5710

List of equipments

Item	Mult	Unit	No	hrs
Air Compressor	0.0173	No	3	8
Rollers	0.0182	No	316	5
Paver	0.0188	No	77	6
Tractor	0.0203	No	173	8

CO2 emission (Ton/year) (Control):

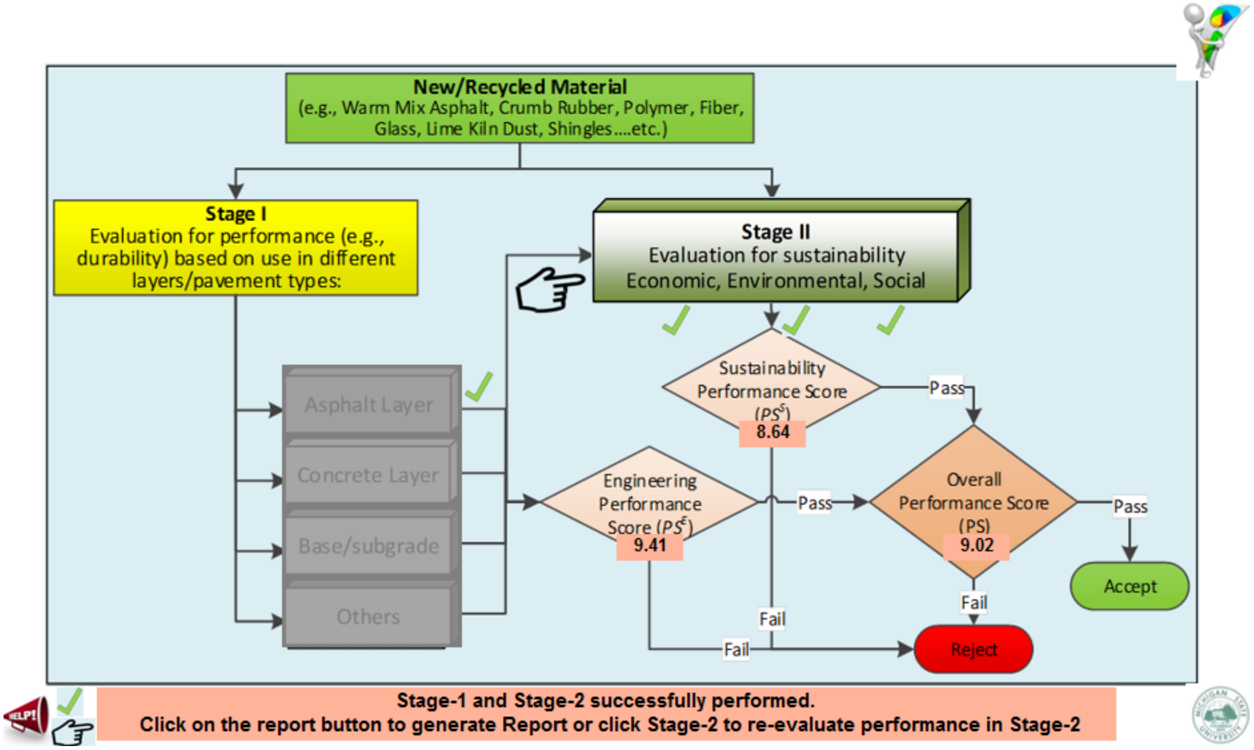
65.86

Environment Performance Score (PSE):

9.73

Figure 27: Snapshot of the NewPave software: Stage II, environmental analysis.

In the software the final sustainability score is computed by taking the average of the scores obtained in environmental, economic and social analysis. Figure 28 shows the main page at the end of the analysis.



Stage-1 and Stage-2 successfully performed.
Click on the report button to generate Report or click Stage-2 to re-evaluate performance in Stage-2

Figure 28 Snapshot of the NewPave software: Main page at the end of the analysis.

CONCLUSIONS

This project produced an analysis framework for evaluation of new and recycled materials that may be proposed to be used in pavements in Michigan. The analysis framework included two basic components: (1) Engineering performance evaluation and (2) Sustainability evaluation. The engineering performance evaluation included several options for each kind of material used in different layers of pavements. For asphalt pavements, there are three options. The first option is based on the field data that may be presented by the proposer of a new/recycled material. The second option is laboratory performance data such as the push pull fatigue, flow number and IDT strength tests. The third option involves prediction of performance using Level 1 inputs in Pavement ME Design software. For concrete pavements, there are two options. First option, similar to asphalt pavements, is based on field data. The second option for concrete pavements is analysis using Pavement ME Design software. For Unbound layers, similar to concrete pavements, there are two options; (i) field data and (ii) an analysis using the Pavement ME Design software. For other types of materials, there is only one option, which is field performance data. Once data for any option is presented to MDOT (by an entity), MDOT can input these data into the NewPave software to calculate an Engineering Performance Score (PS^E). The PS^E represent the percent improvement of performance relative to a control material. For example, PS^E=0 means the new material is expected to perform as good as a control material. PS^E=10 means new material will perform 10% better than the control material (i.e., new material's life is 10% longer than the control) and PS^E=-10 means the new material will perform 10% worse than the control material.

The second stage of the analysis framework presented in this report is the sustainability analysis. The sustainability analysis of a new material includes three basic components: (1) Environmental, (2) Economic and (3) Social analyses. At the end of the analysis of each component, a performance score based on sustainability (PS^S) is computed. It is worth noting here that the engineering performance score is used as an input to the analysis for the sustainability performance, in the environmental and economic analysis components. Once the engineering and sustainability performance scores are computed, they are combined to compute an overall performance score. Several example analyses presented in the report showed reasonable predictions of performance scores that indicate the relative performance of various kinds of new and recycled materials used/proposed in the past.

RECOMMENDATIONS FOR IMPLEMENTATION

This research produced the NewPave software. MDOT engineers are recommended to use this software to evaluate new and recycled materials proposed to be used in pavements. The research team recommends that MDOT requests data from the proposer of a new or recycled material and inputs to the NewPave software to compute the overall performance scores. For example, a new material is proposed by an entity for asphalt pavements. MDOT gives 3 options to the proposer to provide data on an asphalt mixture made with this new material and a control asphalt mixture as close to the mixture with new material as possible. Option I is to present MDOT with field data. Option II is to present laboratory mixture testing data, and Option III is Level 1 data for an analysis using the Pavement ME Design software. Once the proposer presents data by choosing one of these options, an MDOT engineer will input this data into the NewPave software to compute the performance score. If the performance score is larger than 0, this means that the proposed material is expected to perform better than the approved control mixture. A similar approach has been proposed for concrete materials, except that in concrete and unbound materials, there are only two options: (1) Field data and (2) Level 1 analysis using the Pavement ME Design software. For other materials that do not fit in the category of asphalt, concrete or unbound layers, the proposer will have only one option, i.e., provide MDOT with field performance data, which is input into the NewPave software to compute its engineering performance score.

REFERENCES

Allen, D., and Shonnard, D. (2012). “Sustainable engineering concept, design and case studies” Prentice Hall.

Apeagyei, A.K, Diefenderfer, B.K., and Diefenderfer, S.D. (2011) “Rutting Resistance of Asphalt Concrete Mixtures That Contain Recycled Asphalt Pavement” *Transportation Research Record: Journal of the Transportation Research Board, No. 2208*

Apeagyei, A.K., Clark, T.M., and Rorrer, T.M. (2013) “Stiffness of High-RAP Asphalt Mixtures: Virginia’s Experience” *Journal of Materials in Civil Engineering*

Arulrajah, A., Piratheepan, J., Aatheesan, T., and Bo, M.W. (2011) “Geotechnical Properties of Recycled Crushed Brick in Pavement Applications” *Journal of Materials in Civil Engineering*

BE^{2}ST (2010) BE2ST-IN-Highways, Manual, Recycled Material Resources Center, University of Wisconsin-Madison.

Brosseaud, Y., V. Gaudefroy, et al. (2008). "Laboratory assessment of the mechanical properties of in-situ cold-recycled asphalts

Caltrans, (2010). “Smart Mobility 2010 A call to Action for the New Decade.” California Department of Transportation.

Collins, R.J., and Ciesielski, S.K. (1994) NCHRP Synthesis 199 “Recycling and Use of Waste Materials and By-Products in Highway Construction”

CTC & Associates LLC., (2013). “Sustainability tools and practices: An examination of selected state departments of transportation, California metropolitan planning organizations and national tools.” Preliminary Investigation, Caltrans division of research and innovation.

Dongre, R., R. May, et al. (2009). Discussion. Asphalt Paving Technology 2009, AAPT, March 15, 2009 - March 18, 2009, Minneapolis, MN, United states, Association of Asphalt Paving Technologist.

Edil, T.B., Tinjum, J.M., and Benson, C.H. (2012) “Recycled Unbound Materials” Research Project Final Report: Report No. 2012-35 http://www.lrrb.org/pdf/201235.pdf

Edwards, P. (2003). "Recycling and Secondary Materials in Highway Construction." Transportation Professional(10): 18.

Eisenmann, A., (2012), Sustainable streets and highways: an analysis of green roads rating systems, MS thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology.

Evaluacion en laboratorio de las propiedades mecanicas de las mezclas bituminosas recicladas in situ mediante tecnicas en frio." Carreteras 4(158): 74-83.

Fini, E. H., I. L. Al-Qadi, et al. (2012). "Partial replacement of asphalt binder with bio-binder: Characterisation and modification." International Journal of Pavement Engineering 13(6): 515-522.

Forster, S. (2000). "HIPERPAV-Guidance to avoid early-age cracking in concrete pavements." ACI SPECIAL PUBLICATIONS 192: 1109-1122.

Forster, S. W. (1998). "HIPERPAV: A User-Friendly Tool to Help Us" Build It Right"." Public Roads 61(6).

Gabr, A.R., and Cameron, D.A. (2012) “Properties of Recycled Concrete Aggregate for Unbound Pavement Construction” *Journal of Materials in Civil Engineering*

Gibson, N., Qi, X., Shenoy, A., Al-Khateeb, G., Kutay, M. E., Andriescu, A., Stuart, K., Youtcheff, J., Harman T. (2012) Full-Scale Accelerated Performance Testing for Superpave and Structural Validation, Transportation Pooled Fund Study TPF-5(019) and SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements. FHWA-HRT-11-045. 297 p.

Greenroads (2011), Greenroads Manual V1.5.

Hendrickson, C., A. Horvath, et al. (1998). "Economic input-output models for environmental life-cycle assessment." Environmental Science and Technology 32(7): 184A-191A.

Horvath, A. (2003). Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements, University of California Transportation Center (UCTC).

I-LAST (2010). “Illinois-livable and sustainable transportation rating system and guide.” Illinois Department of Transportation and Illinois Joint Sustainability Group.

Kutay, M. E. and H. I. Ozturk (2012). "Investigation of Moisture Dissipation in Foam-Based Warm Mix Asphalt Using Synchrotron-Based X-Ray Microtomography." Journal of Materials in Civil Engineering 24(6): 674-683.

Kutay, M. E. and Jamrah, A. (2013) “Preparation for Implementation of the Mechanistic-Empirical Pavement Design Guide in Michigan, Part 1: HMA Mixture Characterization”, Michigan Department of Transportation (MDOT) Research Report, ORBP OR10-022, REPORT NO RC-1593, 120 p.

Lambert, J. P., P. R. Fleming, et al. (2008). "The assessment of coarse granular materials for performance based pavement foundation design." International Journal of Pavement Engineering 9(3): 203-214.

Louis, R. A. (2010). Sustainable Bridges: Green Links to the Future.

MacDonald, D., Foy, D., Glyn, A., Meyer, M., Partridge, E., Sundquist, E., Halikowski, J., and Hunkins, H. (2011). “SSTI review of PennDOT’s Smart Transportation.” Pennsylvania State Department of Transportation.

Mauricio Ruiz, J., P. J. Kim, et al. (2001). "Validation of HIPERPAV for prediction of early-age jointed concrete pavement behavior." Transportation Research Record: Journal of the Transportation Research Board 1778(-1): 17-25.

Mauricio Ruiz, J., R. O. Rasmussen, et al. (2002). "Paving the Way-User-friendly HIPERPAV software makes it possible to simulate problems before they happen." Public Roads 66(1): 20-24.

McCullough, B. and R. Rasmussen (1999). Fast-Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonded Concrete Overlays, Vol. II. HIPERPAV User’s Manual, Report FHWA-RD-98-168. FHWA, US Department of Transportation.

Mengqi Wu (2011) “Evaluation of High Percentage Recycled Asphalt Pavement as Base Course Materials” M.Sc Thesis. Washington State University.

Miller, T. and H. Bahia (2009) "Sustainable Asphalt Pavements: Technologies, Knowledge Gaps and Opportunities " White Paper, 7.

Mills-Beale, J., and You, Z. (2010) “The mechanical properties of asphalt mixtures with Recycled Concrete Aggregates” Journal of Construction and Building Materials

Moon C. Won (2001) “Performance of Continuously Reinforced Concrete Pavement Containing Recycled Concrete Aggregate” *Final Report: Performing Organization*

Report No. 01-1753-1 [*http://www.depts.ttu.edu/techmrtweb/Reports/Complete%20Reports/0-1753-1.pdf*](http://www.depts.ttu.edu/techmrtweb/Reports/Complete%20Reports/0-1753-1.pdf)

Muench, S. T., J. Anderson, et al. (2010). "Greenroads: A sustainability rating system for roadways." International Journal of Pavement Research and Technology 3(5): 270-279.

NDOT (2011) "North Carolina State Transportation plan challenges and opportunities."

Nunes, M. C. M., M. G. Bridges, et al. (1996). "Assessment of secondary materials for pavement construction: technical and environmental aspects." Waste Management 16(1-3): 87-96.

NYSDOT (2010). "GreenLITES project design certification program, recognizing leadership in transportation in transportation and environmental sustainability." New York State Department of Transportation.

ODOT, (2008). "The Oregon Department of Transportation Sustainability Plan Volume 1: Setting the Context." Oregon Department of Transportation 355 Capitol St. NE Salem, OR 97301.

ODOT, (2012). "ODOT sustainability plan Vol II, Sustainability management framework for ODOT's internal operations." Oregon Department of Transportation 355 Capitol St. NE Salem, OR 97301.

Ozturk, H., B. Tascioglu, et al. (2010). Impact of Crumb Rubber Modified Binder Preparation Process on Hot Mix Asphalt Performance. 5th Eurasphalt & Eurobitume Congress, Istanbul, Turkey.

Ramani, T., Zietsman J., Knowles, W., and Quadrifoglio, L., (2011) "Sustainability Enhancement Tool for State Departments of Transportation Using Performance Measurement." Journal of Transportation Engineering, Vol. 137, No. 6, pp. 404-415.

Ruiz, J. M., R. O. Rasmussen, et al. (2005). Computer-Based Guidelines for Concrete Pavements. Volume II--Design and Construction Guidelines and HIPERPAV II User's Manual.

Ruiz, J., R. Rasmussen, et al. (2007). "Characterization of concrete paving mixtures with HIPERPAV." ACI SPECIAL PUBLICATIONS 241: 77.

Ruiz, J., S. Garber, et al. (2009). "HIPERPAV III-An Enhanced FHWA Software for Simulating Early-Age Concrete Pavement Behaviors."

Saeed, A. (2008) "Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers" NCHRP Report 598, Project 04-31

Saravanakumar, P., and Dhinakaran, G. (2013) "Strength Characteristics of High-Volume Fly Ash–Based Recycled Aggregate Concrete" *Journal of Materials in Civil Engineering*

Stroup-Gardiner, M., and Wattenberg-Komas, T. (2013) NCHRP Synthesis 435 "Recycled Materials and Byproducts in Highway Applications- Summary Report, Volume 1"

Tangchirapat, W., Chaiyanunt, R., Buranasing, R., and Jaturapitakkul, C. (2013) "Influence of Fly Ash on Slump Loss and Strength of Concrete Fully Incorporating Recycled Concrete Aggregates" Journal of Materials in Civil Engineering

Tascioglu, B. (2013) "Performance and sustainability – based analysis of different crumb rubber modified asphalt mixtures." MS thesis, Department of Civil and Environmental Engineering, Michigan State University.

Taskiran, D., E. Taskiran, et al. (1999). "Quantification of total collagen in rabbit tendon by the sirius red method." Turkish Journal of Medical Sciences 29(1): 7-9.

Terrel, R. L. and R. G. Hicks (2008). Viability of Hot In-Place Recycling as a Pavement Preservation Strategy. Chico, California Pavement Preservation Center: 28.

Tupper, K. and J. F. Kreider (2006). A life cycle analysis of hydrogen production for buildings and vehicles. 2005 Materials Research Society Fall Meeting, November 28, 2005 - November 30, 2005, Boston, MA, United states, Materials Research Society.

U.S. Department of Transportation Federal Highway Administration (2012) *INVEST Sustainable Highways Self- Evaluation Tool*.

Uhlman, B. W. and P. Saling (2010). "Measuring and communicating sustainability through Eco-efficiency analysis." Chemical Engineering Progress 106(12): 17-26d.

Vargas-Nordcbeck, A., and Timm, D.H. (2013) "Physical and Structural Characterization of Sustainable Asphalt Pavement Sections at the NCAT Test Track" *Final Report: NCAT Report 13-02* http://ncat.us/files/reports/2013/rep13-02.pdf

WDOT, (2011). "Regional Greenhouse Gas and Vehicle Miles Traveled Reduction Strategies." Report on Section 2(b).

Wu, S., H. Yue, et al. (2009). Performances research of hybrid fiber reinforced asphalt concrete. 6th International Forum on Advanced Material Science and Technology, IFAMST 2008, June 12, 2008 - June 14, 2008, Hong Kong, China, Trans Tech Publications Ltd.

Wu, Z., Zhongjie, Z., and King, Jr., W.M, et al. (2012) "Accelerated Loading Evaluation of Stabilized BCS Layers in Pavement Performance" *Final Report, Report No.: FHWA/LA.08/474* http://www.ltrc.lsu.edu/pdf/2012/fr_474.pdf

Xiao, F., Amirkhanian, S., and Juang, C. H. (2007) "Rutting Resistance of Rubberized Asphalt Concrete Pavements Containing Reclaimed Asphalt Pavement Mixtures" Journal of Materials in Civil Engineering

Zhang, H., G. A. Keoleian, et al. (2008). An integrated life cycle assessment and life cycle analysis model for pavement overlay systems. 1st International Symposium on Life-Cycle Civil Engineering, IALCCE'08, June 11, 2008 - June 14, 2008, Varenna, Lake Como, Italy, CRC Press.

Zietsman, J., Ramani, T., Potter J., Reeder, V., and Deflorio, J. (2011). "A guidebook for sustainability performance measurement for transportation agencies." NCHRP Report 708.