Benefits of MnROAD Phase-II Research

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The Minnesota Road Research Project (MnROAD) is an accelerated pavement test facility owned and operated by the Minnesota Department of Transportation (MnDOT). The facility, located along Interstate 94, northwest of the Twin Cities metropolitan area, was constructed 1990-1993 and opened to traffic in 1994.

This report summarizes the outcome of the many different projects that were completed during MnROAD Phase-II which began in 2007 and is now coming to a close. Detailed information is provided related to the cost of operating the facility, support from MnDOT Office of Materials of Research (OMRR), Minnesota Local Road Research Board (MN LRRB) as well as research funding from MnDOT and external sources.

The approach utilized in this report does not take into account economic factors such as the time value of money. Direct calculation of monetary benefits for a specific research project is difficult at best. Assumptions must be made concerning construction costs and pavement performance. However, where feasible, the potential benefits of these research projects are quantified with the assumptions forming the basis for these estimates clearly stated.

Based on calculations the benefit of MnROAD Phase-II is estimated to be over $10 million per year. This estimate may be increased by $8 million per year provided that a lowering of the minimum noise level reduction requirements could be realized.

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Executive Summary

The Minnesota Road Research Project (MnROAD) is an accelerated pavement test facility owned and operated by the Minnesota Department of Transportation (MnDOT). The facility, located along Interstate 94, northwest of the Twin Cities metropolitan area, was constructed 1990-1993 and opened to traffic in 1994.

Transportation research is essential to help provide safe, efficient and cost-effective movement of people, goods, and services that are the backbone of our economy. Even modest increases in performance and pavement life can result in a reduction of costs for maintenance, repairs, user delays, and congestion. Implemented products from pavement research activities improve our national productivity and quality of life.

This report summarizes the outcome of the many different projects that were completed during MnROAD Phase-II, which began in 2007 and is now coming to a close. Detailed information is provided related to the cost of operating the facility, support from MnDOT Office of Materials of Research (OMRR) and the Minnesota Local Road Research Board (MN LRRB), research funding from MnDOT, and external sources.

The approach utilized in this report does not take into account economic factors such as the time value of money. Direct calculation of monetary benefits for a specific research project is difficult at best. Assumptions must be made concerning construction costs and pavement performance. However, where feasible, the potential benefits of these research projects are quantified with the assumptions forming the basis for these estimates clearly stated. There are several possible approaches to analyze benefits as follows:

- Direct – Savings are realized due to either materials or enhanced performance; defensible monetary benefits in terms of estimates based on known materials costs and stated assumptions;
- Indirect – New or streamlined construction processes that save time and/or improvement to quality, improvements to performance due to enhanced quality; benefits difficult to quantify;
- Avoidance – MnROAD is a more conducive setting for construction of test cells that may be considered risky elsewhere. Due to the nature of MnROAD, it is possible to incorporate treatments that are considered high risk elsewhere. Therefore, it is possible to learn whether a particular approach might work before attempting it on a real project. Benefits are obtained by avoiding similar mistakes elsewhere as well as wasted resources from having to rebuild a section after an early failure, undue traffic delays, and loss of public trust.
- Demonstration – Technology transfer through demonstration of procedures, process, new materials, or equipment; instill confidence in users to try something new; difficult to quantify benefits.

For direct savings, calculation of benefits might include factors such as:

- Economic lifecycle cost analysis based on construction costs and discount rates;
- Cost benefit of avoidance (learning from mistakes);
- Savings in maintenance costs;
- Reduced noise from quieter pavements (environmental cost);
- Savings in materials costs; and
- Savings from extending pavement service life.

As described above, some types of research do not have direct, quantifiable payoffs. In addition, many benefits are qualitative in nature, making it hard to tie to dollar amounts. For example, although MnDOT

will most likely not construct mainline sections of pervious concrete or porous asphalt, the research completed at MnROAD has demonstrated several important results. In fact, the results have prompted some local agencies to implement these systems within their road networks as a means of treating storm water. Furthermore, in terms of data requests by external clients, these sections are some of the most frequently requested. Additionally, many of the Phase-II projects were pooled-fund studies. It is difficult to quantify the benefits of research that are adopted and implemented by project member pooled-fund states, or even states that did not participate. However, by nature of pooled-funds projects, other states gain benefit from the work as well. These are not quantified in this report.

Based on calculations, the benefit of MnROAD Phase-II is estimated to be over $10 million per year. This estimate may be increased by $8 million per year provided that a lowering of the minimum noise level reduction requirements could be realized. In addition, there are other intangible benefits that are difficult to place a dollar figure on such as:

- New product testing and approval – There is value in MnDOT evaluating a new material or process in order to validate industry claims.
- Data to support justification of a new policy or specification – Research results can provide data needed to make a strong case for a new approach to management, or the legislature.
- Cooperative research – MnROAD data is available for use by other agencies and has supported numerous research efforts outside of Minnesota.

Phase-II findings and benefits presented in this report are believed to be a conservative estimate. However, had these types of results been accounted for, it is likely that benefits would be higher.

CHAPTER 1. INTRODUCTION

This report summarizes the outcome of the many different projects that were completed during MnROAD Phase-II which began in 2007 and is now coming to a close. Detailed information is provided related to the cost of operating the facility, support from MnDOT Office of Materials of Research (OMRR), Minnesota Local Road Research Board (MN LRRB) as well as research funding from MnDOT and external sources.

Benefits analyzed in this report primarily document those for MnDOT trunk highways; however, benefits to the local systems are addressed where feasible. Additional research partners including other State Department of Transportations, Federal Highway Administration (FHWA), and Industry have benefitted from partnerships and combined efforts however estimation of their benefits is beyond the scope of this report.

The approach utilized in this report does not take into account economic factors such as the time value of money. Direct calculation of monetary benefits for a specific research project is difficult at best. Assumptions must be made concerning construction costs and pavement performance. However, where feasible, the potential benefits of these research projects are quantified with the assumptions forming the basis for these estimates clearly stated. There are several possible approaches to analyze benefits as follows:

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- Demonstration – Technology transfer through demonstration of procedures, process, new materials, or equipment; instill confidence in users to try something new; difficult to quantify benefits.

For direct savings, calculation of benefits might include factors such as:

- Economic lifecycle cost analysis based on construction costs and discount rates;
- Cost benefit of avoidance (learning from mistakes);
- Savings in maintenance costs;
- Reduced noise from quieter pavements (environmental cost);
- Savings in materials costs; and
- Savings from extending pavement service life.

1.1 MnROAD Background

The Minnesota Road Research Project (MnROAD) is a cold region pavement testing facility and laboratory located near Albertville, Minnesota. Operated by the Minnesota Department of Transportation (MnDOT), this facility celebrated its 20th anniversary in August 2014. Since 1994, MnDOT has partnered with the Minnesota Local Road Research Board (LRRB), state DOTs from around the country, the Federal Highway Administration (FHWA), industry, universities, and international organizations to complete projects related to pavement materials and design, construction techniques, performance, and maintenance.

MnROAD is located along Interstate 94, forty miles northwest of Minneapolis/St.Paul. It currently consists of two separate roadway segments containing over 70 test cells. Test cell length varies from 24 to 512 feet, and each cell is unique, consisting of different combinations of surface materials (asphalt, concrete, pervious asphalt, or pervious concrete), aggregate bases, and subgrades, as well as variations in structural design and drainage features. MnROAD is located in a wet-freeze climatic zone, and over the years, researchers have been able to study new pavement construction, rehabilitation and preservation techniques as each test cell deteriorates.

The three MnROAD roadway segments are:

- A 3.5-mile, 2-lane Interstate mainline carrying "live" I-94 traffic, averaging 26,500 vehicles per day with 13 percent trucks for the westbound lanes providing approximately 750,000 flexible and 1,000,000 rigid Equivalent Single Axle Loads (ESALs) per year.
- A 2.5-mile 2-lane closed loop Low Volume Road (LVR). Traffic on the LVR is restricted to the inside lane, provided by the MnROAD 80-kip, 5-axle, tractor/trailer combination which averages 70 laps a day.
- A 1000-foot two lane roadway in MnROAD's stockpile area used for testing implments of husbandry and allowing contractors to "test" new paving methods before materials are placed on the mainline or low volume roadway.

MnROAD has gone through two phases since it was originally constructed. Phase-I primarily investigated concrete and asphalt structural (thickness) designs. Phase-II was designed around unique partnerships with government, academia, and industry, who worked both through MnDOT and the Transportation Engineering and Road Research Alliance (TERRA) to develop the required support for the construction of test cells and research projects that use and implement the findings. This report highlights the past Phase-I benefits but focuses primarily on documenting Minnesota's economic benefits resulting from MnROAD's Phase-II research. This report will show that small increases in pavement performance can result in large savings for road users.

1.2 Minnesota's Current Highway Assets

The MnDOT trunk highway system consists of approximately 12,000 centerline miles of pavement. This system consists of bituminous, concrete, and composite pavement with a wide range of condition, age, and performance trends. In contrast, the total highway network in Minnesota, comprised of networks listed in Table 1.1 below, is nearly 143,000 centerline miles. Roadways under MnDOT management therefore comprise only about 8 percent of the total network in Minnesota.

Due to the scope of the infrastructure and costs associated with rehabilitation and preservation even modest increases in performance, reductions in cost, or efficiencies in construction, have far-reaching implications in terms of maximizing use of available resources.

During the past year the Office of Materials and Road Research (OMRR) has focused efforts in support of MnDOT's "wildly important goal" of enhancing financial effectiveness. With this objective it is even more imperative to support innovation through an active pavement and materials research program. Pavement research is essential to develop and implement products that improve the ways in which we specify, construct, preserve, and maintain our pavement network. Several ways in which quality research can significantly impact infrastructure asset management are as follows:

- Additional pavement life due to use of better materials
- Conserve resources through optimization of designs, more cost-effective use of materials

- Reduced user delays from faster construction, longer-lasting fixes
- Lower cost fixes

Table 1.1 - State of Minnesota Roadway Network Statistics.

SYSTEM	Total 2014 Centerline Miles	Total 2014 Lane Miles
INTERSTATE TRUNK	916.5	4,055.2
U.S. TRUNK	3,228.9	8,648.7
MINNESOTA TRUNK	7,668.5	16,584.0
COUNTY STATE AID	30,623.9	62,483.0
MUNICIPAL STATE AID	3,504.8	7,793.8
COUNTY	14,197.3	28,415.8
TOWNSHIP	56,633.3	113,266.2
UNORG. TOWNSHIP	2,053.2	4,106.4
MUNICIPAL STREETS	18,910.7	37,873.6
NATIONAL PARK	3.8	7.6
NAT. FOREST DEVEL.	2,785.4	5,570.8
INDIAN RESERVATION	676.6	1,353.0
STATE FOREST	1,308.8	2,617.6
STATE PARK	244.6	489.2
MILITARY	20.3	45.3
NATIONAL MONUMENT	1.3	2.6
NATIONAL WILDLIFE	109.7	219.6
STATE GAME PRESERVE	0.3	0.5
PRIVATE ROADS	26.0	56.0
TOTALS	142,913.8	293,589.0

Overall, Minnesota invests a significant amount of resources in its transportation system. According to the State of Minnesota 2015-2018 State Transportation Improvement Program (STIP) [1] approximately $4.8 billion is designated for highway construction programs over the next four fiscal years.

Table 1.2 - 2015-2018 State of Minnesota State Transportation Improvement Program.

	Program Amounts by FY (millions)				
Program Area	2015	2016	2017	2018	TOTALs
Highway Programs	$1,504	$1,145	$1,227	$936	$4,812
Total STIP	$1,965	$1,687	$1,807	$1,282	$6,741
Highway Programs (%)	77	68	68	73	71

The figures in Table 1.2 represent a comprehensive program including many different types of projects such as bridges, state aid, airports, etc. Of this amount, 15 to 20 percent, or approximately $300 million annually, are anticipated for actual trunk highway pavement rehabilitation projects that extend roadway life by restoring structure, and improving ride quality. In comparison, funding for pavement materials and performance research is small compared to the overall size of the program; the total budget for MnROAD and the Road Research Sections of MnDOT OMRR are about $2.5 million annually.

In contrast, based on MnDOT pavement management system (PMS) records, over the past five years MnDOT has resurfaced an average 1,000 miles of roadway each year. At the same time, the conditions of certain segments of the network are poor and continuing to deteriorate due to several factors including lack of resources and the need for more permanent fixes. Based on 2000 and 2013 data, the Minnesota trunk highway network was comprised of about 14,100 and 14,300 roadway miles, respectively. The health of the MnDOT roadway network is typically quantified using several different performance measures. Two such measures, termed the ride quality index (RQI) and remaining service life (RSL) represent the ride quality (smoothness) of the pavement surface and the predicted time to which a specific roadway section will take to fall below a ride quality index (RQI) of 2.5, respectively. An RQI of 2.5 is accepted as the point below which the road roughness becomes such that some type of work is needed to restore a smooth riding surface.

Like other state transportation agencies across the country, MnDOT faces a significant challenge in terms of the resources required to maintain and improve the system. Figure 1.1a below shows the distribution of remaining service life (RSL) for trunk highway roadway miles based on 2000 conditions. In contrast, the figures for 2013 conditions show a dramatic decrease in system health, as shown in Figure 1.2b. As can be seen, the average RSLs for 2000 and 2013 are 13.7 and 9.4 years, respectively.

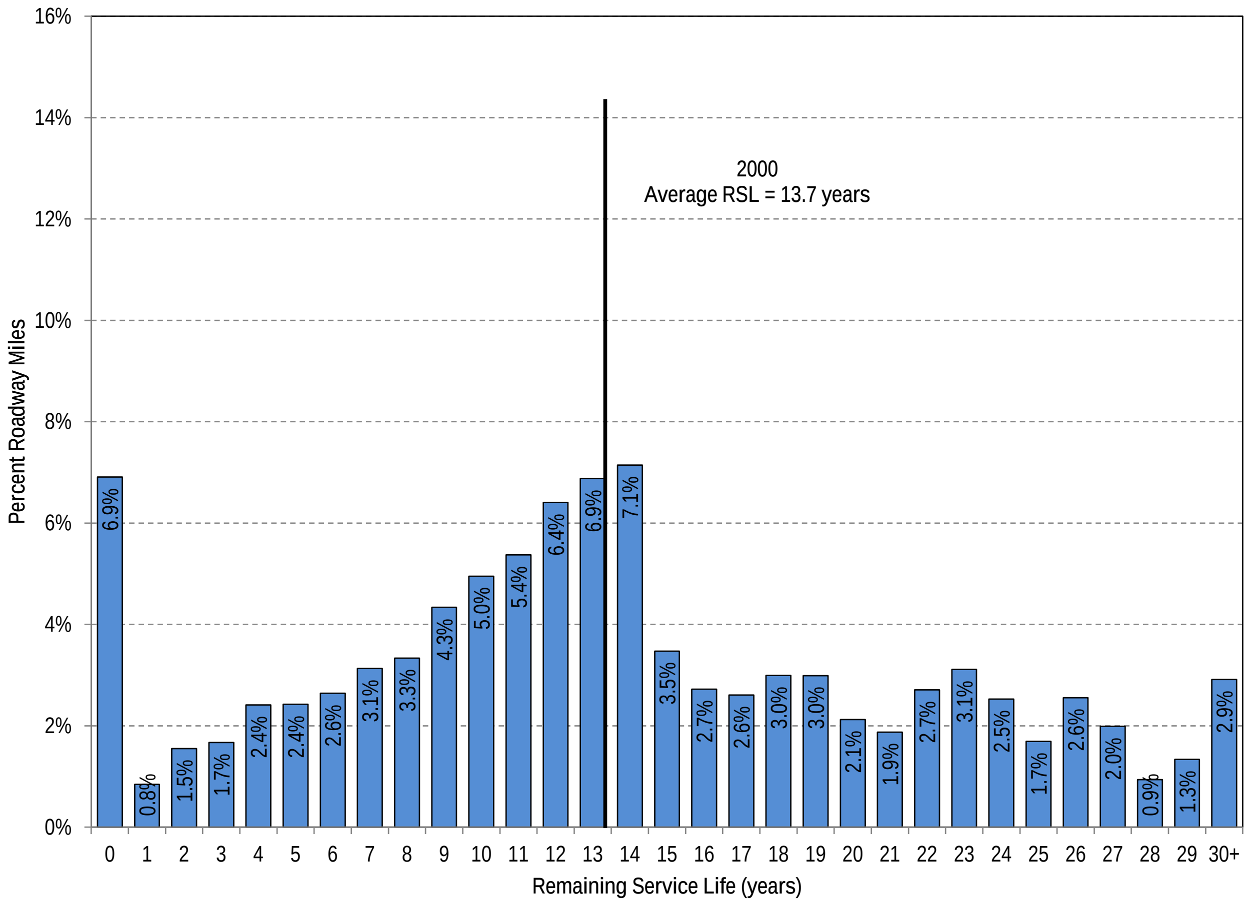

Figure 1.1a - Distribution of roadway miles and their remaining service life (RSL) based on 2000 conditions.

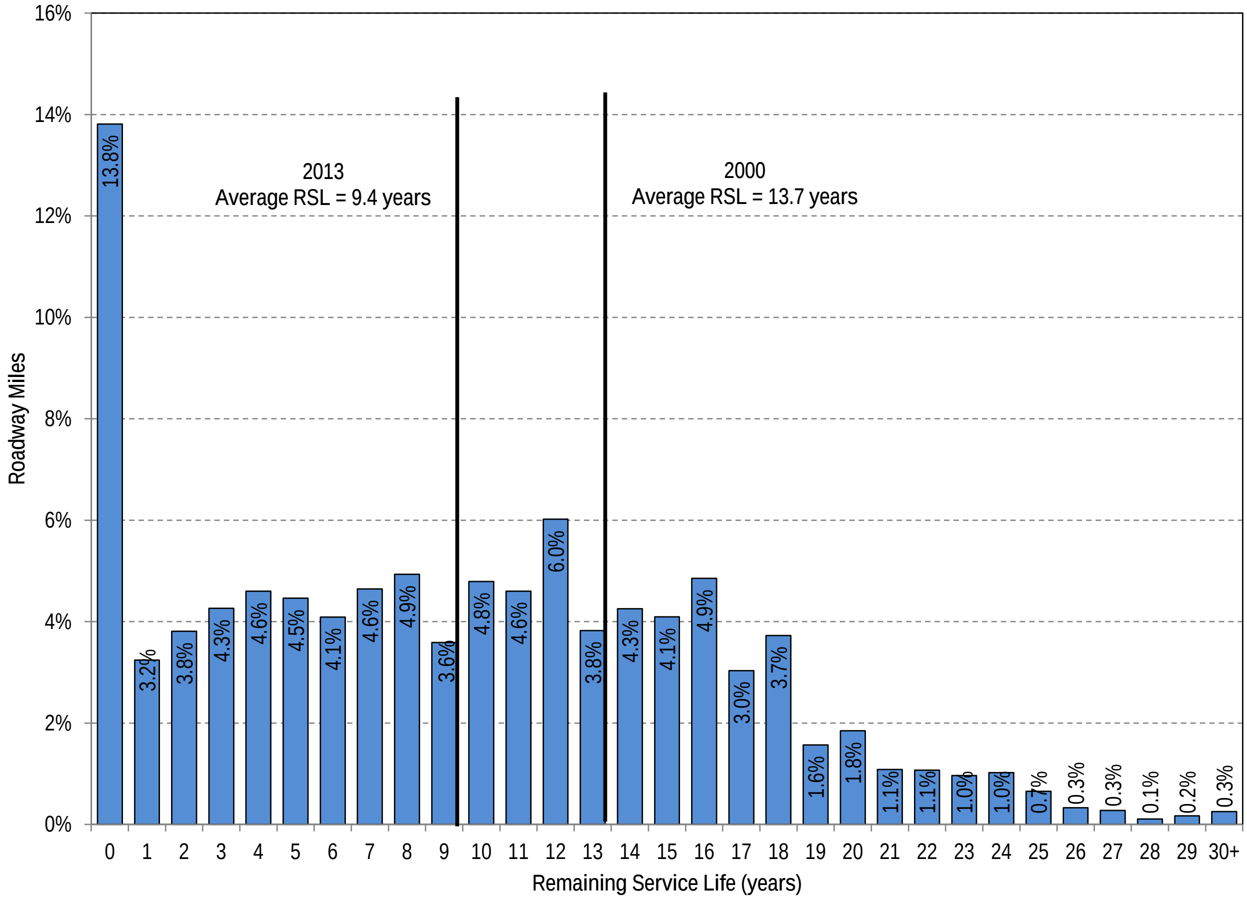

Figure 1.1b - Distribution of roadway miles and their remaining service life (RSL) based on 2013 conditions.

Based on MnDOT PMS figures used in network asset analysis the approximate cost for new construction or reconstructions of roads in rural and urban areas are $1 and $2 million per lane-mile, respectively. Construction of new roadway alignment is few and far between; and more commonly than reconstruction, however, existing roads are rehabilitated through resurfacing projects. Typical project costs from the PMS are summarized in Table 1.3 below:

Table 1.3 - Typical costs used for MnDOT trunk highway network asset management.

Type of Work	Cost per lane-mile (thousands)
Reconstruction, Urban	$2,000
Reconstruction, Rural	$1,000
Thick overlays	$250 - $400
Concrete pavement rehab Medium asphalt overlays	$150 - $250
Minor concrete rehab Thin asphalt overlays	$100

The above are statewide average costs; actual project costs will vary significantly depending on site-specific variables; furthermore, in urban areas such as the Twin Cities these figures are significantly higher.

It can be seen that Minnesota's roadway infrastructure is large and in a wide range of conditions/deterioration. Furthermore the cost to preserve and improve the system is very high. In an environment of competing needs and resource scarcity the potential for research products to provide improvements in pavement performance or construction costs can have dramatic benefits for the program is high.

1.3 MnROAD Phase-I Benefits (1994-2006)

For Minnesota alone, a conservative estimate quantified the annual savings and potential benefits derived from implemented MnROAD Phase-I research at over $33 million per year for the time period 1994-2006. This was determined using cost and quantities estimates from Minnesota state and local cities and counties outlined below. These benefits do not include all of the other research products developed at MnROAD, since many are more difficult and subjective to quantify. Details on how the Phase-I savings were calculated can be found in [2].

The MnROAD project was originally developed and constructed in the early 1990's at a cost of $25 million. These costs covered the initial design, construction, environmental impact study, initial pilot projects, pavement sensors, data collection systems, right of way acquisition along I-94, buildings, and equipment. This consisted of 60 percent Federal Highway Administration (FHWA) funding and 40 percent MnDOT funding.

The majority of MnROAD annual operating costs were funded through a partnership between Minnesota Department of Transportation (MnDOT) and the Minnesota Local Road Research Board (LRRB). LRRB funding comes from legislation stating 0.05 percent of construction costs relating to roadways for Minnesota Cities and Counties that go into a fund for the LRRB board members to distribute towards city and county research needs. MnROAD annual operating costs have averaged around $950,000 consisting of $450,000 MnDOT and $500,000 of LRRB funding. Annual research contracted projects related to MnROAD are estimated to be about $500,000 per year. Total expenditures for the period 1994-2006 were estimated to be $44,300,000 [2].

CHAPTER 2. MnROAD Phase-II (2007-2015)

The benefits analyses presented in this report were considered using several different approaches:

- Direct – savings due to either materials or enhanced performance; monetary benefits are quantifiable estimates;
- Indirect – new or streamlined construction processes that save time and/or improvement to quality, improvements to performance due to enhanced quality; benefits difficult to quantify;
- Avoidance – learn from mistakes; MnROAD is more conducive to risk-taking; benefits difficult to quantify; benefits obtained by avoiding same mistakes elsewhere; difficult to quantify.
- Demonstration – technology transfer through demonstration of procedures, process, or equipment; instill confidence in users to try something new; difficult to quantify benefits.

The approaches utilized in this report do not take into account economic factors such as the time value of money. While some benefits are clearly supported by the research data, monetary estimates of benefits are based on reasonable assumptions. A rigorous economic analysis using discount rates would provide a false sense of confidence and is not warranted.

2.1 Phase-II Benefits

MnROAD Phase-II was designed around the following core research areas through TERRA and other MnROAD research partners. These core areas include the design guide, innovative construction, and preventative maintenance, recycled materials, rehabilitation, surface characteristics, and continued support of non-pavement research using the MnROAD site. The information gained will be available to share with everyone through reports and the MnROAD database.

Using these core research areas MnROAD partners utilized three different funding streams to fund the needed support of the research study, construction, and sensors required for a successful study. These three areas included:

1. *Pooled Fund Studies* – When significant or widespread interest is shown in solving transportation-related problems, research, planning, and technology transfer activities may be jointly funded by several federal, state, regional, and local transportation agencies, academic institutions, foundations, or private firms as a pooled fund study. The Transportation Pooled Fund (TPF) Program allows federal, state, and local agencies and other organizations to combine resources to support transportation research studies.
2. *Partner Research Studies* – Additional research projects were also developed with partners with common pavement research interests.
3. *Minnesota Single State Research Studies* – For some studies MnDOT had its own reasons to pursue the research when no other partners were available to team with.

Each study/benefit is documented in the appendices at the end of this report. Most of the calculated benefits are for MnDOT unless documentation for current and projected local agency projects was available. For some studies savings are not quantifiable at this time even though many benefits have been achieved. Each project summary in the appendix contains the following format:

- Project title
- Partners
- Study objectives
- Study findings
- Potential benefits
- MnDOT cost savings data, cost assumptions, and calculated savings, where feasible.

This report primarily documents the benefits for MnDOT trunk highways; benefits to the local systems are addressed where feasible. Additional research partners including other State Department of Transportations, FHWA, and Industry have benefitted from partnerships and combined efforts however estimation of their benefits is beyond the scope of this report. Table 2.1a below summarizes the annual benefits for MnDOT for Phase-II.

Table 2.1a - MnROAD State of Minnesota annual benefits/savings.

Study	Benefit	Potential Savings
Investigation of Low Temperature Cracking in Asphalt Pavements (Phase-II) - TPF-5(132)	Enhanced pavement life due to reduced rate of LTC occurrence and reduction in damage and resultant effectiveness in maintenance and construction costs.	$2,273,000
Development of an Open Graded Aggregate Base (Stable and Drainable)	Improved pavement life due to reduction in damage that is now occurring at transverse cracks in bituminous pavement and contraction joints in concrete pavements.	$4,770,000
Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements - TPF-5(165)	Optimized designs incorporating actual environmental conditions, and based on recent pavement performance observations, not outdated experiments.	$1,927,000
Development of Design Guide for Recycled Unbound Pavement Materials - TPF-5(129)	Improvements to pavement life cycle and cost-effectiveness due to more sustainable use of existing resources.	$829,000
PCC Surface Characteristics – New Construction MNR-6(021) Concrete Surface Characteristics – Rehabilitation TPF-5(134)	Construct ultimate grind surface texture in lieu of 20-foot noise walls.†	$8,000,000†
Full-Depth Reclamation Stabilized with Engineered Emulsion	Identified a viable technique for design of bituminous pavement rehabilitation that optimizes resource usage.	$505,700
Field Investigation of Highway Base Material Stabilized With High Carbon Fly Ash	Expanded construction window during challenging weather conditions resulting in reduced construction delays.	$92,400
	Total benefits $ per year	$10,397,100 $18,397,100†

†Note that realization of this figure would require lowering of the minimum noise reduction standard from 7 dBA to 4 dBA.

Many types of research and associated products do not have direct, quantifiable payoffs. For example, although MnDOT will most likely not construct mainline sections of pervious concrete or porous asphalt, the research completed at MnROAD has demonstrated several important results. Even so, these sections are some of the most requested by outsiders in terms of data. Similarly, no direct monetary benefits can be estimated for the Warm Mix Asphalt study. These cells were constructed during the 2008 season. However, data from these cells helped provide confidence to Minnesota engineers in specifying this technology for their jobs. Discussed previously is the fact many of the projects result in benefits that are difficult to quantify, intangible, deferred until additional research is completed, or are not being implemented in Minnesota. Table 2.1b provides a brief description for a number of these projects.

Conservative estimates of potential annual savings/benefits based on implemented MnROAD Phase-II research (2007-2015) is estimated at over $18 million a year of operations for Minnesota (state and local agencies). This analysis uses cost and quantities estimates from Minnesota state and local agencies. These benefits do not include all of the other research products developed at MnROAD, since some are more difficult and subjective to define. Examples are shown in Appendices A through E where many projects have calculated benefit shown in this report but led towards better confidence in designs and materials or what not to do statewide. The expected duration of the benefits is expected to be from 2014-2024 or 10 years.

Table 2.1b - MnROAD State of Minnesota additional benefits.

Study	Benefit
Field Investigation of Polyphosphoric Acid Modified Asphalt	The objective of this effort was to determine whether the use of acid modified binders will sacrifice performance compared to traditional polymer modification methods (SBS). To date, performance of all six MnROAD cells has been good, albeit at a relatively low loading rate. This project is believed to provide non-monetary benefits in that acid modification has been demonstrated to provide acceptable service with no obvious problems to date, based on 7 years of MnROAD performance.
Development of Warm Mix Asphalt	Warm Mix Asphalt technology has several potential benefits including environmental, operational, and performance through reduced fuel consumption, lower plant wear, and reduced binder aging during production. In 2008 six test cells on I-94 mainline were constructed using warm mix technology. These sections were a MnROAD first demonstrating WMA use on a high-volume roadway. This fact alone helped foster a sense of confidence in using WMA on a wider scale across Minnesota.
Recycled Materials in Asphalt Mixtures	The goal of the research was to investigate types and percentages of recycled materials that can be incorporated into asphalt mixtures without compromising long-term performance. Included in this study were three cells built in 2008 where higher than standard recycled asphalt content was incorporated to help answer questions related to acceptable percentages, type, and gradation (fractionated recycled asphalt) that can be added. To date, the sections are performing very well
Permeable HMA Pavement Performance in Cold Regions MNR-6(024)	In 2008 two porous asphalt test cells were constructed on the MnROAD LVR, one each on clay subgrade and granular subgrade. Construction of these sections marked firsts for both MnDOT and the contractor that constructed the sections. The objectives of this research were to evaluate the load carrying capacity, durability, hydrologic characteristics and environmental effects of porous asphalt pavement. To date the sections have performed well, holding up to environmental demands for six seasons, including freeze/thaw, and snowplow wear. The surfaces demonstrated lower stiffness and higher strains than dense-graded asphalt mixtures; however the lack of cracking indicates it can be a very resilient pavement.
HMA Surface Characteristics related to Ride, Texture, Friction, Noise, Durability MNR-6(029)	This effort addressed a need to determine the durability and performance of pavements built for certain surface characteristics in northern climates. This comprehensive study evaluated several asphalt surface types including porous, dense-graded, ultra-thin bonded, and taconite. Key findings including characteristics of each these surfaces with respect to level of sound absorption, friction, ride, and longevity when subjected to Minnesota's climate extremes.
Design and Construction Guidelines for Thermally Insulated Concrete Pavements (Pooled Fund TPF-5(149)) SHRP 2 Composite Pavement Study	In support of SHRP2 Composite Pavement Study thermally insulated concrete pavements were constructed at MnROAD during the 2008 construction season. These consisted of a concrete pavement structure (jointed or continually reinforced) overlain by an asphalt layer during initial construction (or soon after) to address ride quality or surface characteristic issues. Potential benefits include initial construction cost savings in the amount of base materials required, quality of the concrete ride and materials, joint spacing, and easier rehabilitation in the future. The research results were instrumental in addressing important results in the design, analysis, and construction of composite (asphalt-over-concrete) pavements in general. Extensive revisions and improvements to the MEPDG were recommended.
Roller Compacted Concrete	Roller Compacted Concrete (RCC) shoulders were constructed adjacent to Cells 505-605 and 306-406 during the 2011 construction season in an effort to demonstrate the technology and evaluate its performance in a freeze-thaw environment. These shoulders have performed very well to date and will continue to be monitored. With further success, engineers will have an alternative to traditional asphalt or concrete shoulders.

Table 2.1b - MnROAD State of Minnesota additional benefits, continued.

Study	Benefit
Pervious Concrete Pavement Studies	The research completed at MnROAD has demonstrated several important results showing that a new pervious concrete pavement as well as overlays can be successfully designed, constructed, operated, and maintained. Pervious concrete pavements and overlay have several inherent advantages, including reduced splash and spray and reduced hydroplaning potential, as well as being a very quiet pavement. These efforts have served as a beneficial demonstration to local road agencies that have adopted this pavement surfacing on their networks. Lessons learned indicate that certain specific design details would need to be refined for full field implementation. For example, provisions for lateral drainage collectors, bonding conditions, and thickness design.
Flexible Micro-Surfacing	Test cells constructed at MnROAD since 2000 have demonstrated the effectiveness of this surfacing material. The enhanced binder for flexible micro-surfacing adds a modest cost increase to the asphalt emulsion which in turn increases the unit cost of final product placement by about 10 percent. For flexible micro-surfacing to be marginally cost-effective as compared to regular micro it needs to extend life by at least 10 percent. Performance has been good to date; research and performance monitoring are ongoing.
Effects of Implements of Husbandry “Farm Equipment” on Pavement Performance TPF-5(148)	Heavily loaded agricultural equipment significantly impacts pavement life and increases maintenance requirements. Wisconsin has implemented weight and size rules for implements of husbandry due in part to this study. Savings would be realized in the future when Minnesota elects to implement the research findings similar to Wisconsin. Conservative estimates indicate that pavement life may be extended by 10 percent on local roadways if appropriate size/weight policies are in place.
Sustainable Pavement Development	This work has successfully demonstrated technologies that are crucial to a sustainable road network in an environment of resource depletion.
Rolling Resistance	Innovative work related to truck fleet efficiency and pavement characteristics. Based on physical measurements and mechanistic analyses.

Based on calculations the benefit of MnROAD Phase-II is estimated to be over $10 million per year. This estimate may be increased by $8 million provided that a lowering of the minimum noise level reduction requirements could be realized.

Total MnROAD Phase-II Benefits = $103,971,000 ($10,397,100 per year * 10 years)

2.2 Phase-II Costs

This section presents costs to deliver the projects comprising MnROAD Phase-II and includes funds received from various governmental agencies, construction costs, resources required to maintain equipment, and many other items. Also presented are details on MnDOT funds utilized for personnel to staff the MnROAD facility and OMRR administration.

2.2.1 Formal Research Costs

The following research studies were developed in MnROAD’s second phase, 2007 through 2014. Some partnerships utilized funding for the whole study (research, construction, instrumentation) in which the actual research costs were estimated. Some of the research efforts were done in house (zero cost shown) and is already accounted for in the MnROAD operations staffing costs. The total cost for Phase-II research work is estimated at $4,571,400 and is summarized below in Table 2.2.

Table 2.2 - MnROAD Phase-II formal research studies.

Year	Study	FHWA	MN LRRB	Partners	Other States SPR	MnDOT SPR	Oper. Funds	Total
2007	Acid Modification HMA MPR6(028) (FHWA)	$87,700						$87,700
	Fly Ash Stabilization TP90701P (Bloom Consulting)							
	Implements of Husbandry TPF5(148)		$100,000	$17,000	$84,600	$80,800		$282,400
2008	60 yr PCC MPR6(017)							
	Composite Pavements TPF5(149)		$50,000		$209,100	$186,600		$445,700
	Full Depth Reclamation T07RD042							
	HMA Surface Characteristics MPR6(029)	$67,800				$232,200		$300,000
	Low Temperature Cracking (II) TPF5(132)		$50,000		$162,700	$274,100	$100	$486,900
	Overlay Unbonded PCC MPR6(016)							
	PCC Characteristics (Construction) MPR6(021)					$120,000	$30,000	$150,000
	PCC Characteristics (Rehabilitation) TPF5(134)				$236,000	$103,300	$30,000	$369,300
	Permeable HMA MPR6(024)		$86,200					$86,200
	Pervious PCC MPR6(027)		$48,000					$48,000
	Pervious PCC Wear Course MPR6(015) (CTRE)				$50,000			$50,000
	Preventive Maintenance HMA TPF5(153)		$57,200		$166,900	$71,600		$295,700
	Recycled HMA Pavements MPR6(022)	$57,400				$217,600	$13,600	$288,600
	Recycled Unbound Materials TPF5(129)				$141,500	$216,000		$357,500
	Taconite MPR6(023)							
	Thin Design PCC MPR6(031)							
	Whitetopping Design TPF5(165)				$135,400	$376,800		$512,200
2010	SHRP2 Long Life Pavements Composite Roadways	$200,000						$200,000
	Lightly Surface Roadway (Cell 28)							
2011	Unbonded Concrete Overlay							
2012	Flexible MicroSurfacing (Kraton)							
2013	DCT Implementation in Minnesota						$125,000	$125,000
	Design for Unbonded Concrete Overlays TPF5(269)				$400,000		$60,000	$460,000
	Sustainable Economical Concrete							
	Thin Fiber Reinforced Unbonded Concrete Overlay						$26,300	$26,300
	Fiber Reinforced Whitetopping							
	Thin Concrete Repair							
	Diamond Grinding of Pervious Concrete							
2014	High Volume Friction Course (Chip Seal for R26 demo)							
	Totals	$413,000	$391,500	$17,000	$1,586,200	$1,878,800	$285,000	$4,571,400
	Percent	9%	9%	0%	35%	41%	6%	100%

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

2.2.2 In-House Research Costs

MnDOT also funded in-house research mostly from Minnesota SP&R dollars to help with the construction efforts and better understand some of the data that was utilized in the second phase. See Table 2.3 for a summary.

Table 2.3 - MnROAD Phase-II in-house research studies.

Study	FHWA	MN LRRB	Other Partners	Other States SPR	MnDOT SPR	Oper. Funds	Totals
Air Voids Testing for MnROAD Cells					$29,600		$29,600
Asphalt Mixture and Binder Fracture Testing for 2008 MnROAD Construction.					$55,000		$55,000
Construction - CE Metro					$123,900		$123,900
Construction D3 Engineering					$32,000		$32,000
Construction Reporter					$8,600		$8,600
Construction - 2009 MnROAD Survey Needs					$12,400		$12,400
Field Evaluation of Built-in Curling Levels in Rigid Pavements					$64,000		$64,000
Lab testing during 2008 Construction					$25,800		$25,800
Materials Testing for Road Reconstruction					$42,400		$42,400
MnROAD 2008 Unbound Quality Control and Construction Report, Review of IC, DCP, and FWD Data					$49,700		$49,700
MnROAD Data Mining, Evaluation and Qualification Phase 1					$8,500		$8,500
Vehicle Position Tracking During Load Response Testing Automated Faultmeter Control Software Program					$50,000		$50,000
Vehicle Position Tracking During Load Response Testing Phase 2 Automated Faultmeter Control Software Program					$48,000		$48,000
Vibrating Wire and Horizontal Clip Data Analysis.					$66,500		$66,500
Dynamic Response Data Analysis						$49,900	$49,900
Totals	$-	$-	$-	$-	$616,400	$49,900	$666,300
Percent	0%	0%	0%	0%	38%	62%	100%

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

2.2.3 Construction Costs

MnROAD and its partners have utilized a large number of test cells that have been maintained, rehabilitated, or reconstructed. The current and past MnROAD research test cells designs for both the mainline and low volume road can be best viewed from the MnROAD web site along with construction reports for each effort. The total cost for Phase-II construction costs is estimated at $4,734,700; details are summarized below in Table 2.4.

2.2.4 Instrumentation Costs

Instrumentation is an important component to much of the research done at MnROAD. MnROAD installs and maintains the instrumentation and its infrastructure with MnDOT staffing and student workers. These staffing costs are accounted for in the MnROAD operation staffing section of this report. State Planning and Research (SPR) dollars were used at 100 percent (multistate pooled fund efforts) and for non-pooled fund projects at an 80 percent federal and 20 percent state/partner funding split. The total cost for instrumentation is estimated at $804,166 and is summarized below in Table 2.5.

2.2.5 Operations Staffing Costs

MnROAD is a part of the MnDOT OMRR, Road Research Section. The unit currently averages 25 positions working on MnROAD, state, and local research projects including the second phase of MnROAD since 2007. To determine the total full-time equivalents (FTE) for MnROAD, each staff member of Road Research was assigned a percentage of effort they work on MnROAD related research studies that was not directly paid by outside funding. Using this percentage along with MnDOT financial records (total cost for each employee with benefits), total staffing costs and FTE were calculated and are shown in Table 2.6.

Table 2.4 - MnROAD Phase-II construction costs.

Year	Study	FHWA	MN LRRB	Partners	Agency SPR	MnDOT SPR	Oper. Funds	Totals
2007	Acid Modification HMA - MPR-6(028) (FHWA)	$111,900					$8,100	$120,000
SP 8680-156	Fly Ash Stabilization - TP90701P (Bloom Consulting)	$129,800					$23,400	$153,200
	Implements of Husbandry - TPF-5(148)				$81,500	$77,800		$159,400
2008	60 yr PCC - MPR-6(017)					$52,700	$13,200	$65,800
	Composite Pavements - TPF-5(149)				$63,600	$56,800		$120,400
	Full Depth Reclamation - T07RD042			$225,000				$225,000
	HMA Surface Characteristics - MPR-6(029)							
	Low Temperature Cracking (II) - TPF-5(132)				$137,700	$231,900		$369,700
	Overlay Unbonded PCC - MPR-6(016)			$12,500		$78,800	$7,200	$98,500
	PCC Characteristics (Construction) - MPR-6(021)							
	PCC Characteristics (Rehabilitation) - TPF-5(134)							
	Permeable HMA - MPR-6(024)					$121,900	$30,500	$152,400
	Pervious PCC - MPR-6(027)					$115,700	$28,900	$144,600
	Pervious PCC Wear Course - MPR-6(015) (CTRE)			$13,600		$54,200		$67,800
	Preventive Maintenance HMA - TPF-5(153)				$22,900	$9,800		$32,700
	Recycled HMA Pavements MPR-6(022)							
	Recycled Unbound Materials - TPF-5(129)				$169,000	$257,900		$426,900
	Taconite - MPR-6(023)			$25,000		$110,300		$135,300
	Thin Design PCC - MPR-6(031)					$82,500	$20,600	$103,200
	Whitetopping Design - TPF-5(165)				$133,900	$372,700		$506,600
2010	Lightly Surface Roadway (Cell 28)						$12,000	$12,000
SP 8680-111	SHRP2 Long Life Pavements - Composite Roadways	$733,900						$733,900
	Unbonded PCC overlay	$496,000						$496,000
2012	Flexible Micro-Surfacing – Kraton						$12,000	$12,000
2013	Sustainable Economical Concrete			$5,000			$406,500	$411,500
SP 8680-169	Thin Fiber Reinforced Unbonded Concrete Overlay						$95,400	$95,400
	Fiber Reinforced Whitetopping							
	Thin Concrete Repair			$2,500			$67,400	$69,900
SP 8680-170	Diamond Grinding of Pervious Concrete						$15,500	$15,500
2014	Mainline Chip Seal (R26 demo)						$7,000	$7,000
	Totals	$1,471,600		$283,600	$608,600	$1,623,100	$747,700	$4,734,700
	Percent	31%	0%	6%	13%	34%	16%	100%

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

Table 2.5 - MnROAD Phase-II instrumentation costs

Year	Study	FHWA	MN LRRB	Partners	Agency SPR	MnDOT SPR	Oper. Funds	Totals
2007	Acid Modification HMA - MPR-6(028) (FHWA)			$5,400			$1,700	$7,100
	Fly Ash Stabilization - TP90701P (Bloom Consulting)	$60,100						$60,100
	Implements of Husbandry - TPF-5(148)				$74,000	$70,600		$144,600
2008	60 yr PCC - MPR-6(017)					$26,700	$6,700	$33,400
	Composite Pavements - TPF-5(149)				$25,200	$22,500		$47,800
	Full Depth Reclamation - T07RD042						$52,000	$52,000
	HMA Surface Characteristics - MPR-6(029)			$7,200		$28,600	$1,500	$37,300
	Low Temperature Cracking (II) - TPF-5(132)				$21,000	$35,300		$56,300
	Overlay Unbonded PCC - MPR-6(016)					$29,400	$7,400	$36,800
	PCC Characteristics (Construction) - MPR-6(021)							
	PCC Characteristics (Rehabilitation) - TPF-5(134)							
	Permeable HMA - MPR-6(024)					$21,400	$5,400	$26,800
	Pervious PCC - MPR-6(027)					$28,300	$7,100	$35,400
	Pervious PCC Wear Course - MPR-6(015) (CTRE)			$3,000		$13,000	$200	$16,300
	Preventive Maintenance HMA - TPF-5(153)				$5,600	$2,400		$8,100
	Recycled HMA Pavements MPR-6(022)							
	Recycled Unbound Materials - TPF-5(129)				$38,200	$58,400		$96,600
	Taconite - MPR-6(023)					$10,300	$5,100	$15,400
	Thin Design PCC - MPR-6(031)					$31,700	$7,900	$39,600
	Whitetopping Design - TPF-5(165)			$12,500	$80,900	$225,100		$318,400
2010	SHRP2 Long Life Pavements - Composite Roadways	$96,100						$96,100
	Unbonded PCC overlay						$22,400	$22,400
2013	Sustainable Economical Concrete							
	Thin Fiber Reinforced Unbonded Concrete Overlay						$15,000	$15,000
	Fiber Reinforced Whitetopping							
	Totals	$156,200	$-	$28,000	$244,900	$603,800	$132,400	$1,165,400
	Percent	13%	0%	2%	21%	52%	11%	100%

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

Table 2.6 - MnROAD total staffing cost (normal salary costs).

Staffing	MnROAD FTEs	Cost/Year
MnDOT – MnROAD Operations Staff	7.5	$650,000
Operations Engineer Forensic Engineer		
Instrumentation Engineer		
Site Manager		
System Integrator		
Electronic Tech		
Truck Driver		
District Support (lane closures and repairs		
Student workers (2-3 per year)		
Road Research Staff	5	$475,000
Yearly Total	12.5	$1,130,000

MnROAD Phase-II funding sources primarily included MnDOT, Minnesota Local Road Research Board, and other partners. To determine the funding source splits, the other (non-MnDOT) outside staff funding must be taken into account for the past 9 years and subtracted from the total salary costs. These included the following as shown in Table 2.7 below.

Table 2.7 - Phase-II total salaries/projects.

Study	FHWA	MN LRRB	Partners	Agency SPR	MnDOT SPR	Oper. Funds	Totals
Minnesota Local Road Research Board		$2,642,900					$2,642,900
Acid Modification HMA - MPR-6(028) (FHWA)	$87,700						$87,700
Fly Ash Stabilization - TP90701P (Bloom Consulting)	$34,700						$34,700
HMA Surface Characteristics - MPR-6(029)	$199,400						$199,400
PCC Characteristics (Construction) - MPR-6(021)	$150,000						$150,000
PCC Characteristics (Rehabilitation) - TPF-5(134)				$99,000			$99,000
Permeable HMA - MPR-6(024)		$82,400					$82,400
Pervious PCC - MPR-6(027)		$50,000					$50,000
Recycled HMA Pavements MPR-6(022)	$200,000						$200,000
SHRP2 Long Life Pavements - Composite Roadway	$51,000						$51,000
Implements of Husbandry (2007 student workers)					$120,000		$120,000
Whitetopping Design (2008 student workers)					$120,000		$120,000
MnDOT non-SPR (normal MnDOT salaries)						$6,333,000	$6,333,000
MnDOT non-SPR (partners, agency SPR, MnDOT SPR)							
Totals	$722,800	$2,775,300	$-	$99,000	$240,000	$6,333,000	$10,170,100
Yearly Avg	$80,300	$308,400	$-	$11,000	$26,700	$703,700	
Total Yearly Avg	$1,130,100						
Percent Total Yearly Avg	7%	27%	0%	1%	2%	62%	

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

2.2.6 Other Operations Costs

MnROAD also has a number of other annual operations costs that need to be included in the total cost of the facility that are not included in the research, construction, instrumentation, and staffing costs. These “other” costs include the activities listed in Table 2.8 over 9 years from 2007-2016.

Table 2.8 - Phase-II “other” operations costs.

Study	FHWA	LRRB	Partners	Agency SPR	MnDOT SPR	Oper. Funds	Totals
Vehicles (initial cost + maintenance + fuel) (MiniVan, Pickup, Dump Truck, 2 Vans, FWD, Skid loader, trailers)		$19,500				$19,500	$39,000
Semi-Tractor and Trailer (initial cost + maintenance + fuel)		$39,200				$9,800	$49,000
Sensors Related (repairs + replacements + data systems)		$16,800				$16,800	$33,600
Facilities (building +utilities + maintenance)		$35,850				$35,850	$71,700
Computer Staff (1.2 FTE) and Equipment/software		$95,000				$95,000	$190,000
Funding for FWD upgrades, cabinet and sensor network upgrades needed for the sensor system at the site overall						$ 305,000	$ 305,000
Totals (yearly)	$-	$206,400	$-	$-	$-	$482,000	$688,300
Totals (2007-2016)	$-	$1,857,600	$-	$-	$-	$4,338,000	$6,195,600
Percent	0%	30%	0%	0%	0%	70%	100%

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

2.3 Phase-II Cost Summary

A summary of the costs established above for both total costs and the 9-year averages is shown in Table 2.9 below and Figures 2.1a and 2.1b.

Table 2.9 - Phase-II cost summary.

Budget Area	FHWA	LRRB	Partners	Agency SPR	MnDOT SPR	Oper. Funds	Totals
Research	$413,000	$391,500	$17,000	$1,586,200	$2,495,300	$1,285,000	$5,237,900
Construction	$1,471,600		$283,600	$608,600	$1,623,100	$747,700	$4,734,600
Instrumentation	$156,200		$28,000	$244,900	$603,800	$132,400	$1,165,300
Salaries	$722,800	$2,775,300		$99,000	$240,000	$6,333,000	$10,170,100
Building - Equipment - IT Support		$1,857,600				$1,593,000	$6,195,600
Totals (yearly)	$307,100	$558,300	$36,500	$282,100	$551,400	$1,121,200	$3,056,100
Totals (2007-2016)	$2,763,600	$5,024,400	$328,600	$2,538,800	$4,962,200	$11,886,000	$27,503,600
Percent	10%	18%	1%	9%	18%	43%	100%

Note: FHWA = Federal Highway Administration; MN LRRB = Minnesota Local Road Research Board; Partners = Specific industry partners; Agency SPR = SP&R funds from participating states; MnDOT SPR = SP&R funds from Minnesota; Oper. Funds = MnDOT operating funds (non SP&R).

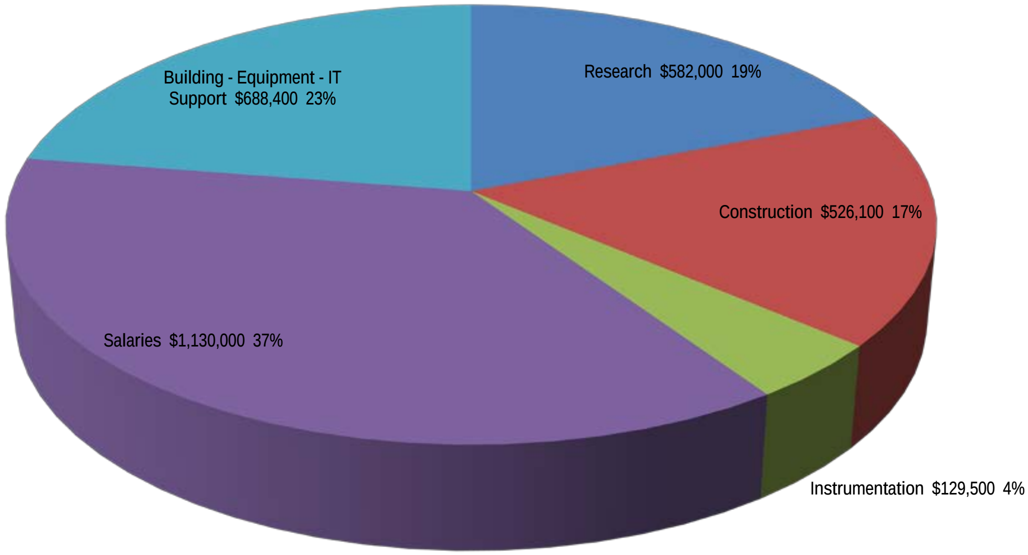

Figure 2.1a - Phase-II yearly average costs per task.

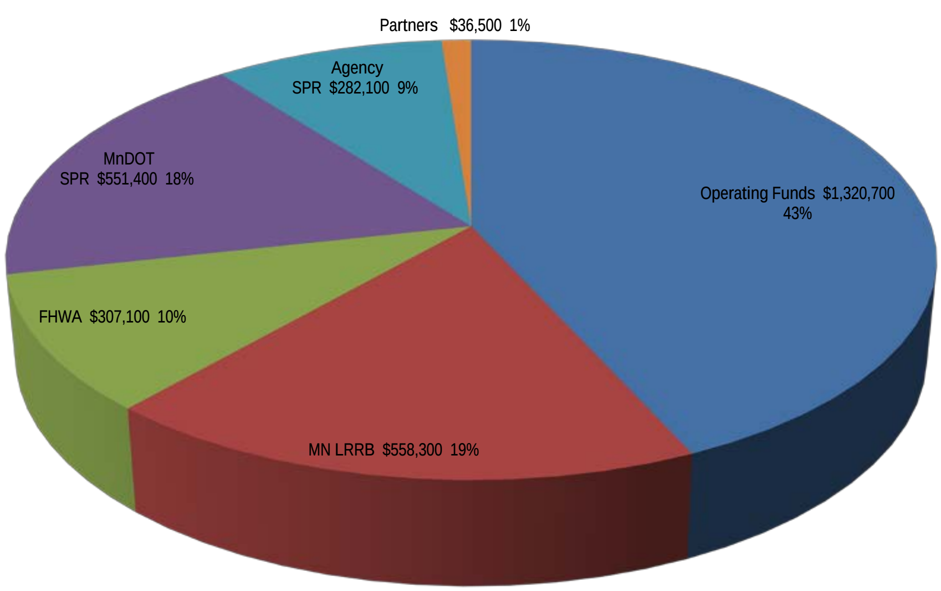

Figure 2.1b - Phase-II yearly average funding sources.

2.4 Phase-II Cost Savings Results

MnROAD Phase-II (2007-2016) costs and benefits were determined. Assumptions made are clearly described. Where specific costs are not quantifiable a discussion of the benefits are given. The estimated costs and potential benefits do not take into account the time value of money nor statistical variability. The authors did not see the benefit to further manipulate the data for this analysis. Note that benefits are estimated for the 10 year period subsequent to the end of Phase-II (2016-2026).

Costs = $27,503,600 (Costs from 2007-2016, see Table 2.9)
Total benefits = $103,971,000 ($10,397,100 per year * 10 years, 2016-2026)

These figures represent a 3.8 benefit to cost ratio and demonstrates the benefits outweigh the costs when using this facility. Note that, provided a lowering of the minimum noise level reduction requirements could be realized, this estimate would be increased by $8 million to $183,971,000 thereby increasing the calculated benefit to cost ratio increases to 6.7.

CHAPTER 3. MnROAD Phase-III Future (2017-2026)

MnROAD Phase-III is currently being planned to establish both the research topics and the role MnROAD will provide in supporting them. A key feature of Phase-III will be expanded use of partnerships with other states as well as research facilities such as the National Center for Asphalt Technology (NCAT).

These partnerships will facilitate high-value pavement research that addresses national needs using full-scale pavement testing facilities in both warm and cold climates on flexible, rigid, and composite pavement structures. There are two main areas of research focus: Pavement Preservation and Pavement Cracking Performance Tests.

The goal of the Pavement Preservation study is to quantify the life-extending benefits of different pavement preservation treatments for roadways in different stages of life and decay. Each facility has a history of evaluating the performance of pavement preservation treatments, including chip sealing, micro-surfacing, crack sealing and thin overlays. Accelerated testing will provide unique opportunities to determine the field performance of breakthrough materials and pavement preservation concepts without the risk of failure that local and state agencies are unwilling to accept. To address the needs of northern and southern climates, similar test sections will be developed and constructed in both Alabama and Minnesota. Off-site test locations on existing roads and highways that can be easily monitored for both low and higher volume roadways are also being pursued. Off-site concrete test sections in Minnesota may also be incorporated.

Through the Cracking Performance Testing study future technologies will be developed more efficiently over a wide range of climate and traffic factors. While many tests have been developed to predict the cracking potential of asphalt mixtures before they are placed in the field, a national effort is needed to verify those that are the most useful for each type of cracking. Types of cracking that may be investigated include top-down, reflection, and low-temperature cracking for new roadways and overlays of asphalt and concrete. Test sections will be developed with a range of crack-susceptible mixes over asphalt and concrete and then subject these mixes to a battery of laboratory tests in order to determine:

- Practicality of the tests for mix design verification and quality control testing;
- Criteria related to field performance;
- The ability to accommodate recycled materials, new and future additives, and mix combinations.; and
- Cost-effectiveness.

Phase-III will ultimately build upon the successes of Phases I and II.

CHAPTER 4. SUMMARY

Transportation research is essential to help provide the safe, efficient and cost-effective movement of people, goods, and services that are the backbone of our economy. Even modest increases in performance and pavement life result in a reduction of costs for maintenance, repairs, user delays, and congestion. Implemented products from pavement research activities improve our national productivity and quality of life.

This report presents the highlights of MnROAD Phase-II studies conducted to date and, where feasible, estimated monetary benefits. Outcomes and benefits of some of these projects include:

- Low-temperature cracking in asphalt pavements - Enhanced pavement life due to delayed and reduced rate of temperature cracking occurrence and reduction in damage and resultant effectiveness in maintenance and construction costs.
- Development of a stable, drainable aggregate base option - Improved pavement life due to reduction in damage that currently occurs at transverse cracks in bituminous pavement and contraction joints in concrete pavements with dense-graded bases. Accelerated learning of performance of certain aggregate base designs such as drainable base with unstable material
- Thin and ultrathin concrete overlays of asphalt pavements - Optimized designs incorporating actual environmental conditions, and based on recent pavement performance observations, not outdated experiments.
- Development of design guide for recycled, unbound pavement materials - Improvements to pavement life cycle and cost-effectiveness due to more sustainable use of existing resources.
- Concrete pavement surface characteristics for new construction and rehabilitation – Development of innovative and ultimate grind surface textures provides not only a smooth ride but also a durable, lower-noise pavement.
- Full-depth reclamation stabilized with engineered emulsion – Demonstrated a viable technique for design of bituminous pavement rehabilitation that optimizes resource usage and provides excellent structural characteristics.
- Field investigation of aggregate base material stabilized with high-carbon fly ash – Results in expanded construction window during challenging weather conditions resulting in reduced construction delays.
- Validation of network designs through detailed instrumentation and monitoring such Cell 53 60-year concrete design, and pervious/porous pavements.
- Validation of optimum concrete pavement thickness design: How thin can we go project and early results.
- Successful demonstration of pavement preservation surface treatment on high-volume roadway (SHRP 2, 2014).
- Furthermore, MnROAD has a long history of providing a venue for varied research on such efforts as:
  - FHWA standard profiler research;
  - Regional and statewide profiler certifications;
  - New technologies such as weigh-in-motion;
  - Truck fleet operational efficiency studies; and
  - Intelligent construction equipment.

This report presents a summary of the costs and benefits of the research and construction activities undertaken at MnROAD for Phase-II (2007-2017). Phase-I (1994-2006) was previously shown to conservatively save the State of Minnesota $33 million a year over a 10 year period. This is not to say that these were the only benefits, because there are many more identified in reports on lessons learned at MnROAD [3]. These other benefits are important, but more difficult to quantify. Examples include:

- Numerous graduate degrees with at least ten persons earning Ph.D. degrees utilizing MnROAD data since 2008.
- Positive contribution to the overall image of MnDOT, nationally and internationally.
- A number of awards from national industry organizations such as American Concrete Pavement Association (2014) and International Grooving and Grinding Association (2010).
- Data from MnROAD supported new PCC pavement structural design table for MnDOT.
- Reliable data from MnROAD to support designs and performance trends are made available with new technologies such as recycled aggregates, warm mix asphalt, pervious concrete, and composite concrete.

Many other states in the country have benefitted from research findings associated with MnROAD. Neither national nor local privately owned pavements were included in the cost savings, even though they also gain a benefit through the research findings and updated construction specifications. If these other benefits were included it would only increase any estimated benefits that are reported.

Highlights of MnROAD Phase-II (2007-2017) were described in this report and included the research core values, partners, studies, focus areas, and possible future benefits. Several key examples of benefits were reviewed and estimated. Although it is too early to predict actual benefits that may be realized they are expected to provide similar outcomes as those estimated from MnROAD Phase-I. This time frame is arbitrary and neglects additional future benefits that exist past the chosen period.

It is worthwhile to mention that the stated Phase-II findings and benefits are believed to be a conservative estimate. Research projects that result in “cost-avoidance” or “what-not-to-do” outcomes are difficult to quantify. However, if it were feasible to factor these results in calculated benefits would be higher.

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APPENDIX A - MnROAD Phase-II Asphalt Project Overviews and Benefits

Investigation of Low Temperature Cracking in Asphalt Pavements (Phase-II) - TPF-5(132)

Partners – CT, IA, ID, MN, ND, NY, and WI DOTs, LRRB

Low-temperature cracking (LTC) is perhaps the most prevalent distress occurring in hot- and warm-mix asphalt pavements in cold weather climates. As the pavement surface cools it contracts, tensile stresses build, and cracks form when the strength is exceeded. Once formed, cracks permit moisture ingress and deterioration from traffic loads, deicing chemicals and freeze-thaw cycles. To mitigate this issue and associated loss of pavement life it is very important to understand the mechanism of crack initiation and propagation. The goal of this project was to evaluate different laboratory procedures, material properties and pavement features in order to develop an optimal system for selecting low temperature crack resistant asphalt mixtures. The optimal system will consist of a test specification for the acceptance of mixtures based on the finding from the first phase of this project. Stated simply the goal is to develop an improved asphalt mixture test to better predict cracking through an understanding of all the materials interactions; fracture toughness (energy) was selected as the key material property for the focus of this work.

Key findings:

- While the current performance-graded (PG) binder criteria have been in place for many years and performed well, they do not take into account mixture factors such as aggregate characteristics, volumetrics, modifiers, or recycled materials used in current day hot- and warm-asphalt mixtures.
- The Disk-Shaped Compact Tension, or DCT test (ASTM D7313-13), was adopted as a practical method for the determination of low-temperature fracture energy properties. The Semi-Circular Bend Test (SCB) was also evaluated but was found to have higher test variation than the DCT.
- This test provides a means to better discern the LTC characteristics of asphalt mixtures and thus, engineers gain better insight into LTC mechanisms and improved methods used to select HMA materials.
- Fracture toughness values have shown to be effected by:
    - Asphalt modification – modification helps mixes gain fracture toughness even with the same traditional PG low temperature grade.
    - Aggregate type – granite mixes have higher fracture toughness than limestone
    - Aggregate size – fine mixes have higher fracture toughness than coarse mixes
    - Binder low-temperature grade – binders with lower temperature PGs have a higher fracture toughness than higher low temperature grades as expected
    - Air voids – lower air voids (4 percent) have outperformed higher air void mixes (7 percent)
    - Recycled mixes – virgin mixes have higher fracture toughness than recycled mixes with the same PG binder.
- While fracture energy has been the emphasis in this study, researchers suggest that it may relate well to predicting an asphalt mixtures ability to resist fatigue and other types of cracking.
- Based on laboratory test results and observed field performance the current recommendations for minimum fracture energy specification to mitigate low-temperature cracking (specimens compacted from loose-mix samples) are:

	Project Criticality / Traffic Level		
	High >30M ESALS	Moderate 10-30M ESALS	Low <10M ESALS
Fracture Energy, minimum (J/m^2) LTPPBind 98 percent +10C	690	460	400
IlliTC Cracking Prediction (m/km)	< 4	< 64	Not required

- Anticipated benefits include enhanced pavement life performance from reduced rates of LTC, associated damage, and maintenance requirements. With a properly implemented test requirement and specification developed, states will be able to better screen poor mix designs, build ones that will maximize life and provide a smoother ride.

MnDOT Savings Data and Assumptions:

- MnDOT bituminous PMS data for new and reconstructed roadways were analyzed to determine performance relative to crack formation and the impact of binder performance-grading (PG) implemented in 1999. Performance data for a period of seven years after initial construction were gathered. The following general observations are reasonable to make: for pavements constructed prior to PG implementation, typical cracking performance 7 years after construction (1991 to 1994) was about 15 cracks per 1,000 feet. For pavements constructed after 1999 observed cracking rate is about 2 cracks per 1,000 feet. Based on these results we can make judgments about the effect on pavement ride (RQI).
- Based on the above performance data the following modest performance increase scenarios were assumed in order to calculate cost benefits to MnDOT and the CSAH systems:
  - New roadways will experience a 20 percent increase in initial pavement life from 17.5 years to 21 years;
  - Existing roads with cracks and defects that are resurfaced and experience a 10 percent reduction in maintenance costs due to a reduction in cracking, from 2,000 to 1,800 linear feet per mile; and
  - Increased resurfacing life due to reduced rates of deterioration the average life of an overlay will increase 10 percent from 13.5 years in 2000 to 14.9 years in the future.

- Based on the MnDOT construction program from 2009 through 2013 approximately 170 lane-miles of new/reconstruction and 400 lane-miles of resurfacing occur each year, and presumably used the specified PG binder.
- The average annual CSAH lane-miles of bituminous surfacing construction over the same period are about 1,100 lane-miles. It is assumed that the ratio between new/reconstruction and resurfacing is about a 20 percent based on MnDOT data.
- Average cost of new bituminous pavement construction and mill and overlays are approximately $273,000 and $122,000 per lane-mile, respectively; crack sealing averages $3,500 per lane-mile. These figures represent bituminous costs only, not total construction.
- One factor that is difficult to quantify is the fact that, by nature of pooled-funds projects, other states gain benefit from the work as well. This particular research is commonly cited by other nearby northern-tier states in their research and implementation activities.

Calculated Savings:

- <u>Maintenance savings</u> with 10 percent less cracks to maintain (crack sealant)
  - MnDOT – (570 lane-miles) * (10 percent reduction of cracks mile) * ($3,500/mi) / 4 yr per seal)
    = $49,900 per year
  - CSAH – (1,100 lane-miles) * (10 percent reduction of cracks mile) * ($3,500/mi) / 4 yr per seal)
    = $96,300 per year
- <u>Overlay savings</u> with 10 percent increase in life
  - MnDOT – ($122,000 per lane-mile) * (400 lane-miles) * [1/13.5 yrs - 1/14.9 yrs]
    = $339,700 per year
  - CSAH – ($122,000 per lane-mile) * (880 lane-miles) * [1/13.5 yrs - 1/14.9 yrs]
    = $747,200 per year

- New/reconstruction savings with 20 percent increase in life
    - MnDOT – ($273,000 per lane-mile) * (180 mi) * [1/17.5 yrs - 1/21 yrs] = $468,000 savings/year
    - CSAH – ($273,000 per lane-mile) * (220 mi) * [1/17.5 yrs - 1/21 yrs] = $572,000 savings/year

Total savings = sum of fewer cracks to maintain + overlay life extension + new/reconstruction life extension

Benefits = $2,273,000 savings per year

Field Investigation of Polyphosphoric Acid Modified Asphalt

Partners – Innophos, Marathon, Paragon, ICL, Mathy Construction, Western Research Institute (WRI), FHWA, MnDOT)

This study is built upon the findings of previous FHWA research to conduct a field trial assessing the performance of PPA modified binders over a 5-year period. PPA has been used for 30 years to modify natural binders to "stiffen" them in order to reach the high temperature rutting criteria needed for a specific area. States with climates similar to Minnesota tend to require modified asphalts to meet the demand placed by the climate on pavement surfacing. Recent research by the FHWA and MnROAD hope to establish mutual cost- effectiveness and asphalt strength to provide a better utilization method for PPA. The objective of this effort was to determine whether the use of acid modified binders will sacrifice performance compared to traditional polymer modification methods (SBS). Six cells were built in 2007 for this study on the LVR. The same surfacing thickness (4 in.) and PG binder were utilized for the HMA on these cells. Binder modification combinations and aggregate base details for these test sections are as follows:

Cell	Acid Modification	Polymer Modification	Base Thickness, in.	Type
33	PPA	N/A	12	Class 6
34	PPA	SBS	12	Class 6
35	NA	SBS	12	Class 6
77	PPA	Elvaloy	8	FDR
78	PPA	Elvaloy	8	Class 6
79	PPA	Elvaloy	8	FDR w/Fly Ash

- Most states only specify the desired performance grade (PG) not the method of modification. MnROAD partners now have a better understanding of the methods contractors modify binders using PPA (acid), SBS, PPA/Elvaloy, and PPA/SBS modification blends.
- PPA modified test cells are performing similar to polymer modified test cells relative to rutting, cracking, and ride at MnROAD.
- PPA (acid) modified samples have shown slightly less resistance to thermal cracking and fatigue compared to polymer modified asphalt binders in laboratory testing.
- PPA (acid) is less costly than SBS modification.

MnDOT Savings Data:
To date, performance of all six MnROAD cells has been good at a relatively low level of loading. This project is believed to provide non-monetary benefits in that acid modification has been demonstrated to

provide acceptable service with no obvious problems to date, based on 7 years of MnROAD performance. It is also believed that performance concerns for acid-modified mixtures on higher volume roads may be addressed through the DCT test or similar performance tests; however, it is recommended that similar evaluations be made for higher traffic volume roadways.

The savings related to modifying asphalt binders with acid compared to typical polymer modifiers could potentially yield large benefits but at this time MnDOT has not made any specification changes to preclude or require specific types of modification.

Development of Warm Mix Asphalt

Partners – Mathy Construction

Warm-mix asphalt (WMA) is the generic term for a variety of technologies that permit producers of hot-mix asphalt (HMA) pavement material to reduce production temperatures at the HMA plant and placed on the road. WMA is typically produced at temperatures between 200° and 275° F, while traditional HMA usually runs 275° to 325° F. Lowering the temperature of asphalt mixes will decrease fuel usage, fumes, and greenhouse gas emissions, preserving resources while addressing growing environmental sustainability. Potential engineering benefits include better compaction on the road, the ability to haul paving mix for longer distances, and the ability to pave at lower temperatures. In addition, researchers hypothesize that the reduced level of oxidation at the HMA plant will lead to better long-term pavement performance.

Six Interstate mainline test cells were constructed in 2008 using Evotherm warm mix technology. Each of these test cells consist of 5 in. of WMA with a number of different types of bases (Cells 16-19, 23) along with one WMA mill and overlay (Cell 15) of an existing HMA roadway. Eight other HMA designs were also constructed in 2008 for research comparisons including one on the LVR (Cell 24) which contains the same mix design but did not contain the WMA additive and was produced at a higher temperature.

Observations to date include:

- These sections were a MnROAD first demonstrating WMA use on a high-volume roadway. This fact alone helped foster a sense of confidence in using WMA on a wider scale across Minnesota.
- MnDOT specifications were used; few changes required relative to HMA specifications.
- Contractor plant operations had no delays producing the mix. A reduction of mixing temperatures was noted. The paving crew felt that the mix was similar to HMA mix and noticed a reduction of fumes and improved compaction. One less roller was required for the WMA compared to the other mixes constructed on the mainline interstate.
- Contractor experienced no issues using the Evotherm WMA additive but the costs were high because of the small quantities. Furthermore, this was the first WMA mix produced by the contractor.
- MnROAD test cells have performed as well as the mixes constructed at the same time with no cracking or rutting issues to date.

Based on a review of experiences conveyed in published literature and online resources potential benefits to using WMA are [4,5,6]:

- Environmental **-** Reduced fuel consumption and greenhouse gas emissions; reduces the need for fume evacuation equipment on plant and paver.
- Operational **-** Lower plant wear, longer haul distances, late season paving, better compaction, early site opening, and more comfortable working conditions for plant and paving crews.

- Performance - Reduced binder aging, more time for mixture compaction, cold weather paving, can use recycled asphalt with WMA, less susceptible to low temperature and fatigue cracking, and eliminates bump at joint when overlaying concrete.

Recycled Materials in Asphalt Mixtures

Partners – FHWA, LRRB

This research is an offshoot of the low-temperature cracking study of which the subject sections were constructed in 2008. The goal of the research was to investigate types of recycled materials that can be incorporated into asphalt mixtures without compromising long-term performance. Questions exist related to acceptable percentages, type, and gradation (fractionated recycled asphalt) of recycled asphalt mix that can be added along with what other type of materials including both manufactured and tear off singles. Although MnROAD at the time did not have a formal study on recycled material use in asphalt, this effort was included together in the low-temperature cracking study for the administration of the funding. Included are three of the cells built in 2008 along with shoulders in which both manufactured and tear-off shingle recycled mixes were incorporated.

Findings:

- The objective was to demonstrate the use of both fractionated and non-fractionated mixes on the mainline using 30 percent recycled asphalt pavement. However, it should be noted that the gradations of both the fractionated and non-fractionated RAP turned out to be the same when the mix design was completed.
- Mixtures with PG 58-34 binder have exhibited a lower amount of transverse cracking as compared to mixtures with PG 58-28 binder.
- Shoulders paved with 5 percent recycled shingles (both tear off and manufacturing waste) have experienced transverse cracking.

Benefits:

- Additional data related to expected benefits or costs of RAP use are expected from the low temperature cracking efforts that used fracture energy using the Disk-Shaped Compact Tension (DCT) testing. It is expected that fracture energy will also be an excellent screening tool related to percentages of recycled material or types of additives that may extend or affect overall pavement performance.
- Effect on base asphalt binder selection for RAP was shown from the laboratory testing based on the three mainline cells constructed.
- Shingles are a viable option as shown from the performance of the MnROAD shoulder material and mainline transitions.
- Over the period 2008 through 2014 all three sections are performing similarly with respect to cracking, rutting, and ride.

Potential Savings:

- Cost benefits of RAP are documented by others in particular, NCAT and FHWA [7,8]. Over $5 per ton can be saved when new asphalt mixtures are produced with 20 percent RAP.
- A study done for the Wyoming DOT concluded that usage of RAP in general is beneficial from a cost standpoint. However, it is most effective when used in new bituminous mixtures [9]. For every ton of RAP included in the mixture, over $40 were saved.
- At this point no calculated savings can be developed for the use of recycled materials used in asphalt paving in Minnesota based on this research. MnDOTs asphalt mix specifications have permitted use of RAP for many years and there is significant experience with it. Although increases in RAP content would likely provide further savings performance may be an issue. It is believed that further increases

in RAP content will not be realized until performance specifications and tests (such as the DCT) are fully implemented and field performance is verified.

Permeable HMA Pavement Performance in Cold Regions MNR-6(024)

Partners – LRRB, MnDOT

The apparent lack of porous asphalt pavement durability research in the seasonally diverse Minnesota climate preceded this research project. The objectives of this research were to evaluate the load carrying capacity, durability, hydrologic characteristics and environmental effects of porous asphalt pavement when used on a low volume roadway in a cold climate. In order to accomplish these objectives, in 2008 two porous asphalt test cells were constructed on the MnROAD LVR, one each on clay subgrade and granular subgrade. Construction of these sections marked firsts for both MnDOT (specifications developed, constructed section loaded by heavy trucks) and the contractor that constructed the sections (first experience placing porous asphalt mixture). Construction and maintenance procedures were monitored allowing for the best possible data from both the construction and data monitoring.

Potential benefits of treating water runoff through the pavement system rather than diverting through a storm water system include reduction or elimination of the need for water detention basins and the attendant right-of-way required to build such facilities.

To date the sections have performed well, holding up to environmental demands for six seasons, including freeze/thaw, and snowplow wear. Observations and conclusions made to date include:

- Mixture performance testing such as with the Asphalt Pavement Analyzer (APA) is recommended during the design phase to ensure pavement strength and durability.
- Construction of porous asphalt pavement involves special mixing, transport, and placement requirements that must be followed closely in cold climates.
- Porous pavement performance and durability is greatly affected by heavy truck loads, distress modes for these sections has been primarily rutting and raveling (not cracking).
- The porous asphalt demonstrated lower stiffness and higher strains than dense-graded asphalt mixtures; however the lack of cracking indicates it can be a very resilient pavement.
- Snow and ice appeared to melt and clear faster on the porous asphalt than the standard asphalt control cell, particularly in sunny conditions.
- Subsurface heat transfer was better below the porous pavement and the pavement and base layers warm faster in the spring than in standard pavements.
- Vacuuming appeared to have a beneficial effect; maintenance of this type is recommended particularly when local conditions could introduce clogging agents.
- Water quality testing indicated that the porous asphalt reduced copper and zinc concentrations in the infiltrated water and can cool stormwater prior to release into sensitive resource waters.

Potential Benefits:
No specific cost benefits are calculated for this project as the results will be project dependent. Furthermore, the relative benefit will depend heavily on the differences in cost between standard and porous asphalt mixtures. Sufficient data are not available to do this.

One potential benefit may be realized from avoiding the necessity to provide storm water collection and conveyance systems. Based on MnDOT average bid prices (2014) costs to construct surface water collection systems are approximately $87 per lineal foot (sewer pipe, structures, and curb/gutter). This includes facilities on both sides of the roadway with drainage structures approximately every 150 feet.

When typical pavement materials are used it is necessary to convey and treat storm water. The cost to construct infiltration facilities varies widely, depending on the size of added impervious areas, excavation quantities, cost of right of way, etc. With a porous/pervious pavement system infiltration and/or detention facilities may be significantly reduced or even eliminated.

HMA Surface Characteristics related to Ride, Texture, Friction, Noise, Durability MNR-6(029)

Partners – LRRB, MnDOT, FHWA

Motivation for this study came from the need to determine the durability and performance of pavements built for certain surface characteristics in northern climates. The aim of this MnROAD research is to satisfy both the surface characteristics and the need for strong pavements in cold weather.

MnROAD initiated this study to evaluate frictional properties, texture configurations, texture durability, ride quality, acoustic impedance and noise characteristics of asphalt surfaces. Study was aimed at ascertaining optimal and economic textures or surfaces that optimize durability, quietness, friction and ride quality. While 4 years were not considered sufficient to accomplish all the objectives particularly in long terms, it aims at accentuating the short-term properties for extrapolations where tenable. Additionally, this study served at the barest minimum as a springboard for continuation of research on asphalt surfaces.

Findings:

- There is an effect of temperature on Tire-Pavement-Interaction-Noise of asphalt pavements. A correction algorithm based on the temperature correlation developed in this research is recommended.
- Porous asphalt surfaces are the quietest, while the chip seal and some of the dense graded asphalt mixtures are the loudest. OBSI levels are lowest in the summer when the pavement surface is warm; they are highest in cold weather. There is a general upward trend of noise levels over time with the porous asphalt showing a more gradual trend and dense graded surfaces showing a sharper increase. In some cases (e.g., UTBWC) the difference between cool and warm weather results is remarkable, while in other cases (e.g. porous asphalt) the differences in OBSI levels between seasons are much less.
- Prior to this study, minimal references describing the rate of degradation of friction or skid resistance of asphalt surfaces in relation to the skid resistance at the time of measurement were available. This study finds the relationship to be similar to the half-life probabilistic function.
- In MnDOT's current asphalt mixture specifications an increasingly more angular and durable aggregate is required as traffic levels increase. Asphalt binder performance grades (PG) are selected according to traffic conditions which relate to rutting and cracking characteristics. Current specifications may be modified to include a simple check for texture orientation to facilitate corrective action towards friction and noise without compromising other required characteristics.
- Porous asphalt surfaces exhibited the highest sound absorption coefficients; UTBWC surfaces are a distant second. Dense-graded asphalt mixtures have extremely low sound absorption coefficients, with the 4.75 mm taconite mixture (Cell 106) having the lowest. The sound absorption coefficients of the open graded surface textures (porous and UTBWC) decrease significantly over time, while this is not the case for the dense graded mixtures.

APPENDIX B - MnROAD Phase-II Concrete Related Project Overviews and Savings

Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements TPF-5(165)

Partners – IA, KS, MN, MO, MS, NC, NY, PA, SD, and TX DOTs

The purpose of this project was to create a unified national design procedure for thin and ultrathin concrete overlays of existing asphalt pavements (BCOA). The tasks in this project included:

- A literature review and collection of field performance history for thin and ultra-thin bonded concrete overlays of asphalt pavements (BCOA) sections around the U.S. In addition to several case histories involving large paving projects in several states, the performance history of test sections at the MnROAD facility and other accelerated load testing facilities were gathered to aid in the development and calibration of the new design procedure.
- A review of existing structural design models was performed. Based on the review three distinct structural models were chosen to be incorporated into the new design procedure. It was determined that the behavior of thin BCOAs is controlled principally by panel size, rather than thickness.
- Large and small-scale laboratory experiments were tested to characterize the effect of layer bonding and structural fiber-reinforced concrete on the performance of BCOAs.
- A spreadsheet-based design procedure for BCOAs, named "BCOA-ME", was created and calibrated. Associated theory and user's manuals were also written. The procedure is formatted such that it could become a module in future AASHTO pavement design procedures.
- Updated guidelines for project selection were developed. Guidelines for effective repair and rehabilitation were also created.
- To aid implementation, training videos were created.
- The design procedure and all associated information and training materials are available on a dedicated web site: *http://www.engineering.pitt.edu/Vandenbossche/BCOA-ME/*

Benefits of the new procedure include:

- Designs are based on panel size, rather than thickness. This reflects the actual fatigue cracking mechanisms and performance observed in the field.
- The effect of the climate on the underlying asphalt layers is accounted for. It was discovered that the performance of BCOA is highly dependent on the daily and seasonal behavior and support provided by the underlying HMA.
- Due to the previous two factors, the design thicknesses are better optimized and tend to be significantly thinner than those predicted by older, less rational, design procedures.

Benefits to MnDOT:

- With optimized (thinner) designs for BCOAs, they can become cost competitive when analyzed as an option for alternate bid projects.
- Less raw materials (concrete) and reduced construction times (less bituminous milling, more paving completed per truck load) will reduce costs.
- More rational BCOA designs will increase design lives and overall performance.
- MnDOT has since implemented a 20-year design option for selecting pavement rehabilitation alternates and life-cycle cost analysis.

MnDOT Savings Data:

- As an example, in 2009 MnDOT constructed a 7-mile long, 6-inch thick whitetopping project on I-35 north of North Branch for a cost of approximately $345,000 per lane-mile (approximately 28 lane-miles in total). The existing bituminous pavement was about 12 inches thick overlying an aggregate base paving platform, and fine, sandy soils.

- At the time this project was designed, the design procedure officially available to MnDOT resulted in an 8.5-inch thick concrete section. A 6-inch section was opted for due to the positive performance results of 6-inch concrete whitetopping at MnROAD.
- This same reduction may not be applicable for other jobs so a more defensible assumption is a 1.5-inch reduction for MnDOT whitetopping. This equates to about 300 CY of concrete per lane-mile of paving. At the County level, a modest assumed reduction in 1 inch of concrete seems reasonable.
- Based on the MnDOT pavement preservation program for 2009-2013 on average approximately 20 lane-miles of whitetopping were constructed. A review of recent county paving projects indicates that about 50 lane-miles of whitetopping have been constructed in recent years, on average.

Assumptions:

- MnDOT historical average bid prices for structural concrete - $75 per cubic yard.
- At the County level, over the past several years, there have been about 50 lane-miles of whitetopping paved at an average of $3.73 per square-yard per inch. These are typically two-lane roadways and are paved at 27-feet wide.
- In this analysis the reduction in cost is primarily attributed to reduced volume of concrete required. Reduced costs for milling and/or slope paving were not accounted for.
- Since 2010 the number of miles of concrete overlays that have been constructed statewide (MnDOT and local) has increased dramatically. It is anticipated that this resurfacing method will find increased use in the future.

Example Savings:

- For SP 1380-74 the reduction in paving concrete due to 2.5 inch reduction in overlay thickness = 13,500 CY. The resultant estimated savings = 13,500 CY * $75 per CY = $1,000,000 (for this specific project).
- For MnDOT projects in general: 20 lane-miles * 300 CY * $75 = $450,000 per year.
- For County projects: 50 lane-miles * 7,920 square yards * 1-inch * $3.73 = $1,477,000 per year.
- This is a total estimated savings of $1,927,000 per year and is considered to be conservative owing to the expected increase in use noted above.

Development of an Improved Design Procedure for Unbonded Concrete Overlays TPF-5(269)

Partners – GA, IA, KS, MI, MN, MO, NC, and OK DOTs

One pavement rehabilitation option that has been gaining popularity in the U.S. recently is unbonded concrete overlays of existing concrete or composite pavements (UCOCP). While thicker (greater than 7 inches) unbonded concrete overlays have performed very well in many states, current economic restrictions, as well as an interest in conserving materials (sustainability), are guiding agencies toward optimizing concrete overlays. This can be done by making the best use of the existing pavement structure and designing a cost effective interlayer and concrete overlay.

One area of deficiency in the application of unbonded concrete overlays is the lack of a rational design procedure that addresses all components of the structure, environmental factors, and their interaction. While several design procedures have been formulated by local agencies and the concrete paving industry, few are based on detailed research and actual long term field performance. The increasing number of UCOCP projects, as well as test tracks like the MnROAD facility, are beginning to provide detailed performance data that can be used to develop a much improved and unified mechanistic-empirical based design procedure for unbonded concrete overlays.

Overall guidance on economics and design of such features as pavement widening, super elevations, and safety features (raising guardrails) are covered in publications such as the National Concrete Pavement Technology Center's (NCPTC) "Guide to Concrete Overlays" [10]. Detailed guidance on using existing unbonded concrete overlay design procedures is provided in NCPTC publication "Design of Concrete Overlays Using Existing Methodologies" [11].

Characterization of the behavior and performance of the interlayer is critical in the design of unbonded concrete overlays. Many different materials have been used for the separation layer. The most common practice is to use an asphalt based material. This material is placed prior to the concrete overlay on existing concrete pavements, or for composite pavements (asphalt overlay on old concrete) the existing asphalt is often milled to a minimum specified depth. Questions arise over whether the separator layer needs to be drainable, or what condition an old asphalt layer must be in to provide the long term functions of a separator layer. Several states, including Missouri, Kansas, Iowa, and Minnesota have recently used non-woven geotextiles for the separation layer. This is an adaptation of the practice in Germany of using geotextile between cement treated base layers and concrete pavement.

Objectives:
The primary purpose of this project was to create a unified, national design guide for unbonded concrete overlays of existing concrete and composite pavements. This consists of the following distinct objectives:

1. Study and understand the field performance history of UCOCP as demonstrated by various test sections and in-service pavements.
2. Determine suitable separator layer (interlayer) materials and properties to ensure long term performance of UCOCP systems.
3. Develop a design procedure for unbonded concrete overlays of existing concrete and composite pavements utilizing existing validated performance models, as well as new analytical models derived to address deficient or missing design parameters in existing methods. The design guide will be based on mechanistic-empirical principles, including the effects of various concrete overlay materials, separator layer (interlayer) types, panel thickness (4 in to 10 in?) and panel size, joint load transfer mechanisms, traffic loads, and climates (nationwide) in which they must perform.

The study began in June 2013 and will not be completed until March 2017. Therefore, it is too early to realize or estimate savings at this time.

Design and Construction Guidelines for Thermally Insulated Concrete Pavements (Pooled Fund TPF-5(149)) SHRP 2 Composite Pavement Study

SHRP 2 Partners – ERES, University of Minnesota, MnDOT
Pooled Fund Partners – CA, MN, and WA DOTs, FHWA, LRRB

MnROAD worked on two projects related to composite pavement design. Sections built in 2008 supported the Design and Construction Guidelines for Thermally Insulated Concrete and sections built in 2010 supported the SHRP 2 Composite Pavement Study.

Thermally insulated concrete pavements consist of concrete pavement structure (jointed or continually reinforced) covered by an asphalt layer during initial construction (or soon after) to address ride quality or surface characteristic issues. TICPs combine the structural longevity of PCC pavements with the serviceability of HMA pavements. There are no definitive guidelines for effective design and construction based on the understanding of the effects of design, materials and construction parameters. The research objective of this pooled fund study is to establish these guidelines for mechanistic design and construction. The goal of using this composite pavement system is to take advantage of both HMA and

PCC materials so they can be optimized when they are originally built together in the same construction season.

Potential benefits include initial construction cost savings in the amount of base materials required, quality of the concrete ride and materials, joint spacing, and easier rehabilitation in the future.

The research results were instrumental in addressing important results in the design, analysis, and construction of composite (asphalt-over-concrete) pavements in general. Extensive revisions and improvements to the MEPDG were recommended.

Concrete Pavement Structural Design Optimization – Determining the Lower Threshold of Slab Thickness for High Volume Roads MNR-6(031)

Partners – MnDOT

With the growing trend in shrinking budgets, as well as increased concern for sustainable engineering, there is strong interest in determining how thin jointed concrete pavements can be constructed and still provide predictable long term performance. To address this question, in 2008, five thin concrete test sections were constructed at the MnROAD mainline pavement test facility. Design slab thicknesses ranged from 5 to 6.5 in. and the sections were exposed to accelerated loading in the form of live, high volume interstate traffic. Other than some variations in panel length and dowel type for the thinnest sections, all other design variables were kept constant.

Several pavement performance parameters were analyzed, including visual distress, joint faulting and load transfer efficiency, panel deflections, and ride quality. Observed performance was also compared to performance predicted by the current MnDOT pavement design procedure. The thinnest sections experienced both transverse and longitudinal cracking. While the sections with slabs less than 152 mm (6 in) thick in this study survived over 1.5 million CESALS before cracking, it is clear the thicker sections have much greater capacity. The data and observations gathered from these cells will certainly benefit the continuing development of mechanistic-empirical design procedures for thin concrete pavements. Benefits include better distress and life prediction models for more optimized concrete pavement structural sections which in turn will improve resource usage and sustainability.

Investigation of High Performance Concrete Pavement (60-year Concrete) MNR-6(017)

In 2008, MnDOT constructed a test cell on the MnROAD low volume road to study the performance of a 60-year design concrete pavement. The 250-foot test cell consisted of two 12 foot wide lanes, 12 inch thick slabs, and a high performance concrete mix. The transverse joints included 1.5 inch diameter stainless steel dowels. In general, after five years of performance monitoring and analysis of the instrumented test section, it was found the performance has been consistent with other 60-year design concrete pavement built around the state. Some of the highlights from the 5-year performance report completed in 2014:

- Evidence of lesser strain in the concrete from the sensor data in comparison to other concrete pavements with less than 12 inches thickness at MnROAD. A two tailed T –test showed that the strain levels were generally dissimilar.
- Concrete joint load transfer remained high and did not significant decrease over time when compared to the initial test results. The average load transfer was approximately 85 percent, which was in some cases over four times as high as another MnROAD concrete pavement test cell tested with the FWD.
- Skid resistance was adequate and was consistent over time for the transverse broomed surface. A slight disparity friction was observed between the inside (trafficked) and the outside (environmental) lane with the outside lane generally having higher friction than the inside lane.

- Faulting between the concrete panels was insignificant with no change over time.
- Ride quality, in terms of the International Roughness Index (IRI), was somewhat high (attributed to construction issues with short sections) but has remained relatively constant over time. A slight disparity of IRI between the inside (trafficked) lane and the outside (environmental) lane was evident.
- OBSI (noise) on the inside lane was consistently lower than the outside lane. The lower noise may be due to traffic wearing down the surface of the transverse broom finish. Finally, the mean texture profile depth in the outside lane was consistently higher than the inside lane.
- Deflection basins (FWD) from 2009 and 2013 showed deflections under 100 microns (4 mm) for both similar dates (spring and summer similar weather conditions), which also suggests good performance.
- ELMOD was used to determine the layer properties from the FWD data. Again, similar dates in both spring and summer seasons were compared for the year 2009 and 2013. The analysis returned inconsistent results for the spring season comparison, suggesting that the base conditions may have been different between years with respect to thaw progress in spite of the deep frost free materials comprising 1 foot of class 5 aggregate base and 4 feet of MnDOT select granular material. However, the results for the summer did show a slight decrease in calculated moduli values for the base, subbase and subgrade layers, for both the inside and outside lane. This slight decrease over the period of five years could be expected, and was not be interpreted as failure in the base layers.

Roller Compacted Concrete

Roller Compacted Concrete (RCC) shoulders were constructed adjacent to Cells 505-605 and 306-406 during the 2011 construction season in an effort to demonstrate the technology and evaluate its performance in a freeze-thaw environment. Provided the RCC shoulders perform well at MnROAD, designers will have an alternative to traditional asphalt or concrete shoulders.

Findings to date:

- First instance of placement on a pavement shoulder by MnDOT
- Special provisions based on specification used by other states
- Contractor found it to be easily constructible
- Materials, labor, and equipment costs lower than conventional concrete shoulders

Potential benefits include:

- Longer-lived shoulder alternative
- Could use as a lower layer of a composite pavement
- May be option for low-volume roadway surfacing
- Provides the strength of a concrete structural slab with rapid construction
- Uses equipment similar to that for paving asphalt.

No quantifiable benefits were determined for this study however the successful demonstration of the technology coupled with excellent performance to date is considered a significant benefit.

Unbonded Concrete Overlay MNR-6(016)

Partners – CPAM, ACPA, MnDOT

MnROAD gives a unique opportunity for researchers to include additional environmental and traffic factors in validating the performance of unbonded concrete overlays. Several test cells were constructed in 2008, 2011 and 2013. Variables under study include the following:

- Effect of panel size
- Characterization of performance when using various interlayers, including nonwoven geotextile fabric
- Determining the lower limit of slab thickness
- Determining the contribution of fiber-reinforced concrete toward extending overlay life.

Much of the data from these instrumented sections will be utilized in the Pooled Fund Study TPF-5(269), which as described previously, is dedicated to developing an improved design procedure for unbonded concrete overlays.

PCC Surface Characteristics – New Construction MNR-6(021)

In pavement infrastructure asset management functional characteristics typically take precedent over structural characteristics when making maintenance and replacement decisions. Evidently, agencies invest in provision or restoration of friction (skid resistance) and make policies to minimize traffic noise. Most agencies accept (or reject) construction projects based mainly on initial ride quality. State pavement management practices typically include measures and reports of pavement performance in various pavement smoothness metrics such as International Roughness Index (IRI), Ride Number (RN), etc. Other surface features such as faulting and cracking in addition to terminal ride quality are output parameters in all concrete pavement design tools including Pavement ME. Consequently, a study of these functional characteristics is indispensable to an overall investment in concrete pavement infrastructure.

In the original 1993 MnROAD test cells the predominant texturing indicative of what was prevalent in the network at that time was the transversely tined texture. The original transversely tined cells that were still available through a major period of this this study thus included low volume road Cells 36-40, and Mainline Cells 12, 96 and 97. In 2000, three cells (cells 6, 32 and 52) were drag-textured. Later in 2004 when whitetopping cells 60-63 and the Taconite aggregate cell (cell 54) were built, they were also textured with the turf drag.

The need to study surface characteristics was identified as a major focus area for the Phase-II of MnROAD to improve pavements' ability to provide safe, quiet, smooth and durable surfaces [12]. New concrete surface textures constructed in the 2008, 2010, and 2011 initiatives included pervious pavements and varying surface texture methods such as longitudinal turf drag, exposed aggregate, longitudinal tining, and transverse broom. Note that transverse tining was preponderant at MnROAD until 2008. Cells 36, 38 and 12 are still transverse tined and their performance continues to be monitored.

This study examined various new textures and monitored them over time with a litany of standard tests. In the process certain analytic initiatives were performed.

Highlights of this research effort include:

- MnROAD field validated the Purdue University laboratory study by first demonstrating the innovative grinds were both constructible and effective on the LVR and then on MnROAD's mainline interstate I-94.
- Improvements in noise reduction, durability, and safety (texture) were demonstrated and documented with the use of innovative, ultimate, and whisper grinding configurations over more traditional diamond grinding.
- MnDOT and other states are starting to specify the use of non-traditional grinding for rehabilitation which has helped lower costs.
- Updated innovative grinding configurations have not only been used at MnROAD but also I-94 at Clearwater, and I-35 in Duluth.

- Benefits include a reduction of noise (when no room for noise wall or making then not required), quick rehabilitation (less driver delays), an alternative to other rehabilitation techniques, and safer pavements for public use.
- MnDOT has developed Special Provision specifications for future work in the state.
- Diamond grinding on pervious pavement surfaces worked well to reestablish the ride and did not appear to clog the pavement system pores.
- MnDOT invests a significant amount of resources towards construction of noise barriers. Using actual noise reduction measurements from MnROAD cells benefit-cost analyses that incorporate a life cycle approach (accounting for monetary discount rates) have been performed [12]. Realistic construction costs for both noise walls and berms, and surface diamond grinding were used. While noise walls provide more noise reduction in terms of overall dBA savings as compared to innovative surface grinding (8 dBA as compared to 4 dBA) the economic benefit-cost analysis indicates that mitigation of noise with surface grind have a much more attractive benefit-cost ratio as compared to construction of noise walls.

Savings:

- Also see Concrete Surface Characteristics – Rehabilitation TPF-5(134) in Appendix C.
- Note that implementation of surface grinding as an acceptable noise reduction method in lieu of noise walls would require lowering of the current minimum noise reduction requirements (minimum 7 dBA reduction).
- Assuming this option were available, based on the work described above [12], the estimated cost to construct 20-foot tall noise walls on either side of a 1-mile long, 4-lane corridor is $6.4 million while the cost to provide an ultimate-grind textured surface is $240,000 per mile (4 lanes).
- The benefit vs. cost for the ultimate grind is 10 times as effective as a noise wall. Assuming a total of 3 miles of noise wall is typically constructed each year at a cost of $9 million. The cost to instead construct innovative diamond grind would be about $1 million resulting in a net savings of $8 million per year.

Pervious Concrete Pavement Study

Partners – LRRB (Study 879), MnDOT MNR-6(027)

Two full-depth pervious concrete test cells (Cells 85 and 89) were constructed in 2008 using industry standard specifications and practices. These test cells were built subsequent to trial test sections constructed and evaluated at MnROAD in 2006 (parking lot) and 2007 (sidewalk).

Construction began on October 17, 2008, using fixed form pavers and roller compaction. Each cell was equipped with vibrating wire static strain gauges and thermocouples at various depths to detect freeze thaw cycles and monitor maturity. The cell was allowed to cure for 28 days using a “Confilm” curing compound and 2 layers of polyethylene sheeting. Ride characteristics, noise characteristics, surface properties, and physical properties of the two cells were tested immediately after construction, and periodically over the next three years to gain a comprehensive understanding of pervious pavement performance.

The following lessons have been learned:

- The pervious concrete section constructed on engineered base and a granular (sand) subgrade is performing much better in comparison to that built over native (impervious) soil suggesting the need to follow best practice for pervious base construction. The pervious concrete cell with impervious subgrade soil is not performing well due to freeze-thaw movements resulting in widespread cracking.

- Pervious concrete provides very high sound absorption properties and very low noise characteristics which would make them attractive for noise reduction on roadway applications. The maximum relative acoustic benefit occurs at 1,000 Hz which is the same frequency of resonance of most car tires, thus providing the best benefit where it is mostly needed.
- Good maintenance practices including frequent vacuuming can extend the life of pervious pavements. Poor maintenance practices result in clogging that can increase susceptibility to freeze-thaw damage. Fine-grained soil particles such as clay and silt constitute the worst clogging agents.
- Skid resistance properties of pervious pavements compare favorably in performance to those of most non-pervious pavements on the network. Construction techniques employed for the MnROAD sections resulted in a lower ride quality than is typically obtained with normal concrete paving. Improvements may be realized with the use of conventional slip-form paving.
- Greater acceptance of pervious concrete is evident around Minnesota based on deployment for a boat landing (Detroit Lakes), pervious shoulder (Rochester), and pervious residential streets (Shoreview). Additionally LRRB is developing guidelines for pervious concrete through a project with the University of Minnesota.
- Successful diamond grinding of a pervious concrete overlay test cell in 2013 validated the feasibility of surface restoration of pervious pavements safely and beneficially.

Although MnDOT may not construct mainline sections of pervious concrete or porous asphalt, the research completed at MnROAD has demonstrated several important results. In fact, the results have prompted some local agencies to implement these systems for their road network as a means of treating storm water. Data requests and inquiries regarding this section and other pervious concrete and porous asphalt sections rank as some of the highest from researchers nationwide.

Pervious Concrete "Overlay" Mix Design for Wearing Course Applications MNR-6(015)

Partners – CTRE, MnDOT

In an effort to study construction, surface characteristics, and performance a 4 inch pervious concrete overlay was constructed on existing MnROAD Cell 39 in 2008. The project was designed to address two issues: 1) a combination of fundamental material property investigations, test method development, and addressing constructability issues before actual construction could take place; and 2) construction and long-term testing. Overall successes, failures, and lessons learned were subsequently documented.

This project is an example of research that does not necessarily have direct, quantifiable payoffs. For example, although MnDOT will most likely not construct mainline sections of pervious concrete or porous asphalt, the research completed at MnROAD has demonstrated several important results.

The results of the studies conducted show that a pervious concrete overlay can be successfully designed, constructed, operated, and maintained. A pervious concrete overlay has several inherent advantages, including reduced splash and spray and reduced hydroplaning potential, as well as being a very quiet pavement. In 2013 this pervious concrete overlay was successfully diamond ground and the smoothness was improved. The pervious concrete was able to withstand the diamond grinding and the pavement did not completely clog. MnROAD has more information on the construction effort and permeameter readings.

While the performance of this overlay was fairly good for the first 5 years the cell is now exhibiting significant cracking and raveling. Lessons learned indicate that certain specific design details would need to be refined for full field implementation. For example, provisions for lateral drainage collectors, bonding conditions, and thickness design.

APPENDIX C - MnROAD Efforts Related to Pavement Preservation

Optimal Timing of Preventive Maintenance for Addressing Environmental Aging in HMA Pavements TPF-5(153)

Partners – MD, MN, OH, and TX DOTs, LRRB

The primary goal of this study is to develop and validate technology that can be used by MnDOT and other highway agencies to determine the proper application timing of preventive maintenance treatments in order to mitigate damage caused by asphalt aging. An additional goal is to determine the primary factors that affect asphalt aging, and the proper timing of preventive maintenance treatments in order to optimize life cycle costs and pavement performance. Expected outcomes include identification of an asphalt binder or mixture parameter related to durability as a result of environmental aging that can be determined from testing of pavement cores. This pooled fund study conducted preventive maintenance research on test sections at MnROAD as well as in-service pavements in Minnesota and around the country. Cell 24 on the MnROAD LVR was built and designed for this study to allow surface treatments to be placed at 100-foot segments each year for a 5-year period starting in 2008. These surface treatments were essentially a heavy application of emulsion (CRS-2P), in other words a chip seal without the cover aggregate. Cores from the 3 in. asphalt surface layer and other test cells around the country were then tested to determine the aging of the asphalt binders for each of the segments compared to a control section. At MnROAD cores were taken from each of the 100 foot segments each year so the aging could be documented to a control.

Results indicate:

- In order to minimize binder aging surface treatments should be placed 1 year after initial construction.
- Typical MnDOT practice is to perform surface treatments on average 7 years after construction. The researchers point out that, although 1 year might be the optimal timing, every 7 years is beneficial compared to “do nothing” over the life of a pavement.

Savings:

- Cost savings in terms of life extending benefit resulting from preventive maintenance treatments are extremely difficult to quantify. Performance differences between sections may require years to manifest themselves. Although this study indicates that the asphalt aging process can be quantitatively detected within the first year of placement, the impact to overall long-term life and performance cannot be determined at this point: the performance on this section under all treatment scenarios is still quite good.
- MnDOT has recently applied chip seals as pavement preservation to higher volume roadways to help extend life. If 1 year is the optimal time it might make more sense to apply surface treatments during the initial construction to allow MnDOT to save money related to administering one construction contract compared to two in multiple years. This will likely result in fewer user delays.

Concrete Surface Characteristics – Rehabilitation TPF-5(134)

The objectives of this project were to better understand concrete pavement surface characteristics and provide tools for engineers to help meet pre-determined requirements for ride quality, quietness, safety against hydroplaning, splash/spray and durability. MnROAD is exploring these qualities through diamond grinding the surface of the pavement. Variables that factor into diamond grinding include blade spacing, depth of cut, kerf configuration, etc. These variables have not been previously studied sufficiently to produce guidelines to create a system to predict best possible performance. In other words, what is the optimal diamond grinding configuration to produce a smooth concrete road, reduced tire-pavement noise, greatest surface texture with optimal durability and friction? This project included a number of test cells at MnROAD from 2007 through 2011. In the spring of 2007, Cell 37 (LVR) was used to evaluate three grinding configurations with the regular tined surface. Knowledge from this was then used in the fall of 2007 when Cells 7-8 (innovative and traditional grinds) were done on the mainline interstate. Mainline interstate Cells 305-405 received a traditional grind, and Cell 9 received an ultimate grind in 2008. In 2010, grinding was performed on mainline interstate Cell 71 (Innovative grind). In 2011, grinding was done on mainline whitetopping Cells 63 and 96 (traditional grind). Finally, the pervious concrete overlay on Cell 39 received a traditional grind in 2013.

Highlights of this research effort include:

- MnROAD field validated the Purdue University laboratory study by first demonstrating the innovative grinds were both constructible and effective on the LVR and then on MnROAD's mainline interstate I-94.
- Improvements in noise reduction, durability, and safety (texture) were demonstrated and documented with the use of innovative, ultimate, and whisper grinding configurations over more traditional diamond grinding.
- MnDOT and other states are starting to specify the use of non-traditional grinding for rehabilitation which has helped lower costs.
- Updated innovative grinding configurations have not only been used at MnROAD but also I-94 at Clearwater, and I-35 in Duluth.
- Benefits include a reduction of noise (when no room for noise wall or making then not required), quick rehabilitation (less driver delays), an alternative to other rehabilitation techniques, and safer pavements for public use.
- MnDOT has developed special provisions for future work in the state.
- Diamond grinding on pervious pavement surfaces worked well to reestablish the ride and did not appear to clog the pavement system pores.

Flexible Micro-Surfacing

The expected life of micro-surfacing is dependent on many factors, including the in-place pavement condition, and pre-treatment surface preparation. Determination of life extension in a specific situation can be elusive in the absence of supporting performance data. It is commonly understood that the intent is to apply these treatments in a preventive maintenance type program, oftentimes they are applied to extend the life of a section to defer more intensive work to a later date.

MnROAD demonstrated the advancements in the effectiveness of traditional and flexible micro surfacing during the course of five maintenance projects starting with a single test cell in 1999.

In 2003, MnROAD studied the benefits of different crack repair techniques before micro surfacing as part of major study that focused on restoring ride quality. In the study, a matrix of 12 test cells received crack re-sealing, leveling of cupped transverse cracks, filling of rutted wheel paths, and control treatments. MnROAD learned that multiple applications (crack repair with two lifts) provide the longest effect on ride, but costs need to be taken into account.

An in-house research effort conducted by the Road Research Unit at the Maplewood Lab was undertaken in 2006 to determine if the performance of a micro-surfacing product could be improved with different base asphalt emulsion properties. The relative cost and performance are compared to a thin HMA mill and inlay.

Originally implemented in Minnesota in the late 1990s, micro-surfacing at that time was typically specified with PG 64-22 base asphalt. Based on situations where performance involving excessive cracking, peeling, and/or debonding of layers were observed it was surmised that softer base asphalt might improve performance. The first flexible micro-surfacing projects used either a PG 58-28 or PG 49-34.

The enhanced binder for flexible micro-surfacing adds a modest cost increase to the asphalt emulsion which in turn increases the unit cost of final product placement by about 10 percent. This is attributed to the emulsion content being increased from 13 percent to 16 percent and polymer loading increased from 3 to 6 percent. For flexible micro-surfacing to be marginally cost-effective as compared to regular micro it needs to extend life by at least 10 percent (24.5/22.5).

TREATMENT	TYPICAL COST (per lane-mile)
Micro-surfacing	$22,500
Micro-surfacing (flexible)	$24,500
Mill/overlay (1.5 in.)	$34,200

Application of flexible micro-surfacing on Cell 1 in 2012 returned the section to an RQI level it had not seen for about five years prior. At that time, a 1.5-inch mill and inlay was performed on the driving lane only. After six years of traffic the RQI of that surface had decreased from 3.3 to 2.6. While the improvement in ride from the flexible micro-surfacing was not as large as the 2006 thin mill and inlay it brought the RQI from 2.6 to 3.2 after it was placed in 2012.

Based on cost ratios above, to be marginally cost-effective as compared to the thin mill and overlay, a flexible micro-surfacing treatment needs to maintain a RQI above 2.6 for a period of at least 6 years * (24.5/34.2) = 4.3 years, or approximately 1.5 more years. Currently (2014) the section is performing well with RQI at about 2.8; performance will continue to be monitored.

Thin Asphalt Overlays

Asphalt overlays are a commonly used rehabilitation technique in Minnesota, and study of a PG 58-34 warm-mix asphalt (WMA) overlay at MnROAD indicate that PG 58-34 binder combined with lower plant temperatures for WMA may help extend the life due to less aging.

In 2008 MnROAD placed a PG 58-34 WMA overlay on an original MnROAD mainline asphalt cell that had poor ride, severe top-down cracking, and transverse cracking every 20 feet. Three inches of WMA were placed over the existing pavement surface. The WMA modifier provided benefit to the contractor in achieving density. Only 40 percent of transverse cracking has returned after nearly 7 years of interstate service and the RQI remains very good. Furthermore, the amount of medium and high severity cracking has been effectively eliminated compared to pre-overlay conditions.

Concrete Partial Depth Repairs

In September 2011, MnROAD worked with several concrete repair material manufacturers to install 13 different types of patching materials on several mainline concrete test sections. Observations indicate that the emulsion-based products have not performed as well as the cement- and epoxy-based products. Monitoring continues into 2016. A 3-year performance report will be completed spring 2015.

Full-Depth Concrete Repairs

Effective full-depth patch techniques for concrete repairs include installing dowel bars into the existing pavement using some form of anchoring material, such as grout or epoxy. If properly anchored, the dowels provide long term load transfer across the full-depth joint repair. Statewide, MnDOT has experienced problems related to the effectiveness of our current dowel bar anchoring techniques, prompting controlled full-scale experiments at the MnROAD facility. With industry participation, various materials and techniques for anchoring dowel bars into drilled concrete holes, were tried. Preliminary findings show that grout capsules, or using a grout bag, typically results in the best anchorage of dowel bars in these types of repairs.

MnROAD has also completed some full-depth joint repairs on both low-volume road and mainline test cells in 2010 and 2013. These repairs were designed to demonstrate the feasibility of restoring the load transfer efficiency of both distressed thin and standard thickness pavement joints. MnROAD, in a partnership with PNA Construction Technologies, installed plate dowels at various intervals across the transverse joints to provide load transfer between the patch material and the existing slab. Installations on the MnROAD low volume road with a minimum of 6 plate dowels across a 12 foot wide lane are showing good performance.

Concrete Sealers

Surfaces of some concrete pavements can deteriorate prematurely at the joints due to the environment and deicing chemicals used for winter maintenance operations. In September 2013, MnROAD partnered with Michigan Technological University to investigate the use of different concrete sealers (supplied by industry) to protect concrete materials near and within the joints. Core samples were also taken to better understand the pavement’s permeability and other concrete properties before and after the sealers were applied, to determine their effect on such factors as chloride penetration and permeability. This research is associated with pooled fund TPF-5(224) “Investigation of Jointed Plain Concrete Pavement Deterioration at Joints and the Potential Contribution of Deicing Chemicals.”

APPENDIX D - MnROAD General Studies

Development of an Open Graded Aggregate Base (Stable and Drainable)

The purpose of this effort is to improve aggregate base courses used in Minnesota by striking a balance between stability and permeability. This is an in-house research effort being conducted by the Road Research and Grading and Base Units at the Maplewood Lab. Drainage has always been considered crucial for long-lasting pavements; however, MnDOT specifications have remained unchanged for many years. The driving force behind this study are observations and forensic investigations from past MnROAD test cells where environmental damage has been observed in both asphalt and concrete pavements.

Both MnROAD Phase-I and II included a number of cells with drainable bases, including permeable asphalt stabilized base (PASB), large stone base (Cell 23), pervious test cells (Cells 85-86, and 88-89), and a drainable based installed under a thin concrete test cell (Cells 306-406). Based on forensics of both HMA and PCC pavements at MnROAD, it is apparent that damage occurs when water remains on top of the base layer for extended periods of time (more than one day). This interface needs to be better designed to avoid saturated conditions and deterioration of the pavement surface. While MnDOT does consider conventional edge drains and sealing as an effective practice both must be maintained in order to perform properly. It may be more practical to simply provide a drainable base layer. Typical MnDOT dense-graded aggregate bases are not considered permeable.

Forensics observations on asphalt cells have demonstrated:

- Major internal joint deterioration occurred when slow draining dense-graded aggregate bases were used
- Full-depth transverse cracks tend to deteriorate from the bottom up. Over time, pumping of the base material and deterioration of the asphalt crack face causes the typical dipped or cupped transverse cracks observed both at MnROAD and throughout the northern states. Excess water on top of the base is the primary driver of this deterioration.

Forensic observations on PCC cells have shown

- No internal joint deterioration observed when PASB base used
- Some internal joint deterioration observed when edge drains were functional and joints remained effectively sealed.
- MnROAD assisted in the development of a drainable, stable base (DSB), designed for a performance balance between permeability and stability), which helped develop the 2013 new specification.
- Open-graded base materials tend to develop about half the frost depth as traditional dense-graded aggregate base pavements. Currently MnDOT requires 36 inch frost free materials for new construction on its higher volume roadways and 30 inches on its low volume roadways. In cases where highly porous bases are constructed savings may be realized by reducing the required depth of “frost free” granular material.

Based on the general observations above it is presumed that additional pavement life can be realized through the use of drainable, stable bases:

- MnDOT unit prices for concrete pavement rehabilitation (CPR) and surface grind – $156,000 per lane-mile (major) and $87,000 per lane-mile (minor).
- MnDOT unit prices for asphalt rehabilitation – full-depth reclamation and overlay $172,000 per lane-mile and medium mill and overlay $118,000 per lane-mile.
- For the period 2009-2013 MnDOTs program included an average of 60 lane-miles of CPR work and about 100 lane-miles of full-depth reclamation and overlay.

Assumptions:

- PCC pavements – Anticipate less damage of the concrete joints requiring less costly repairs into the future. Assume half the miles of major CPR and grinding reduces to minor CPR and grinding in the future.
- HMA pavements – Less damage at the bottom of the asphalt pavement allows MnDOT to focus its work on the pavement surface issues such as ride. Assume half of the future reclamation and overlays are reduced to a medium mill and overlay.

Calculated Savings:

- PCC savings = 60 miles per year * (1/2 the projects) * ($156,000 per mile-$87,000 per mile) = $2,070,000
- HMA savings = 100 miles per year * (1/2 the projects) * ($172,000 per mile-$118,000 per mile) = $2,700,000
- Total savings = $4,770,000.

Effects of Implements of Husbandry "Farm Equipment" on Pavement Performance TPF-5(148)

Partners – MN, IL, and IA DOTs, LRRB, Professional Nutrient Applicators Association of Wisconsin (Industry Consortium)

The objectives of this study were to determine the pavement response under various types of agricultural equipment (including the impacts of different tires and additional axles) and to compare this response to that under a typical 5-axle semi tractor-trailer. This was accomplished by constructing new instrumented test sections at MnROAD and by retrofitting instrumentation into existing test sections. The results may influence policy and legislation in Minnesota and surrounding Midwest states. In 2007 MnROAD constructed asphalt test cells 83 and 84 with 7-ton and 10-ton designs, respectively, in the stockpile area. These sections were built in a loop configuration that allowed the continuous trafficking from loaded vehicles so that pavement response and performance could be monitored in a realistic setting. Cell 32, a 5 in. concrete section on the low-volume road was also included as part of this study. During testing periods agricultural test vehicles traveled a circuit over cells 83 and 84 in the stockpile area to Cell 32. A cross-over in the median area ensured that damaging loads were avoided on other low-volume road test cells.

Results of the study indicate that:

- Large farm equipment shows greater damage than a 5-axle tractor-trailer loaded to the legal limit. This is due to higher magnitude of measured strains at the bottom of the asphalt layer during the same testing times.
- On asphalt surfaced roadways greater damage occurs when the temperatures are higher and the asphalt mixture is correspondingly softer. In other words, the damage from the same loading changes throughout the course of a day when temperature increases and asphalt strength decreases.
- More damage occurred on the test cell without a paved shoulder. Paved shoulders provide extra strength and permit wide farm equipment to travel on a hard surface thereby eliminating the need for frequent shoulder maintenance of an unpaved shoulder.
- Based on measured pavement responses flotation tires were not observed to provide a benefit in terms of reducing pavement damage.
- In some states equipment manufacturers are moving towards smaller equipment and tanks.
- Wisconsin has implemented results by using information obtained on farm equipment classification, tire and contact pressure, axle weights and measurements, loaded and unloaded weights, and pavement performance. They implemented local meetings to stress communication of the issues related to farming needs and preserving the local roadways they depend on. Key areas include:

- Communication of the issues / Sharing information related to roadway damage
- Development of the use of one-way roads (stay off the edge of the pavement)
- Travel on the roads in the morning (less pavement damage)
- Potential for high savings of the local roadway system

Potential benefits:

- There are no direct savings to be computed at this point. To date, Minnesota has not implemented project results to address this issue. This would most likely come in the form of legislation. It is important to note that, in general, this issue is much more of a concern for local agencies.
- Savings assume that in the future Minnesota cities and counties will also organize like Wisconsin and implemented the research findings to provide pavement life savings. Could assume it would extend pavement life by 10 percent on the city and county roadways.

Use of Taconite Aggregates in Pavement Applications MNR-6(023)

Partners – Natural Resources Research Institute, MnDOT

The construction and maintenance of highway infrastructure creates a demand for high quality paving aggregates, which are becoming scarce in many parts of the country. Taconite industry waste rock and tailings are a potential source of virgin aggregates. However, there is limited information available for implementing these products in construction design specifications. Over the years MnDOT has partnered with the Natural Resources Research Institute (NRRI) at the University of Minnesota Duluth and the Minnesota Department of Natural Resources on several successive projects investigating the viability of using taconite aggregates in pavement applications.

The goal of this research is to assess available taconite aggregate resources with the potential to supply an abundant, high-quality, low-cost aggregate for roadway use, especially in areas where aggregates are becoming scarce. The main issues surrounding this coordinated research effort involve both engineering/material properties and economics/logistics of transportation. Four cells were built at MnROAD under the partnership with NRRI. In 2004 MnROAD built a 4 in. HMA (Cell 31) and 7.5 in. PCC (Cell 54) both located on the low volume road. In 2008 a 2-inch, 4.75 mm asphalt mix (Cell 106-206) was constructed using taconite mix as the wear surface over an existing concrete test cell. That same year a section comprised of large stone taconite aggregate base (Cell 23) was constructed with a warm mix asphalt surface (non-taconite aggregates). OMRR Road Research has also been working with University of Minnesota Duluth researchers on high-quality taconite asphalt-based pothole patching materials.

Highlights of this research are as follows:

- Taconite aggregates may be used in any layer of the roadway provided they meet applicable MnDOT specifications. MnROAD has demonstrated that taconite aggregates perform well or better as traditional aggregates for HMA, PCC, and aggregate base applications. University and MnDOT laboratory testing has demonstrated that performance under freeze thaw durability or chemical reaction tests meet or exceed applicable requirements when used in concrete.
- Taconite aggregates provide a safe, high quality, long lasting durable surface material that retains its friction with little wear due to its hardness and shape (crushed material).
- Due to the location of the source of taconite aggregates its current use is limited by transportation costs.
- Taconite aggregates tend to become flat and elongated if proper crushing practices are not followed. Experienced contractors can provide a consistent product related to aggregate size and shape needed for highway applications.

- Large stone base applications typically experience about half the frost depth as standard MnDOT aggregate base designs. Furthermore, the large stone taconite base beneath Cell 23 has demonstrated superior performance in terms of increased modulus, bearing capacity, and reduced seasonal thaw weakening relative to standard MnDOT bases.
- Asphalt mixes with 4.75 mm taconite can provide a rut resistant mix that is both quiet and safe (high friction).
- NRRI and MnDOT are currently working to develop a high quality patch material and system using microwaves to take advantage of the high iron content of the aggregate.
- MnDOT District 1, cities, and counties located within the Mesabi Range of northern Minnesota have successfully used taconite aggregates for years. FHWA is investigating taconite aggregates in high friction courses for high speed curve applications. Other DOT's including Illinois have utilized taconite as a high quality aggregate to replace their locally produced poorer quality aggregates.

Potential benefits:

- No cost savings are included in this report but benefits are shown in the findings and deployment statements above. Taconite materials can be beneficial to use in situations provided they meet the specification requirements for the particular application. However, transportation costs are limiting the use on a broader, statewide basis.

Field Investigation of Highway Base Material Stabilized With High Carbon Fly Ash

Partners – US Department of Energy (contract with Bloom Consultants and Mathy Construction)

The purpose of these test sections was to evaluate the physical and environmental properties of base materials stabilized with high carbon fly ash in comparison to recycled pavement materials and crushed stone. Work included aggregate characterization, construction and field testing, and long-term performance monitoring of the test cells. Fly ash may also provide constructability benefits due to assurance of a stable construction platform under when in place base quality is marginal or when wet weather complicates placement of the surface materials.

Through a partnership with Bloom Consulting, MnDOT built three cells in 2007 for this study on the LVR, one cell used FDR stabilized with high carbon fly ash, one cell used FDR with no stabilization, and a control cell using a MnDOT Class 6 (granular base). The following findings were realized because of this study:

- Fly ash was successfully used to stabilize full depth reclamation (FDR) material during construction. The fly ash treated cell provided a stable construction platform for asphalt paving operations whereas the two sections without fly ash presented constructability issues due to soft subgrade conditions. Construction delays were averted by using fly ash during wet fall construction. Using this stabilizing agent provided construction assurance when wet weather is encountered.
- Environmental monitoring showed that in general contaminant levels were below limits permitted by U.S. Environmental Protection Agency and Minnesota regulations. In some cases, concentrations measured in base percolation (but not in groundwater) modestly exceeded these standards. However, computer modeling showed that under most conditions these concentrations are expected to decrease with time and become diluted with distance from the roadway, yielding groundwater that meets environmental standards.
- All three test cells have performed well related to ride and cracking. Currently the fly ash treated cell is the only one with transverse cracking but this is very minimal. Note that shrinkage cracking is a concern if excessive fly ash is used in the base.
- The fly ash treated cell has outperformed the other two cells related to rutting.

- FDR did eliminate the reflective cracking for both the FDR cells.
- Increase strength with the fly ash cell compared to non-treated FDR and Class 6 control cells.

MnDOT Pavement Data:

- MnDOT spent an extra $10,282 per cell (375 feet) on the force account work to dry out the non-stabilized base materials at MnROAD in 2007 using conventional techniques. This is in comparison to the $8,970 for fly ash stabilization, or a 15 percent cost savings. A major benefit of the use of fly ash was in the form of time savings; paving was able to be advanced six weeks sooner than the non-stabilized sections. Although the force account work will likely not be required on many jobs, and MnROAD paid a premium price for the fly ash because of the small quantity, this project serves as a useful illustration of what can happen in the real world.
- MnDOT had 170 miles of new construction in 2011 that paved directly on prepared aggregate bases.

Assumptions:

- Savings related to less construction delays related to wet weather periods.
- Of the 170 miles stated above assume that only one job had similar construction delays for soft wet bases that could not be paved on. Assume each job is 5 miles (34 jobs) in length and one (3 percent) construction contract had similar issues as MnROAD.
- The unit price for fly ash is expected to be less expensive on larger jobs but this is not reflected in the calculations.

Calculated Savings:

- Savings related to reduced construction delays
- (5 miles per year) * (MnROAD $20,564 overrun-$17,940 fly ash cost)/(750 ft * 5,280 ft per mile)
- Benefits = $92,364 savings per year.

Recycled Unbound Pavement Materials - TPF-5(129)

Pooled Fund Partners – CA, MI, OH, TX, and WI DOTs
Contractor – University of Wisconsin, Madison

The objective of this study was to monitor the performance of several test cells at MnROAD constructed using recycled materials in the aggregate base layers, including blended with virgin materials and 100 percent recycled asphalt and concrete pavement materials (Test Cells 16-19). The material properties were monitored during construction and throughout the pavement life in order to determine their effects on pavement performance. The properties were used to verify mechanistic-empirical design inputs, especially their variation with changing seasons and moisture regimes.

Key observations to date have been:

- Demonstrated good field performance and a better understanding related to the use of these materials. Pavement ride is very smooth with little cracking or rutting observed.
- Measured potential leaching of these recycled materials using lysimeters installed in the field.
- Developed seasonal material properties parameters for both crushed concrete and recycled asphalt base materials through field deflection measurements and laboratory resilient modulus testing.
- Changed MnDOT specification 3138 and 3149 to allow up to 75 percent crushed concrete or recycled asphalt pavement (if less than 3 percent bitumen) in our base layers. http://www.dot.state.mn.us/pre-letting/spec/2014/2014-Materials-Lab-Supplement.pdf
- Greater use of recycled onsite materials will reduce overall costs for new construction with less hauling and disposal costs.

- Ability to use less base materials (thickness) since both the crushed concrete and recycled asphalt materials are stiffer/stronger than Minnesota's traditional granular base materials.

MnDOT Pavement Data:

- Based on data from 2009-2013 MnDOT has built on average 180 lane-miles per year of new and/or reconstructed pavement for which Class 5 or 6 aggregate base is typically specified. However, contractors almost always substitute with less expensive Class 7 (recycled) base. This results in increased innovation and competitiveness, and reduced agency costs.
- Average aggregate costs/ton
    - Class 7 (recycled base) = $16.00 per cubic yard (estimated)
    - Class 5 (virgin base) = $19.84 per cubic yard

Cost Assumptions:

- Typically 6 inches of Class 5 base is specified in both our asphalt and concrete designs
- Approximate volume of base per lane-mile = 1,200 cubic yards

Calculated Savings:

- 180 lane-miles * 1,200 cubic yards per lane-mile * ($19.84-$16.00)
- Benefits = $829,000 per year

Full-Depth Reclamation Stabilized with Engineered Emulsion

Partner – RoadScience

The purpose of this project was to demonstrate performance of designs for older, cracked bituminous pavements in which a mill and overlay typically is not expected to perform well. Characteristics and performance of three test cells on an existing cracked HMA roadway rehabilitated using full depth reclamation (FDR) with asphalt emulsion stabilization were examined. This includes full depth pavements (HMA directly on subgrade) and other HMA pavements that are deteriorating from the bottom up making traditional mill and overlays ineffective. The results will be used to develop the best-cost design procedures to achieve the strength and flexibility needed for performance.

Findings and observations from this Phase-II effort include:

- Demonstrated construction of three different methods of full depth reclamation of heavily cracked asphalt pavements using engineered emulsion. In the past pavements in this condition were only considered as total reconstruction candidates, which is much more expensive than FDR rehabilitation.
- Performance – Constructed in 2008, the three 2.5 in. asphalt surfaces on 6 in. stabilized FDR are performing very well with very little cracking or rutting while being subjected to heavy interstate traffic.
- The engineered emulsion provides a balance between structural stiffness and flexibility.
- Sustainable construction practices through the use of recycling of the existing pavement using full depth reclamation.
- Demonstrated alternative construction administration for future projects.
- Provides an alternate design to compete against whitetopping for beneficial rehabilitation practice for deteriorated asphalt pavements including full-depth asphalt roadways without an aggregate base.
- Detailed information related to the seasonal design inputs for more detailed M-E designs has been obtained.
- Effective MnROAD and RoadScience partnership.

MnDOT Pavement Data:

- Based on 2011 MnDOT PMS data the total miles of state roadways where this might be a reasonable fix are: a) 113 lane-miles of full-depth pavement (bituminous on soil, with no base), b) 15,088 lane-miles of bituminous overlays of bituminous pavement, and c) 2,913 lane miles of bituminous over aggregate base.
- Cost of a thick mill and overlay from the MnDOT PMS standard unit price = $180,651 per mile
- Cost of FDR and overlay from the PMS standard unit price = $171,670 per mile ($8,981 savings)

Assumptions:

- Of the 113 lane-miles of full-depth pavement a total of 10 percent are getting fixed each year by FDR and overlay. Full depth miles per year = 113 lane-miles*10 percent = 11.3 lane-miles.
- For the remaining 18,001 lane-miles of asphalt roadways in the state assume that 5 percent of these roads are being replaced each year and of them 5 percent would be good candidates for emulsion stabilized FDR with overlay.

Savings:

- Asphalt over aggregate base, miles per year placed = (15,088+2,913 miles) * 5 percent being fixes * 5 percent FDR fix = 45 miles
- (FDR full-depth with emulsion + FDR asphalt over base with emulsion) * (repair cost difference)
- (11.3 + 45 miles per year) * ($180,651 per mile-$171,670 per mile)
- Benefits = $505,652 per year

Sustainable Pavement Development

MnROAD has taken strides to research technology designed to reduce dependence on virgin materials throughout a pavement structure by reusing pavement materials and various waste products including taconite aggregates, fly ash, shingles, RAP, and other materials. Application of today's technology enables more efficient, sustainable designs.

The concept of using different materials in various layers is common in pavement design. Asphalt roads are often constructed with a more durable layer on the surface than the lifts below. Similar concepts have been applied to concrete pavements. European countries have a long history of using mixes containing recycled concrete in the lower lift of two-lift concrete pavement systems [13]. Using recycled or lower quality materials in the lower layer not only optimizes the use of valuable materials, but reduces the adverse environmental effects of disposal of the materials.

In 2010 MnROAD constructed three composite test cells: Cell 70, HMA over a recycled aggregate concrete; Cell 71, diamond grind concrete over recycled aggregate concrete; and Cell 72, exposed aggregate concrete over a low cost concrete. The construction of these cells was part of the SHRP 2 R21 Composite Pavement project.

Results indicate that construction of two-lift concrete and traditional asphalt-over-concrete composite pavements can be accomplished successfully. The exposed aggregate concrete surface does not provide significant noise reduction. Exposed aggregate surfacing can provide more than adequate friction for skid resistance and safety. Overall, however, these two lift concrete pavements proved to address issues such as high cost of virgin aggregates and high trucking costs for areas that don't have quality aggregates to use. Continued monitoring of these test cells will help develop the extensive understanding of composite pavements needed for effective design and accurate service life models [14].

In 2013, with some of MnROAD's test sections due for reconstruction or rehabilitation after years of traffic, MnDOT saw an opportunity to establish experiments to evaluate innovative pavement designs that it does not commonly use on its road network. The agency was especially interested in the use of recycled materials, fibers and geosynthetics to support sustainable pavement design. The goal of this project was to construct and rehabilitate test sections at the MnROAD pavement research facility, in order to conduct performance testing of sustainable concrete pavement designs.

In June and July 2013, MnDOT constructed three new MnROAD test cells and rehabilitated two others:

- Former cells 113 to 513 were replaced with cell 613, a 7.5-inch thick concrete pavement containing a 75 percent recycled concrete aggregate mix, or RCA. RCA is not yet widely used for transportation infrastructure in the United States, but may become a tool for sustainable concrete pavement design if it can be shown to perform well. Geocomposite joint drains were installed beneath selected joints as part of a drainage study to extend pavement life.
- Former cells 60 to 63 were removed and replaced with cells 160 and 162, which along with cell 163 use whitetopping, the overlay of distressed asphalt pavement with 4 and 5 inch thick concrete slabs. This concrete is reinforced with polymer fibers, which are intended to increase slab strength both before and after cracking. After cracking, the fibers increase the residual strength of the concrete by bridging cracks.
- Existing cell 40, exhibiting multiple distresses after 20 years in service, was covered with an ultra-thin 3-inch thick fiber reinforced unbonded concrete overlay, placed over two different thicknesses of a geotextile fabric interlayer, becoming cells 140 and 240. These layers will be monitored continuously for their effectiveness in draining excess moisture and decreasing reflective cracking. The concrete was also reinforced with fibers.
- Cell 32, consisting of 5-inch thick concrete, was repaired and retrofitted with unique oval shaped load transfer devices. Typically 15 to 18 inch long cylindrical dowel bars (1 inch diameter) are used to repair faulting pavements by transferring loads between concrete panels. However, with the increasing use of mechanistic-empirical design to build thinner pavements, the required slots for installing these bars would be too deep for the thin pavements. The alternative oval shaped devices, suitable for thinner pavements, will be monitored for effectiveness.
- Cell 39, consisting of a pervious concrete overlay, was diamond ground to determine whether this grinding could be performed without damaging the surface and clogging its pores with the resulting slurry. Researchers will also evaluate associated skid resistance, acoustic, durability and ride quality.

During construction, researchers conducted initial sampling and testing of the materials used in the cells for various mechanical properties. Directly after construction, researchers conducted initial performance testing of surface texture, friction and noise levels. These tests allowed researchers to draw some tentative, preliminary conclusions:

- RCA optimum at 75 percent substitution determined by previous MnDOT research was validated. Geosynthetic joint drains are functioning as designed.
- The use of fibers in concrete did not have a significant effect on its mechanical properties. However, the required ASTM 1609 residual strength of 120 psi was achieved with 6.5 percent fiber content.
- There appeared to be slower deployment of transverse joints beneath the sawcuts probably due to reduced restraint in the interlayer.
- The diamond grinding on cell 39 was successful, and did not damage the pavement or clog its pores. It may be possible to use diamond grinding as a restoration tool for pervious concrete.

Researchers will continue to monitor cell ride, surface texture, friction and noise levels, as well as signs of distress such as cracking. They will also conduct field tests for such characteristics as strength, stiffness and ride quality, and will collect data from sensors installed on the cells to measure temperature, moisture and strain. Data from MnROAD cells is typically used on a variety of projects by MnDOT and other state departments of transportation, as well as by federally supported transportation pooled fund studies.

Rolling Resistance

Pavement characteristics can influence fuel efficiency and greenhouse gas (GHG) emissions of vehicles through three identified mechanisms which together can be called the pavement related rolling resistance. These mechanisms are the energy losses due to pavement roughness, texture, and stiffness.

MnDOT and MnROAD are actively utilizing partnerships with two organizations that have interest in quantifying the effects of pavement characteristics on vehicle rolling resistance and vehicle/pavement interaction. These partnerships provide the organizations with a controlled facility with well-documented characteristics to research and develop their respective approaches, and afford MnROAD the benefit of quantifying vehicle dynamic loading and the impact on pavement response.

The Minnesota Department of Transportation and Minnesota State University, Mankato, contracted with the Technical University of Gdańsk, Poland, to conduct rolling resistance measurements. While the rolling resistance testing was conducted on all cells of the MnROAD mainline, the primary objective of this project was to obtain the rolling resistance data for Cells 7, 8, and 9 – the Portland cement concrete pavement cells with conventional and two innovative diamond grinding applications. The research team from Poland conducted the testing for a week in the middle of September, 2011, and again in May 2014. All cells on the MnROAD mainline were tested, as well as one off-site location (US 212 near Shakopee, Minnesota). The collected rolling resistance data were analyzed and are presented elsewhere [15]. Additional analyses that were conducted include a comparison of the rolling resistance data to surface texture, friction, and noise. Some of the comparisons are not consistent with those measured on other pavement surfaces (in Europe), but the authors present some possible reasons for the differences.

In a study currently in progress, FuelMiner, Inc. is performing work that utilizes MnROAD mainline and LVR test sections for measurements of heavy truck power consumption and vehicle dynamics. The goals of this study are to measure fuel consumption of an instrumented vehicle and through advanced modeling and analysis, differentiate between the various components that contribute to fuel consumption, particularly those contributing mechanisms of pavement-vehicle interaction. This project will use the instrumented State's MnROAD truck and a mechanistic model of vehicle fuel consumption that differentiates between vehicle components, aerodynamics drag, and rolling resistance, to estimate the total rolling resistance and its contribution to vehicle fuel consumption for the various MnROAD test cells.

APPENDIX E - MnROAD Phase-II Partnerships

MnROAD Partnerships

The tables below highlight the current and completed partnerships and research related to both "Materials" and "Facility/Equipment" testing that has and continues to take place at MnROAD under Phase-II.

Table E1 - MnROAD materials related partners.

Partner	Description
PNA Construction Technology, Inc.	2013 donation of plate dowel bars used for full depth concrete repairs in Cells 32 and 12 Website - http://www.pna-inc.com/
TCC Materials, Unitex Chemicals, CTS Cement Mfg. Corp. / Rapid Set® Products, RCM Inc.	2011 donation of materials and labor during installation of partial depth concrete repairs done on various MnROAD PCC cells. Materials included 3U18, Ready Mix, HMA Patch, Permapatch, Propoxy 2500, Patch Set 928, Taconite HMA, Rapid Patch PCC, 3U18 with accelerator, Rapid Set (Fine Mix), Rapid Set (DOT Repair Mix), Blow Patch from Trailer
Mathy Construction (MTE)	**Field Investigation of Polyphosphoric Acid Modified Asphalt** has active test (cells 33-35, 77-79), even though the research funding is now complete. MnROAD continues to monitor the test cells and our partners are still very active following up this study, including testing samples from the field.
GA, IA, KS, MI, MN, MO, NC, OK	**Development of an Improved Design Procedure for Unbonded Concrete Overlays** (TPF-5(269)). Active test cells (505,605,140,240). Study objective consists of development of a unified national mechanistic-empirical design procedure for unbonded concrete overlays http://www.pooledfund.org/Details/Study/498.
LRRB, MA, MN, OH, TX, WI	**Optimal Timing of Preventive Maintenance for Addressing Environmental Aging in HMA Pavements** (TPF-5(164)). Active test cells (24). Study goals include determination of the proper timing of preventive maintenance treatments in order to optimize life cycle costs and pavement performance. Project goal is to obtain a better understanding of the aging mechanism and how it can be reduced through pavement preservation. Study completed in November 2013. More details: http://www.pooledfund.org/Details/Study/380
Road Science, LLC, MnDOT	**Full Depth Reclamation Stabilized with Engineered Emulsion** MnDOT's study of the structural design and field performance of stabilized full-depth reclamation layers. Very good performance since 2008.
Mankato State University	Provided no-cost assistance with data validation and initial review of monitoring and material testing data through student's professional development.
University of Minnesota	Assisting in the development of the MnROAD truck instrumentation and the effort to match. MnROAD dynamic pavement response to vehicle response.
PNA Construction Technology, Inc.	2013 Donation of plate dowel bars used for full depth concrete repairs to tie the existing panels to concrete patches used on Cell 32. Website - http://www.pna-inc.com/
Propex	2013 partnership to supply two fabric interlayers used in unbonded overlays constructed at MnROAD (Cells 140 and 240), along with helping guide MnROAD staff in the use of effective us of structural fibers used in 4 test cells (Cells 140, 240, 160, 162). Website - http://www.propexglobal.com/
D.S. Brown	Donation (2013) of neoprene joint sealant used on Cell 613. Website - http://www.dsbrown.com/Pavements/

Table E1 - MnROAD materials related partners, continued.

Partner	Description
Tensar Syntec	2013 donation of concrete transverse joint drainage materials consisting of a plastic drainage layer sandwiched between two layers of separation fabric. Used in Cell 13 to determine if this material could drain water away from both sealed and unsealed concrete joints. MnDOT internal project with Tensar. Web site - http://www.tensarcorp.com/
TCC Materials, Unitex Chemicals, CTS Cement Mfg. Corp. / Rapid Set® Products, RCM Inc.	Partial depth concrete repair study was done at MnROAD in 2011 and MnROAD and its material partners are following up with performance monitoring. Results are expected in 2014. Materials included 3U18, Ready Mix, HMA Patch, Permapatch, Propoxy 2500, Patch Set 928, Taconite HMA, Rapid Patch PCC, 3U18 with accelerator, Rapid Set (Fine Mix), Rapid Set (DOT Repair Mix), Blow Patch from Trailer
Mathy Construction (MTE)	**Field Investigation of Polyphosphoric Acid Modified Asphalt** has active test (cells 33-35, 77-79) even though the research funding is now complete. MnROAD continues to monitor the test cells and our partners are still very active following up this study including testing samples from the field.
GA, IA, KS, MI, MN, MO, NC, OK	**Development of an Improved Design Procedure for Unbonded Concrete Overlays** (TPF-5(269)). Active test cells (5, 40). Study goals include a summary of existing design procedures, develop/improve both interlayer, pavement response and performance prediction models, and develop a unified national mechanistic-empirical design procedure for unbonded concrete overlays with follow-up training. Ends May 2016 – More details http://www.pooledfund.org/Details/Study/498
IA, KS, MN, MO, MS, NC, NY, PE, SD, TX	**Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements** (TPF-5(165)) Active test cells (14,160-163,96). Study goals include better understanding of the field performance history nationally, update/create models for both HMA and PCC layers, create a user-friendly design guide software program and user manual that can be a module in the future national Mechanistic-Empirical Pavement Design Guide (MEPDG). Ends September 2013 - More details http://www.pooledfund.org/Details/Study/389
LRRB, MA, MN, OH, TX, WI	**Optimal Timing of Preventive Maintenance for Addressing Environmental Aging in HMA Pavements** (TPF-5(164)) Active test cells (24). Study goals include determination of the proper timing of preventive maintenance treatments in order to optimize life cycle costs and pavement performance. This project is looking for a better understanding of the aging mechanism and how it can be reduced through pavement preservation. Ends November 2013 - More details http://www.pooledfund.org/Details/Study/380
Road Science, LLC, MnDOT	**Full Depth Reclamation Stabilized with Engineered Emulsion** MnDOT's study of the structural design and field performance of stabilized full-depth reclamation layers. To-date very good performance since 2008.
Mankato State University	Assisting at no cost some of the data validation and initial review of monitoring and material testing data through student's professional development.
University of Minnesota	Assisting in the development of the MnROAD truck instrumentation and the effort to match the MnROAD dynamic pavement response to what the truck experiences from above.

Table E2 - MnROAD facility-equipment related partners.

Partner	**Description**
NDSU, University of Missouri	2013 National Science Foundation funded project looking at different fiber optic pavement sensors and data acquisition equipment in MnROAD's Cells 140 and 240 (ultra-thin unbonded concrete overlay).
Intercomp	Rental of MnROAD facility for the development of traffic detection devices including license plate readers and weight in motion technology. Website - http://www.intercomp-scales.com/
LRRB, University of Minnesota Duluth	Development of a portable weigh-in-motion is being worked on at MnROAD using the low volume road and MnROAD semi-tractor trailer for calibrations both at MnROAD but also at other field installations in both cities and counties of Minnesota.
State Patrol Kare-11 News	Trailer safety television news feature showing the proper ways to haul trailers and goods on our roadways. The farm loop was used to demonstrate what can happen when done improperly. http://www.kare11.com/dontmiss/1026703/387/Grieving-mom-hopes-tragic-loss-prevents-towing-accidents State Patrol traffic stop training pictures to be used in future PSA and State Patrol Officer training documentation.
FHWA	Hosted June 2013 rodeo of Surface Profilers Surface Characteristics – Bob Orthmeyer leading the effort for FHWA to develop a smoothness specification for equipment manufactures to utilize. September 2014 Traffic Speed Deflectometer Rodeo tested a number of different manufacturers systems. This technology may be a future tool to help evaluate the strength of our roadway network. FHWA will have the Greenwood TSD available for testing using pooled fund dollars for agencies interested in further testing. http://www.pooledfund.org/Details/Study/518.
FuelMiner	MnDOT has partnered with FuelMiner using the MnROAD facility and instrumented MnROAD Semi tractor trailer to better understand how road characterization and fuel consumption maybe related. Output includes calibration of the MnROAD truck instrumentation and a 2014 TRB paper. Website - http://www.fuelminer.com/
IRD	Ongoing partnership with funding to use the MnROAD facility for the development of traffic detection devices including weight in motion technology. Website - http://www.irdinc.com/
LRRB, University of Minnesota Duluth	Development of a portable weigh-in-motion is being worked on at MnROAD using the low volume road and MnROAD semi-tractor trailer for calibrations both at MnROAD but also at other field installations in both cities and counties of Minnesota.
State Patrol, Kare-11 News	Trailer safety news report showing the proper ways to haul trailers and goods on our roadways. The farm loop was used to demonstrate what can happen when done improperly. http://www.kare11.com/dontmiss/1026703/387/Grieving-mom-hopes-tragic-loss-prevents-towing-accidents State Patrol traffic stop training pictures to be used in future PSA and State Patrol Officer training documentation.

Table E2 - MnROAD facility-equipment related partners, continued.

Partner	Description
FHWA	Surface Profilers rodeo was done in June 2013. Surface Characteristics – Bob Orthmeyer leading the effort for FHWA to develop a smoothness specification for equipment manufactures to utilize. Traffic Speed Deflectometer Rodeo this September testing a number of different manufacture systems. This technology may be a future tool to help evaluate the strength of our roadway network. FHWA will have the Greenwood TSD available for testing using pooled fund dollars for agencies interested in further testing. http://www.pooledfund.org/Details/Study/518.
MnDOT - Traffic Data and Analysis	MnROAD semi-tractor trailer (known axle loadings) and operator is used to calibrate MnDOT statewide weigh-in-motion systems though out the state. Ben Timerson is the contact for MnDOT.