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Porous Asphalt Pavement Performance in Cold Regions

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Minnesota Department of Transportation

April 2012

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16. Abstract (Limit: 250 words)

Local agencies are interested in porous asphalt pavement's potential for improved water quality and quantity control by allowing direct infiltration through the pavement structure. However, prior research in the seasonally diverse Minnesota climate is lacking. The purpose of this research is to study the durability, maintenance requirements, hydrologic benefits, and environmental considerations of a full-depth porous asphalt pavement, installed on a low-volume roadway in a cold climate.

This report includes the design, construction, and performance of two porous asphalt test cells and one dense graded asphalt control cell constructed at MnROAD in 2008. These cells were constructed to evaluate the performance of porous asphalt pavements on a low-volume road in a cold-weather climate. The cells discussed in this report are as follows: full-depth porous asphalt over granular subgrade, full-depth porous asphalt over cohesive subgrade, dense graded HMA on mixed materials subgrade.

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EXECUTIVE SUMMARY

The purpose of this research is to study the durability, maintenance requirements, hydrologic benefits, and environmental considerations of a full-depth porous asphalt (PA) pavement, installed on a low-volume roadway in a cold climate. This report includes the design, construction, and performance of two porous asphalt test cells and one dense graded asphalt control cell at the Minnesota Road Research Project (MnROAD) facility. Pavement installation was completed and test loading began in in December 2008. Data collection for this project ended in December 2011.

At the time of this report writing, the test cells had been loaded for three years and received approximately 40,000 applied asphalt ESALs. The porous asphalt test cells are performing well, in spite of what is considered to be significant loading for this type of pavement. The only significant pavement distresses observed to date are rutting in the loaded lane and shallow surface raveling. The porous cells are also performing well in characteristics of ride quality, permeability, stiffness modulus, strain response, safety, and quietness. Significant findings resulted from this study that will contribute to the design and maintenance of porous asphalt pavements in Minnesota and other cold climates. A few of these conclusions are listed below:

- Some decrease in surface permeability is evident. However, the lowest measured flow rate on the porous pavement is still over 0.5 inches per second; more than adequate for any expected rainfall event. The 14-inch open-graded base and both the sand and clay subgrades appear to allow adequate hydraulic conductivity for the rainfall events they have experienced – no overflows were observed.
- Pavement deterioration in the form of raveling (first observed soon after construction) has progressed steadily, but affects only the top 1 inch (or less) of the pavement. Initial raveling appeared to be related to mixture temperature segregation; possibly caused by the long wait time to begin rolling the relatively thick pavement in low ambient temperatures.
- As of fall 2011, no cracking or other significant distresses have been observed on the PA cells, and the standard asphalt pavement “control” cell 87 had not developed any significant distresses.
- The average rutting on the porous asphalt sections is significant; approximately 0.60 inches, and seasonal vertical movement and settling have occurred across the entire loaded lane. The cause of the rutting cannot be determined without deconstruction of the test cells: however, the rutting likely would be worse had the asphalt binder not been changed to PG 70-28 in the design stage and non-crushed aggregates used in the mix.
- The porous hot mix asphalt (HMA) cells demonstrate lower resilient modulus and undergo more pavement strain than a comparable dense graded HMA, under similar loading and temperature conditions. However, there is still not enough distress (no cracking) to form conclusions about the ultimate result of these characteristics.
- The porous/pervious sections are quiet pavements with a maximum on-board sound intensity (OBSI) – measured sound intensity of approximately 101.2 dBA.
- The PA pavement has about 50% better skid resistance than dense grade asphalt, with an average friction number (FN) of approximately 50.
- Vacuuming appeared to have a beneficial effect on the permeability of the porous cells; however the effects were difficult to quantify due to permeability testing repeatability

issues.

- Snow and ice was observed to melt faster on the PA cells than standard pavements in sunny conditions, even in very low ambient temperatures and frozen subsurface conditions.
- Thermocouple data show that the internal temperature of the porous pavement warms much faster and more often than standard asphalt pavement in winter. Subsurface heat transfer appears better in the PA cells, but the mechanism for that is unknown.
- Challenges were encountered during water quality testing; however, the average measured values showed that the porous asphalt does reduce copper and zinc concentrations through the filtering action of the permeable layers.
- Subsurface temperature measurements indicate the porous pavement could be used as part of a treatment plan to cool stormwater prior to discharge into sensitive resource waters.

1 POROUS BACKGROUND AND SUBSURFACE EXPLORATION

1.1 PROJECT INTRODUCTION

1.1.1 Objective

The objectives of this project were to study the pavement performance, durability, maintenance requirements, hydrologic benefits, and environmental considerations of a full-depth porous asphalt (PA) pavement in a cold climate. In order to meet this objective, two porous asphalt test cells were constructed on the MnROAD low-volume road (LVR) test loop. One porous asphalt cell was constructed over a sand subgrade (MnROAD cell 86) and one over a clay subgrade (cell 88). In addition, a sealed/impervious, dense graded hot mix asphalt (DGHMA) control section (cell 87) was constructed directly adjacent to the porous sections, for comparison of water runoff, pavement performance and pavement durability.

1.1.2 Scope

The MnROAD test site employs experienced technicians and automated testing and measuring equipment. An 80,000 lb. test vehicle is regularly operated on one lane of the low-volume test loop, applying approximately 18000 ESALs per year. There are two local automated weather stations that continuously record ambient conditions. Strain gauges, as well as pressure, temperature, and moisture sensors are imbedded in the pavement and the base material. They are configured and hardwired to automatically upload data to the MnROAD database.

The PA pavement performance research included measurement of the following parameters: pavement distress, skid resistance, pavement noise, and falling weight deflectometer (FWD) testing among other things. The Minnesota Department of Transportation (MnDOT) performed monitoring activities at various times of the year, with the intention of capturing the effects of loading, environment, and time on the measured results. Laboratory and acceptance testing was performed on materials used in the construction of the PA cells. The FWD testing was used to back-calculate layer moduli and to determine seasonal, moisture, and temperature dependent in-situ stiffness. The pavement distress surveys are used to measure localized pavement deterioration. The pavement was also tested for skid resistance in different ambient conditions. Pavement noise and texture was also tested. Snow and ice maintenance activities were recorded and evaluated. Water quality and other environmental effects were monitored and reported. Forensic analysis of the pavement was also performed near the completion of the study period. The results of this study are expected to inform future installations of porous asphalt in Minnesota and other locations with cold climates.

1.2 SYNTHESIS OF POROUS ASPHALT INFORMATION

1.2.1 Porous Asphalt Background

Porous asphalt is an emerging pavement technology first developed in the United States out of experimentation with seal coats. It has been researched, improved, and installed in numerous locations worldwide. Porous friction courses (PFC) are a form of porous asphalt pavement surfacing that has become well established in the United States. However, full-depth porous pavements are primarily installed for parking lot use domestically. Full-depth Porous Asphalt (PA) roadways are common in Europe, and interest is increasing worldwide due to the significant potential benefits. The need to reduce water runoff is becoming increasingly important in Minnesota (and other wet climates) to mitigate the runoff associated with impervious surfaces. Porous Asphalt has been shown to reduce runoff, and the water quality degradation that can be associated with it [1]. The potential safety and noise benefits are equally compelling.

Although porous asphalt mix design, construction methods, and maintenance have improved with experience, there is a need for additional research – particularly in cold climate applications. This synthesis was adapted [2] to compile current information about PA roadway mix design, construction methods, pavement performance and maintenance practices. A summary of observed advantages and disadvantages of Porous Asphalt is also included. It was also written to inform and guide this research as to current state of the practice of PA, with an emphasis on cold-weather applications.

The problems associated with traditional chip seals, including windshield damage, led to experimentation with plant-mix seal coats [3]. The special mixes evolved into thinly placed plant produced mixes, with gap-graded 0.5-inch size aggregates, and relatively high asphalt content. Plant mix seal coat use became well established in the 1970s with the Federal Highway Administration's (FHWA) program to improve frictional characteristics of US road surfaces [4]. The mixes initially were called open-graded asphalt friction course (OGFC), and the FHWA developed a mix design method in 1974 [4]. Mixes similar to the original OGFC are currently in widespread use and are known by many other names including: porous friction course (PFC), asphalt concrete friction course (ACFC), popcorn mix, and permeable European mix (PEM) or simply, porous asphalt (PA). Open Graded Friction Courses combine the advantages of porous asphalt and the structural contribution of a dense graded (usually asphalt) base layer. However, an impermeable base requires lateral draining of absorbed water. Several DOTs in the United States routinely utilize OGFC – notably Georgia, Florida, Oregon, Texas, and California [5]. In Minnesota, installations of OGFC have demonstrated many of the advantages seen elsewhere, but suffer from decreased durability due to the damage caused by freezing of water unable to drain laterally from the porous surface layer.

The permeability of the OGFC was well known, and was recognized as a desirable pavement characteristic in certain situations. Permeable aggregate bases were also being tested at this time. In 1971, the Franklin Institute, in conjunction with the U.S. Environmental Protection Agency, first investigated a thicker, full-depth porous pavement [6] installed in conjunction with a permeable base and subgrade to control runoff and enhance water quality. The prevalence of porous asphalt and its different applications and configurations has increased continuously since then and the technology has spread globally.

In the 1980s, porous asphalt increasingly began to be installed in full-depth configurations to take better advantage of the water infiltration potential [6]. As the technology diversified, various agencies adopted the different nomenclature for porous asphalt cited earlier, and confusion exists in the literature due to the non-standard terminology and very similar mix designs for the different types. OGFC pavements do consist of asphalt that is porous - usually with somewhat lower air voids than full-depth porous mixtures [7]. However, the focus of this project is a low-volume test roadway, constructed in the form of full-depth porous asphalt pavement with an open-graded stone recharge base. This type of porous pavement is most often referred to simply as Porous Asphalt (PA). Therefore, the specific design and construction method for this project will be referred to in this report as Porous Asphalt (or PA), to differentiate it from a porous friction course surface layer. The terms normally used to describe a thinly laid porous surface layer such as OGFC or PFC, and information about them, is included in this report when necessary for clarification or further information.

1.2.2 Porous Asphalt Design Basics

Contemporary full-depth porous asphalt [8] consists of bituminous asphalt pavement with greatly reduced fine aggregate particles (gap graded) and a relatively high (>18%) interconnected air void content. The surface permeability and high porosity allows water to pass vertically through the pavement to the base below. The base material is usually a clean, uniformly graded aggregate storage layer thick enough to allow sufficient water storage during anticipated rain events. A filter or "choker" layer of aggregate is often installed on the top of the base to provide a uniform, stable construction platform. The water in the base is stored temporarily, often allowed to infiltrate into permeable subgrade soils, and can recharge the groundwater directly or have other means of egress. All layers are usually installed without crown or slope to maximize infiltration potential. A typical full depth porous asphalt structure is shown in figure 1.1.

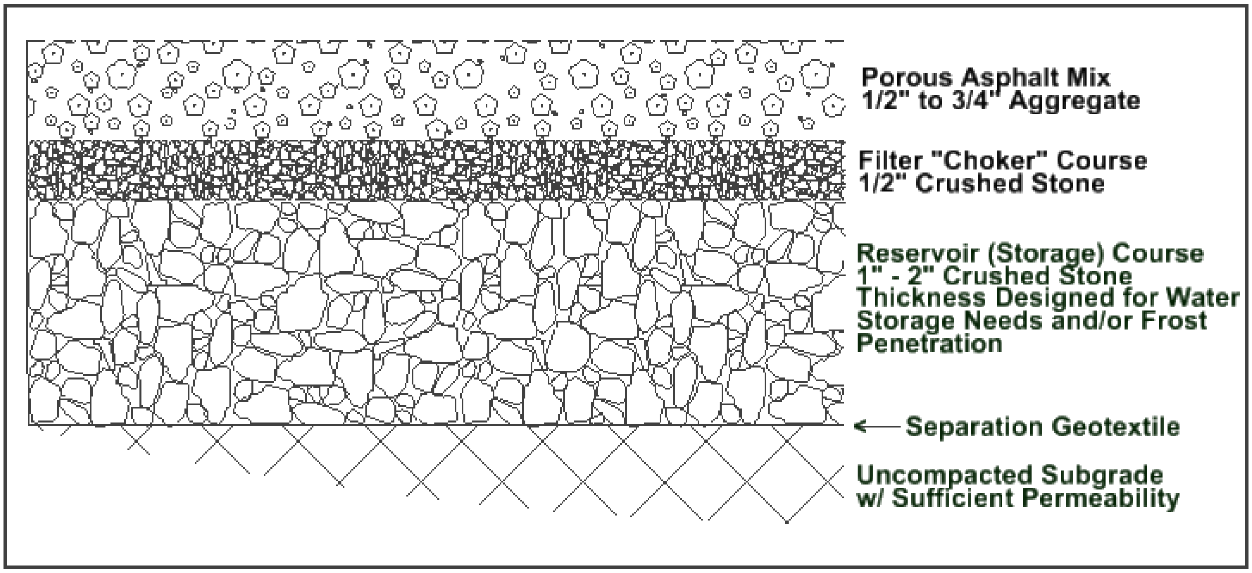


Figure 1.1. Typical full-depth porous asphalt pavement structure

Watershed districts in Minnesota are increasingly requiring a higher level of water quality and quantity control in new developments [10, 11]. The direct infiltration of stormwater through properly designed PA into the subgrade soils can reduce both the volume and peak intensity of stormwater runoff. This can subsequently reduce the need for costly drainage structures, ditches, and additional right-of-way acquired for stormwater mitigation. Other advantages of porous asphalt are improved water quality, the absorption of tire and engine noise, improved safety, and environmental benefits. Potential disadvantages include: special construction practices, higher material costs, reduced pavement performance and structural contribution, clogging-induced maintenance, and increased need for deicing chemicals [12].

For parking lot applications, PA is well established in the USA and has benefited from previous research [13]. It has also been installed and researched domestically on a more limited basis in low-volume roads. Porous asphalt durability and mixture design research in climates warmer than Minnesota has been ongoing in the USA [5] and abroad [14, 15], and has yielded improvements. Some research in colder climates has also occurred, notably in Sweden, Japan, Northern Europe, and Canada [16-19]. However, research focusing on the durability and effectiveness of full-depth PA low-volume roadways in cold climates located in the USA is minimal. The need for additional cold-weather-specific porous asphalt research precipitated this project. The data acquired from this project will be used to improve designs & specifications, quantify environmental effects, and to recommend best maintenance practices for PA in Minnesota and other similar cold climates.

1.2.3 Advantages and Disadvantages of Porous Asphalt Systems

The main advantages of the use of Porous Asphalt pavements are improvements in safety, economy, and benefits to the environment [2, 6]. The main safety advantages of PA [2] in comparison to dense graded asphalt are related to the porosity and the surface texture (demonstrated in figure 1.2, below). The Porous Asphalt provides reduced hydroplaning, better (high-speed) wet pavement friction, and a reduction of splash and spray. Better visibility (especially in night conditions) results from reduced pavement surface glare.

Figure 1.2. Porous asphalt surface texture versus dense graded asphalt surface texture

Economic advantages are realized from a potential decrease in the drainage structures, facilities and right-of-way needed for stormwater mitigation. However, higher PA construction and material costs may offset these savings in certain situations. Porous Asphalt pavements apparently facilitate better vehicle fuel efficiency and reduced tire wear as well [15]. Both tire/pavement and engine noise are attenuated as a product of the high surface porosity [20-24]. Driver comfort levels are enhanced due to the noise and glare reduction aspects.

Porous Asphalt also provides significant environmental benefits. The direct infiltration of stormwater reduces storm surges and total runoff volume, and subsequently lowers surface water turbidity and stream water temperature [25]. Vegetation near the porous pavement may benefit from the infiltration of air and water to the root systems [26]. Evidence suggests that dust and other contaminates adhere to the asphalt binder inside the porous pavement, and bacteriological digestion processes may take place in the base. Although hazardous materials may have a more direct route to the groundwater through PA, the porous pavement and reservoir base can contain spills and reduce uncontrolled runoff into surface water sources [9]. Recycled products (i.e., crumb rubber, waste fiber) can be effectively incorporated in PA mixes [2].

Porous asphalt does demonstrate some disadvantages in comparison to traditional dense graded asphalt. Although further research is needed to clarify the issue, it is generally assumed that the less dense, open-graded PA pavement provides a reduced structural contribution [5].

Pavement performance is negatively impacted due to clogging and raveling issues, and winter maintenance is problematic.

Increased costs are incurred with PA due to the high asphalt content, higher quality aggregates, a liner below a crushed stone base, and extensive site preparation. Successful construction of PA requires extraordinary mixing, transportation, and placement measures and specialized equipment [8]. Finally, generalized knowledge about porous pavements among the public and industry professionals is still limited in many areas. Porous pavement clogging failures have occurred from unwitting applications of sand and surface sealing.

1.2.4 Porous Asphalt Mix Design Approaches

Prior to 2000, there were many different approaches to PA mix design [27]. FHWA Technical Advisory T5040.31 (1990) was used by some state agencies [4], others specified draindown limits, minimum VMA, or retained binder after boiling. Most agencies in the United States currently designing porous asphalt use the National Center for Asphalt Technology (NCAT 2000) design method [27]. The main parameters of this method specify minimum asphalt content, maximum draindown, 17–19% air voids, maximum abrasion loss, and retained tensile strength ratio. The NCAT method does not specify (but does recommend) a minimum permeability of inplace PA. The porous asphalt used for this project was designed according to the current MnDOT (modified) Specification 2360 - Porous Asphalt [28], which is based on the NCAT 2000 method, with modifications. The significant modifications to general the NCAT design on this project were a PG70-28 binder, no recycled materials (for better mixture control in the research setting), and class A aggregates only (for better resilience under heavy test loading). Mix design details and mix test results are presented in Chapter 2.

European, Japanese, and other foreign porous asphalt designs are similar to the NCAT 2000 method in many aspects, but vary from agency to agency [2]. Their designs usually specify a minimum air voids content in conjunction with maximizing the asphalt content. The use of polymer modified binders and the addition of fibers to minimize draindown is common in Europe. The Netherlands and Switzerland are still employing conventional binder although in Switzerland the use of modified binder is allowed [2]. The specified air voids content (normally > 20%) is similar to U.S. designs, but can be as high as 26%. The addition of fiber is usually specified to avoid draindown issues during mixing, handling, and placement [29]. The Cantabro test (performed on either dry or moisture conditioned samples), is commonly used to determine the mixture's resistance to disintegration and to specify the minimum binder content. Switzerland [30, 31] specifies a retained tensile strength ratio (TSR) for porous asphalt. As with the NCAT method, a minimum post-construction permeability is not typically required for porous asphalt in Europe. However, the United Kingdom specifies minimum field permeability, measured immediately after mix placement [32].

1.2.5 Porous Asphalt Mix Production and Site Preparation

The production of PA mixtures requires careful aggregate moisture control to prevent vapor release after coating [32]. Additionally, mixing temperature control is critical due to draindown susceptibility [7]. Batch plant dry and wet mixing times should be lengthened to augment fiber distribution (whether mineral or cellulose). The addition of fibers and the use of modified binders as required for most PA mixtures are successfully performed by adapting conventional asphalt batch and drum plants [2].

Issues have been identified with transportation of PA mixes. The potential draindown problems require time limits on mixture storage and transportation [29]. Tarps are necessary to avoid cooling and crusting of the PA materials during transportation. Some agencies also require insulated or round belly truck beds for PA transportation to prevent temperature loss and segregation [32]. Trucks used to transport the rich PA mixtures should have a full application of an asphalt release agent applied prior to loading.

The main considerations for PA pavement site preparation involve proper preparation of the base and subgrade, and measures to protect the permeability of the pavement. Areas adjacent to the porous pavement must be free of loose soils, etc. that could clog the pavement if runoff or construction operations carried foreign materials onto the PA surface. If danger of such contamination exists, stabilization and/or separation should be maintained using filter fabric, check bales, etc. [12]. Completion of soil stabilization and landscape development prior to construction is optimal.

1.2.6 Porous Asphalt Pavement Structure Design

Most PA pavement systems are composed of four layers [9]. At the bottom, a minimally compacted, adequately permeable subgrade is usually needed. Replacement of inadequate subgrade materials is usually not feasible, but disking to loosen soils may be advantageous. The reservoir base usually consists of a 1-2 inch diameter, clean, durable, crushed stone aggregate. A filter or "choker" layer of approximately two inches of ½-inch crushed stone aggregate is commonly applied at the top of the base to provide surface uniformity and stabilization for paving operations. The thickness of the base layer is normally determined based on water storage needs and frost depth considerations. A porous asphalt surface course is installed with thickness determined from bearing strength and pavement design requirements. Most parking lot installations of PA pavement are approximately 3 inches thick.

The aggregate reservoir base is typically an integral part of the design of PA pavements. The base should have sufficient storage capacity for expected local rain events to prevent overflow and flooding of the pavement, although contingency surface or subsurface ingress or egress structures are sometimes installed. If allowances for overflow are not made, the subgrade materials must possess sufficient permeability to allow water discharge from the reservoir base. As such, it is recommended to install PA systems over minimally compacted, granular subgrade [8]. The PA structure would not necessarily require a separate storage base layer if the subgrade were both sufficiently supportive and permeable to allow the maximum expected infiltrated flow. Although many sources recommend designing the reservoir base depth equal to frost penetration, more research is needed to clarify base depth needed to prevent frost damage in cold climates.

Porous asphalt is not proficient at correcting profile inconsistencies or structural insufficiencies; therefore the surface of the underlying base should be prepared adequately before PA placement. Excessive vehicle access to the base surface during paving should be minimized, and preparations made to take remedial action before and during paving operations if necessary. Construction of level (flat) subgrade, reservoir base, and pavement layers is highly desirable to prevent pooling in low areas, minimize clogging, and maximize vertical infiltration efficiency.

1.2.7 Paving Operations

Finished PA smoothness is highly dependent on proper construction practices [8], and surface depressions are more difficult to correct with PA than with dense graded asphalt. Placement of PA mix over aggregate stone reservoir bases is best accomplished by the use of track pavers. The modified asphalt binders and high asphalt content demand special attention to mixing, transport, placement, and compaction temperatures - thermal cameras have been utilized to spot inadequate temperatures or thermal segregation of the mix.

Compaction of PA mixtures is typically performed by applying only one or two passes from static, 10-ton, steel-wheel rollers. More intensive rolling would cause shifting of the materials and densification of the surface. Pneumatic-tired rollers are not used for PA compaction because their kneading action reduces the mixture drainage capacity by closing surface pores [7]. Porous Asphalt may be placed in multiple lifts; however additional lifts should be installed within 24 hours. If a tack coat is specified it should be carefully applied at a reduced rate to prevent clogging. Technology is now available for simultaneously placing both layers of the two-layer PA that is currently employed in Europe and Japan. Longitudinal and transverse joints in PA require close attention since they are more difficult to construct than with dense graded asphalt. Avoidance of longitudinal cold joints is always preferred [9, 27].

Mixture approval in most agencies is based on minimum asphalt content, void content, gradation, and a visual inspection after compaction to evaluate (qualitatively but not quantitatively) the density (and associated porosity), material consistency, and segregation. Adequate compaction is necessary to prevent raveling. However, a specified density or permeability of the installed pavement is not normally required [7]. Usually a minimum final smoothness is specified for pavement acceptance.

1.2.8 Porous System Functionality and Permeability

Typical porous asphalt pavement functional life expectancy is 5 to 8 years [2]. Functionality is negatively impacted by clogging-induced permeability reduction. Without pavement cleaning or vacuuming to mitigate clogging, permeability and noise reduction capacity are expected to decrease and eventually cause the PA to behave like dense graded asphalt. If site conditions produce minimal dust and debris, and high traffic speeds are allowed, clogging will be delayed due to the cleaning action of tire-generated suction forces [18]. Europe and Japan are pursuing the noise reduction capability of PA by a strategy that involves designing and constructing two-layer PA, limiting construction of PA to high-speed roads only, and applying frequent cleaning with special equipment [33, 34]. However, different agencies around the world do not agree on the efficacy of cleaning PA, and its practice is still not standardized. New technological developments (i.e., new Japanese cleaning technology) are modifying the current cleaning practices and improving the cost-benefit ratio of this practice.

Although adequate permeability is one of the defining properties of PA, the measurement of this parameter is not widely practiced or standardized. Experience has shown that adequate permeability is normally provided by meeting the mix design parameters of air voids and aggregate density, in concert with proper construction and maintenance techniques. However, minimum air voids content is also not specified by many agencies in the United States [7]. When permeability has been measured, the common approach is to determine the time of infiltration of a specific water volume. Porous Asphalt permeability has been measured in this manner using permeameters with either falling head or constant head [34, 35]. Modeling the PA pavement internal water flow is problematic due to the tortuous, unconfined, 3-dimensional internal flow through the system.

1.2.9 Pavement Durability

The service life of PA is highly variable but usually less than 10 years [15]. A major factor influencing PA durability is the type of binder used. The majority of agencies reporting successful PA systems are using modified binders. Tire rubber, SBS, and SBR-modified asphalt have been employed in PA. The most frequently reported cause of PA pavement failure is raveling [5, 7]. Raveling is mainly associated with binder aging, but also by binder softening due to oil and fuel drippings. Mechanical raveling can occur due to heavy loading and vehicle turning movements. Inadequate compaction or insufficient asphalt content also contributes to raveling [2]. Research is needed to assess the aging potential of PA mixtures and the resulting impact on durability.

Comparisons of the structural capacity of PA, and dense graded hot mix asphalt (DGHMA) available in the literature do not lead to a definitive conclusion on the structural contribution of porous mixtures. Some authors state that DGHMA and PA are comparable in terms of mechanical response [2, 5]; others show that lower modulus is obtained for PA [36]. Permanent deformation in the form of rutting is not generally considered the primary failure mode in PA due to stone-on-stone contact. Field measurements and extensive experience in Europe suggest that PA mixtures are highly resistant to permanent deformation [37].

1.2.10 Maintenance and Repair

Most agencies using PA apply standard dense graded asphalt patch mixes to repair surface deterioration and potholes, due to the expense of producing small quantities of porous mix [5]. General recommendations and actual practices for major rehabilitation of PA in the United States include milling and replacing existing PA with new porous asphalt, or dense asphalt mixture [2, 5]. However, ideal rehabilitation methods for of PA would be milling, recycling, and repaving with PA. Direct placement of a dense graded asphalt overlay above PA is not recommended because water accumulation inside the porous layers negatively affects the dense surface course. Overlay with porous material, or application of chip seals is not recommended [2, 5].

If the PA functionally fails due to clogging, it will essentially behave like a dense graded asphalt mix [7]. Service life may be extended, or major maintenance may be deferred, if the initial site design includes alternate provisions for surface runoff (possibly into the base) in the event of catastrophic pavement clogging.

Porous asphalt pavements can suffer from earlier and more frequent frost and ice formation, apparently as a result of the insulating thermal properties of the extensive air voids [4]. Formation of black ice and extended frozen periods are currently considered the main problems associated with PA (and porous friction course) maintenance in the United States [5, 14]. European research however, has indicated that surface snow appears to melt faster and with less refreezing [13, 16]. Regardless, PA requires several specific winter maintenance practices. Salt (or other deicing agents) must be applied more frequently, and in somewhat greater amounts, than on comparable dense graded pavements and the timing of the application is critical [5, 7, and 17]. Additionally, control must be exercised in the consistent and comprehensive application of the deicing chemicals. Pre-wetting of the salt or adding brine can provide additional adhesion to retain salt particles on upper surface (where icing is critical), and prevent downward migration into the voids. The direct application of sand (or excessive vehicle on-tracking of sand) is clearly unwanted because it contributes to the clogging of pavement voids [8]. The maintenance process can be improved by operator education, operational flexibility, and close monitoring of road conditions to maximize treatment effectiveness.

Some agencies using PA or friction courses apply fog seals to perform preventive maintenance [5]. Cleaning of PA in the United States is not common, but is increasing in practice. In some European countries and Japan, vacuuming and washing techniques are employed to maintain surface permeability [33, 34]. In addition, countries are testing two-layer PA in order to maximize functionality, improve durability, and reduce clogging [38]. Most agencies have no specific recommendations about pavement markings; however, thermoplastic markings are specified in the U.K. [29].

1.3 PROJECT SITE DESCRIPTION

1.3.1 MnROAD Low-Volume Road

Construction of the Porous Asphalt test cells planned for the LRRB Investigation 878 project was completed at the MnROAD facility, LVR in August, 2009. MnROAD was constructed by MnDOT in 1990-1993 as a full-scale accelerated pavement testing facility, with traffic opening in 1994. Located near Albertville, Minnesota (40 miles northwest of St. Paul-Minneapolis), MnROAD is one of the most sophisticated, independently operated pavement test facilities of its type in the world. Its design incorporates thousands of electronic in-ground sensors and an extensive data collection system that provide opportunities to study how traffic loadings and environmental conditions affect pavement materials and performance over time. MnROAD consists of two unique road segments located parallel to Interstate 94:

- A 3.5-mile Mainline interstate roadway carrying “live” traffic averaging 28,500 vehicles per day with 12.7 % trucks.
- A 2.5-mile closed-loop LVR carrying a MnROAD-operated 18-wheel, 5-axle, 80,000-lb tractor-semi-trailer to simulate the conditions of rural roads. The tractor/trailer travels multiple laps each day (80 per day on average) on the inside lane of the LVR loop. The outside lane remains unloaded except for lightweight test vehicles. ESALs on the LVR are determined by the number of laps and are entered into the MnROAD database. The PA test cells were installed as part of reconstruction of MnROAD (Phase-II) that began in 2007 and continued into 2009. Test cell layouts shown in Appendix A represent the MnROAD test cell regime in 2011 after completion of Phase-II construction. Additional information on MnROAD is found at: http://www.dot.state.mn.us/mnroad/

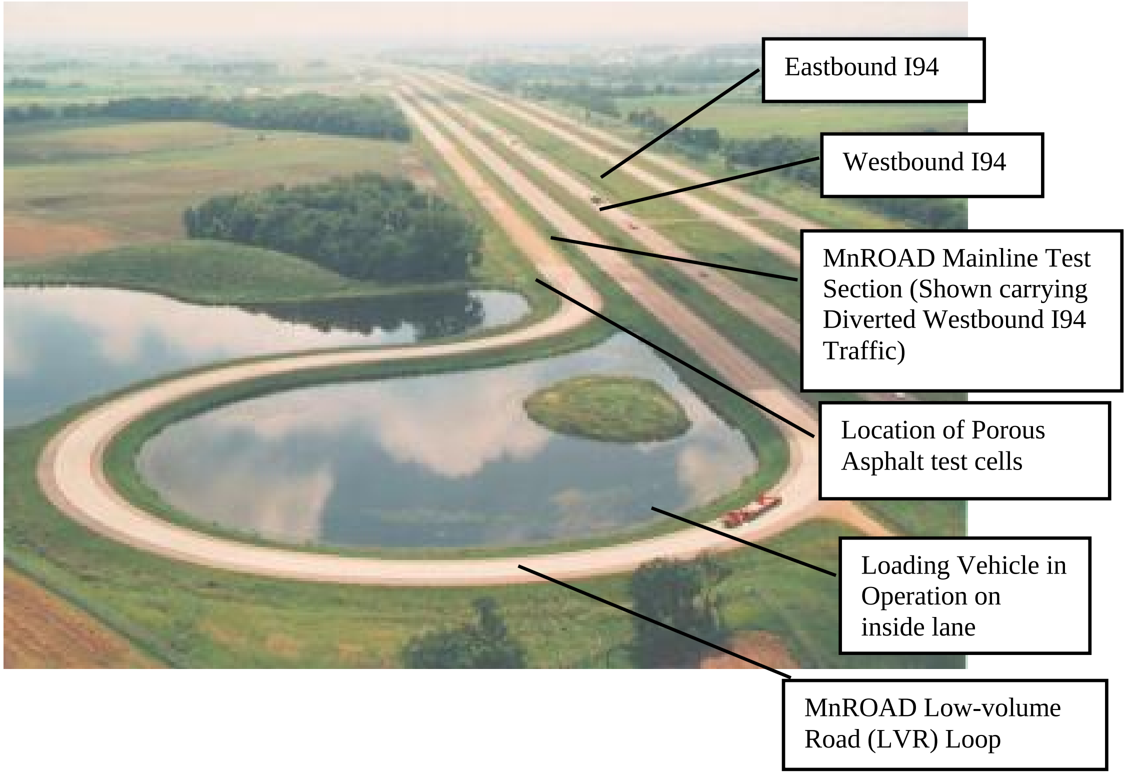


Figure 1.3. MnROAD mainline and low-volume road aerial photo

1.3.2 Porous Asphalt Test Cells

Construction of the porous asphalt pavement cells outlined in this report was completed in August 2009 on new LVR cells 86 and 88. A standard hot mix asphalt, impervious “control” cell (cell 87) was installed between cells 86 and 88 on the transition area between subgrade types. Pervious Portland Cement Concrete test cells 85 and 89 were installed adjacent to the PA cells and researched [42] under a separate project (LRRB 879). Table 1.1 contains the test cell descriptions, stationing, and lengths of the constructed cells 85-89 on the LVR. The locations of new cells 86 through 88 on the LVR are shown in Figure 1.4, on the following page.

Table 1.1. Description, MnROAD stationing, and lengths of LVR cells 85-89

Cell	Road	Cell Description	Starting Station	Ending Station	Cell Length(ft.)
85	Low-Volume Road	Pervious PCC on Sand	16368	16594	226
86		Porous HMA on Sand	16594	16820	226
87		Superpave on Sand/Clay	16820	17046	226
88		Porous HMA on Clay	17046	17272	226
89		Pervious PCC on Clay	17272	17498	226

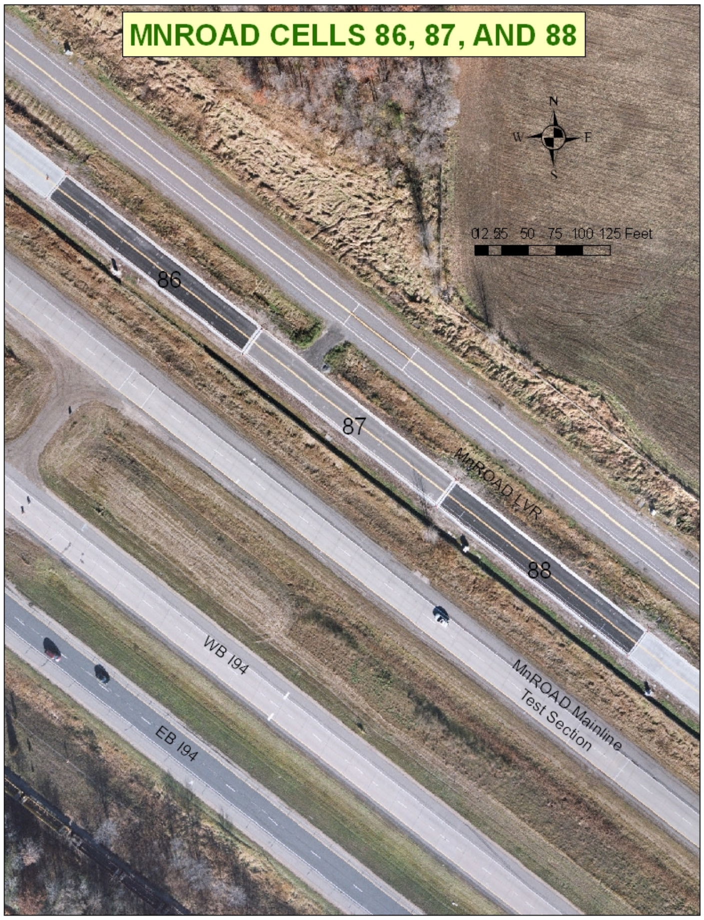


Figure 1.4. MnROAD LVR cells 86, 87, and 88

1.3.3 MnROAD Instrumentation and Performance Database

Data collection at MnROAD is accomplished with a variety of methods to help describe layer properties, the pavement response to loads and the environment, and actual pavement performance. Data is collected from different types of sensors extending through the pavement surface and sub-layers. The sensors measure variables such as temperature, moisture, stress, strain, deflection, and frost depth in the pavement**.** MnROAD personnel have continuously increased the effectiveness of sensors, developed specifically designed sensor configurations, and improved automated data collection and transfer. Sensors are wired to roadside cabinets, which are connected to the MnROAD database for data storage. Data can be drawn from the MnROAD database for each sensor, along with other performance data that is collected throughout the year. This includes pertinent ride, distress, rutting, faulting, friction, forensic analysis, and materials data.

1.4 SUBSURFACE CONDITIONS INVESTIGATION

1.4.1 Introduction

The recommendation by industry to construct the pervious pavements over both a granular and a cohesive subgrade precipitated the choice of former MnROAD cells 25 and 26 as the destination cells for this project. Historical data indicated former cell 25 was built over a granular (sand) subgrade. The sand was known to have been brought in at the time of initial MnROAD construction. It was so highly drainable, percolation tests were not performed. A mixed-materials transition area of approximately 50-feet long separated cell 25 from cell 26. Test Cell 26 was recorded as a pavement underlain by cohesive (clay) subgrade soils. Saturated hydraulic conductivity, k_{sat}, describes water movement through saturated media. Original construction reports referenced the measured clay $k_{sat} = 2.75$ E-6 m/s. The volumetric moisture content of the saturated clay is 49%.

The two former adjacent cells with differing base materials allowed installation of identical porous asphalt pavements with two radically different subgrades in one location of MnROAD (although with shorter than normal cell lengths). The materials transition area between the former cells 25 and 26 was chosen as an effective area for an impervious control cell (cell 87). The cross section and plan views of the constructed porous asphalt and dense graded control cells are shown in Appendix B. Multiple exploration strategies were performed in order to more accurately locate and characterize the subgrade soils and determine hydrologic characteristics of the site. This section describes the methods employed and the results of the investigations.

1.4.2 Subsurface Investigations

To perform subsurface investigations [42], three arrangements were made to adequately characterize the soils and drill into layers of cohesive material:

- The MnROAD Operations Section provided four piezometer-equipped borings in the vicinity of the project in an apparent downstream location.
- The MnDOT Foundations Section was employed to use the Cone-Penetrometer Test (CPT) equipment to ascertain descriptive features such as the extent of granular/cohesive layers, true phreatic surface, and soils characterization.
- The MnDOT Foundations Section was also requested to obtain additional Geotechnical borings from the project site.

The MnROAD Operations Section borrowed drilling-equipment from the MnDOT, District 2 Materials Office in Bemidji. The crew drilled Piezometer Wells #1, #2, #3, and #4 in their respective locations adjacent to cell 24 on November 5th and 6th, 2007. Appendix C shows the location of the piezometer wells used for water quality sampling and analysis with this project. Each well boring was equipped with screens having slots that meet the hydrogeological characteristics of the water bearing strata. Appendix D describes the soil profiles encountered in Wells #1 through #4.

Well #1 was drilled in the vicinity of the existing pond. This boring encountered clay 3 feet below the surface. This may represent the lining of the pond that was constructed 14 years ago. The clay lining was not fat clay but it formed 2-inch ribbons before breakage. The clay soils were underlain by a layer of wet-to-saturated clay extending to 10 feet below the surface. Beneath this layer was found a layer of saturated clean sand extending to a depth of 32 ft. below the surface. It is not historically apparent whether this was borrowed fill, but the layer was underlain by a layer of stiff, cohesive, dark gray clays. The layers encountered from 10 to 32 ft. below the surface are considered to be in a confined aquifer. The depth of the underlying containing (but not confining) clay layer was not immediately known, though it extended beyond the 36ft depth at which the drilling was concluded.

Well #2 encountered wet to saturated sands from the surface to a depth of 10 feet. A layer of saturated sand lies beneath this material to a depth of 32 feet. Similar to Well #1, the aquitard (perched aquifer) was underlain by stiff gray clays extending to below the depth of drilling. Wells #3 and #4 encountered wet to saturated sands from the surface to a depth of 10 feet. The sand was underlain by gray, stiff clays, which also extended to below the extent of drilling.

The permeability of the underlying clay is negligible and provides bottom containment for the perched aquifer. More importantly, where saturated sands are encountered 3 ft. below the surface; the result may be a reduced storage capability of the perched aquifer to rapidly accommodate all water infiltrating via the pervious pavement. Observations and records of the soils encountered were made at the time of installation of the wells. Figures 1.5 and 1.6 show images of the soils encountered during the drilling operations.

The granular saturated soils were fairly easily retrieved from the auger but the stiff clays tenaciously adhered even after auger sections were dropped on the pavement. The apparently westward sloping aquiclude was supported by the material shown in figure 1.6. It was encountered at 10 ft. in Wells #3 and #4 and at 30ft in Wells #1 and #2.

Figure 1.5. Well #2: Saturated sands at up to 30-foot depths

Figure 1.6. Well #2: Stiff gray clays between 32 and 36 feet

The cone penetrometer (CPT) exploration was performed on cells 24, 25, and 26 by the MnDOT Foundations Section on the 13th of December 2007. Each probe provided additional information about the subsurface layers. The CPT probe quantifies the resistance of soils to the tip and sleeve. After analyzing the penetration rates, inferences about the soil cohesiveness can be made. In the interpretation of the CPT Data: a sleeve stress / tip stress ratio less than 2 to 4 psi is indicative of a granular soil, a sleeve stress / tip stress ratio exceeding 4 psi is indicative of cohesive soils. Pore pressure is a dynamic measure; stress relief indications and static pressures will describe saturated conditions at any depth. The four CPT log reports are shown in Appendix E.

Logs showed that the friction ratios ranged from 2 to 4. This indicates that the sands encountered were not clean but may include some silt or clay. This dirty sand may be more prevalent in the vicinity of the clay layers. The soils encountered were generally granular between depths of 10 ft. and 32 ft. The perched aquifer encountered in cell 24 is believed to slope westward towards the pond in the northwest end of the MnROAD low-volume loop. Groundwater sampling was done with the understanding that contaminants probably travel longitudinally along the cell’s subgrade with the upstream side being east and the downstream west.

Foundation borings were also taken to depths of 45 ft. adjacent to the test cells. The boring log reports are contained in Appendix F.

2 POROUS ASPHALT MIX DESIGN, REFINEMENTS AND TESTING

2.1 POROUS ASPHALT MIX DESIGN

The porous asphalt mixture that was needed for this project is a rarely used product in Minnesota, with minimal design experience both at MnDOT and among local contractors. Therefore the specified process was to have the asphalt-paving contractor initially design the mix, and then employ a verification process by retesting the main design parameters at MnDOT. It was expected from previous installations of porous asphalt in Minnesota, that the contractor would be able to meet the specifications with the available materials. The contractor was tasked to develop a mix design that met the Specifications, and submit the design and samples of the mix to MnDOT for retesting and verification at the MnDOT materials laboratory, in Maplewood, Minnesota.

The porous asphalt used for this project was designed according to the current MnDOT (modified) Specification 2360-Porous Asphalt [28], which is based on the NCAT 2000 method [27], with modifications. The significant modifications to general the NCAT design on this project were a PG70-28 Binder (changed from the initially specified PG64-34, for reasons described below), no recycled materials (for better mixture control in the research setting), and class A (crushed granite) aggregates (for better resilience under heavy test loading). The mix design was prepared by the asphalt contractor for the MnROAD phase II reconstruction project; Hardrives, Inc. of Saint Cloud, Minnesota. A summary of the porous asphalt design specifications for this project are as follows:

- Minimum asphalt content 5.5% - 6.5% by weight
- No recycled material
- Mix Gradation; 100% passing ¾, 75% retained on #4 (no Class B aggregates allowed)
- LA Rattler Loss <35% for any individual source.
- Mineral Filler allowed / Maximum Draindown $\leq$ 3%
- Coarse Aggregate Angularity >55% (No Fine Aggregate Angularity Spec)
- Coarse Aggregate Absorption $\leq$2%
- Voids in Coarse Aggregate; $VCA_{max} < VCA_{drc}$
- Flat & Elongated Particles$\leq$ 5 (5:1 ratio)
- Maximum Clay Content, Maximum Spall, % Lumps retained on #4
- Air Voids; 17 - 19% (ensures permeability)
- Placement of Asphalt @ > 50°F ambient temperature, 275°F minimum mix laydown temperature
- Modified Lottman test; TSR $\geq$ 80%
- Mix Storage; 90 minutes maximum
- Mix to be placed with a track paver only
- 10-ton steel wheeled non-vibratory rollers only (1 or 2 passes)
- No vehicular traffic on finished surface for > 24hrs, prevent contamination of surface

The mix design was initially prepared and submitted to MnDOT in July 2008 meeting all specifications, except the TSR requirement (Modified Lottman Test, ASTM D-4867). The Lottman results were verified at MnDOT's Materials Laboratory - the PG64-34 sample did not survive the 140°F water bath process, could not be tested, and therefore did not pass. The validity of the Lottman test for porous mixes was investigated, and it was learned that some agencies have discontinued its use on friction courses. However, it was agreed at MnDOT that it is indicative of the potential strength of the mix. Recent porous asphalt mix design literature [39] was reviewed and based on the published research data, the decision was made to request the contractor to change the initially specified PG64-34 asphalt binder to PG70-28. A PG70-28 mix was prepared by the Contractor, which then appeared to meet all original design specifications, including the TSR requirement. Lottman testing was repeated at MnDOT and results verified that the PG70-28 mix met the requirements for TSR. Lottman Test Results for each asphalt binder are attached in Appendix G.

At that time the redesigned Porous Asphalt mix using PG70-28 binder was accepted by MnDOT and a Mix Design Recommendation (MDR) was issued. The final accepted MDR for the Porous Asphalt installed with this project is attached in Appendix H. Samples of redesigned (prepared) mix were also submitted to MnDOT for further testing and verification.

2.2 ASPHALT PAVEMENT ANALYZER (APA) TESTING

After verification of the initial TSR failure, an asphalt pavement analyzer (APA) test was ordered for the mix at the MnDOT laboratory. The APA test was performed in accordance to the AASHTO TP63. The APA testing system is shown in figure 2.1 The APA test results are considered to be an indication of rutting potential. After specimens are prepared by gyratory compaction, samples are preheated and tested at 137^o F (58^{o}C). This testing point is considered to be the highest temperature typically experienced by pavements in Minnesota. The apparatus applies mechanical pressure “strokes” to the surface of the preheated specimen.

The test was performed on both the PG64-34 and PG70-28 mixes. The APA test results for each binder are illustrated in figure 2.2. It can be seen that the mixture with PG70-28 has a better and more linear response than the mixture with PG64-34. This illustrates the PG64-34 has a higher potential for rutting. The PG64-34 mix also showed very poor results in comparison to those normally seen with a typical dense graded asphalt mix.

Figure 2.1. Asphalt pavement analyzer (APA) apparatus

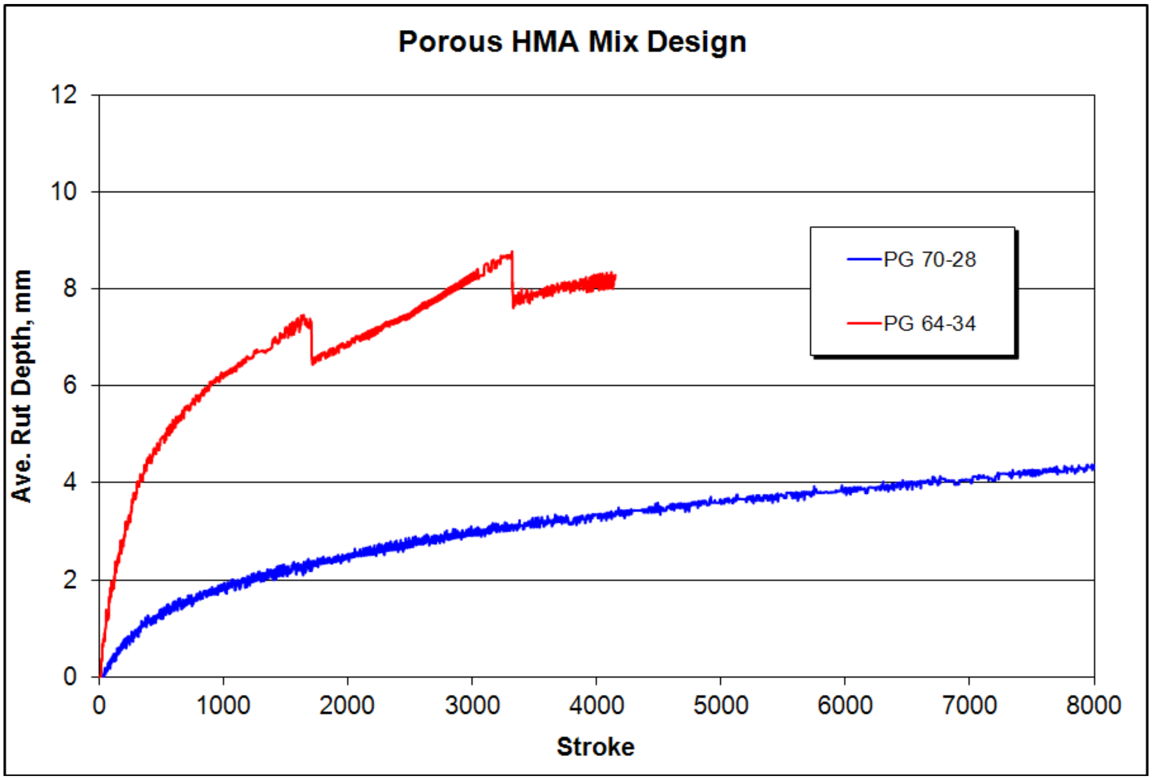


Figure 2.2. APA samples for porous asphalt with binders PG 64-34 and PG 70-28

2.3 POROUS ASPHALT ACCEPTANCE AND SPECIAL TESTING

The Porous Asphalt mix was also sampled at the time of paving operations in October 2008, and subjected to further testing. Normal acceptance testing was performed; some of it by MnDOT personnel and some by testing contracts executed during the 2008 construction. The pertinent acceptance test results are contained in the MnROAD database and Appendix I. Two non-standard laboratory tests were also performed; dynamic modulus and freeze-thaw testing. These tests were for information only, so they were not specified at the time of mix design. It was decided that samples collected during paving would be representative of the inplace materials, and therefore more valid.

2.3.1 Dynamic Modulus E Testing*

The dynamic modulus test (E*) is used to describe viscoelastic response of the asphalt mix, which is a measure of material stiffness. It is determined from laboratory testing on a specimen subjected to sinusoidal loading conditions. The E* value is calculated dividing the peak-to-peak stress by the peak-to-peak strain from the specimen under a sinusoidal loading at multiple frequencies and temperatures. The E* value determined from this research can be used to compare mixture stiffness and assist in the characterization of the mixture for pavement design using the mechanistic-empirical pavement design method.

The dynamic modulus testing was performed using an Interlaken Universal Material Testing machine in accordance to the AASHTO TP62 at MnDOT's Maplewood Laboratory. The testing system is a servo-hydraulic, computer-controlled and closed-loop system, which also contains a tri-axial cell and environmental chamber (Figure 2.3).

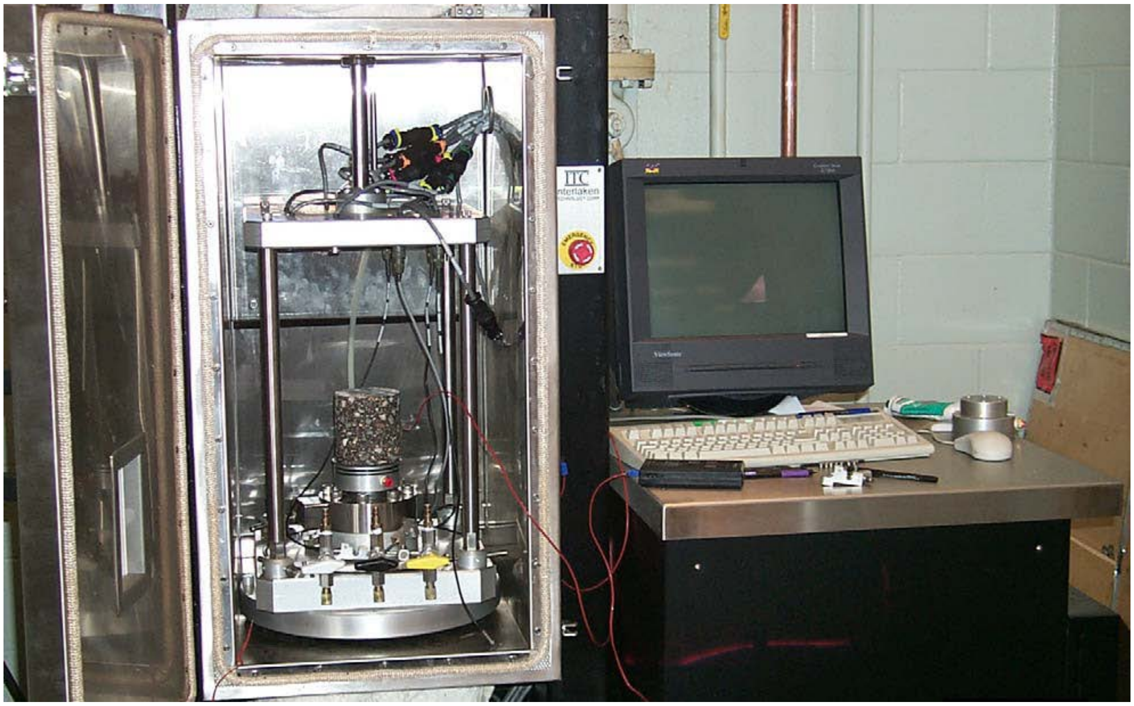


Figure 2.3. Dynamic modulus E* testing device

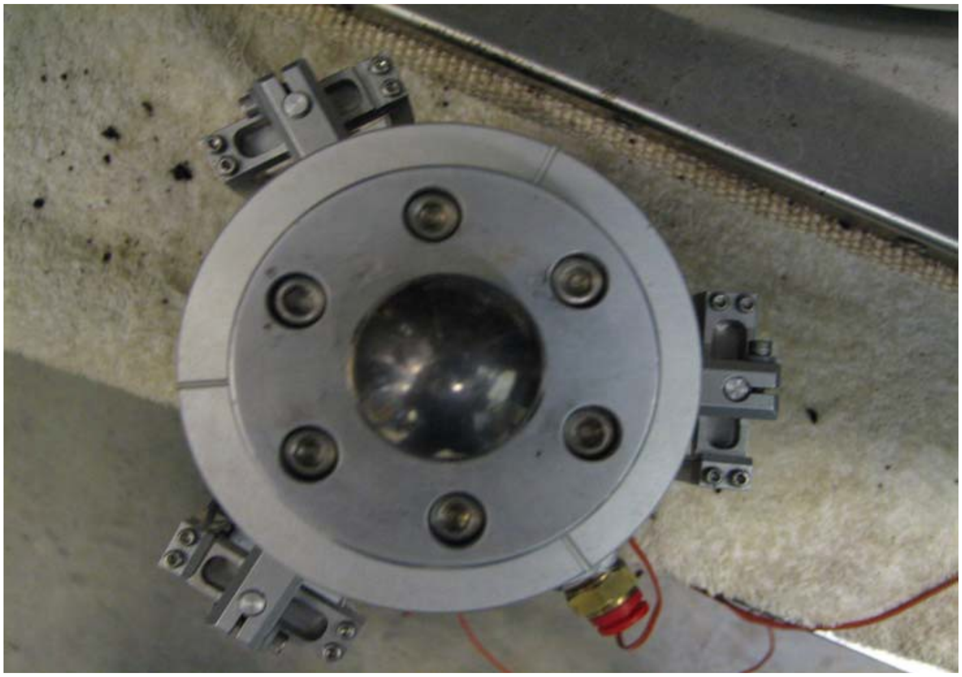


Figure 2.4. LVDT setup

Three linear variable differential transducers (LVDT) were used to measure specimen deformation (Figure 2.4). The dynamic modulus test was performed on three samples of the porous asphalt and one sample of a standard, dense graded HMA with PG58-28 binder. The test was conducted under multiple loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) and five different temperatures (14, 40, 70, 100 and 130°F).

Dynamic modulus master curves were then developed using test data at different temperatures and frequencies to compare mixture stiffness. Figure 2.5 shows a comparison of master curves of the two mixtures. The data indicates that the installed PG70-28 PA mix should perform well in comparison to a standard dense graded PG58-28 mix. The porous asphalt mixture should have a better resistance to deformation at lower temperatures, while retaining an adequate material stiffness at higher temperatures.

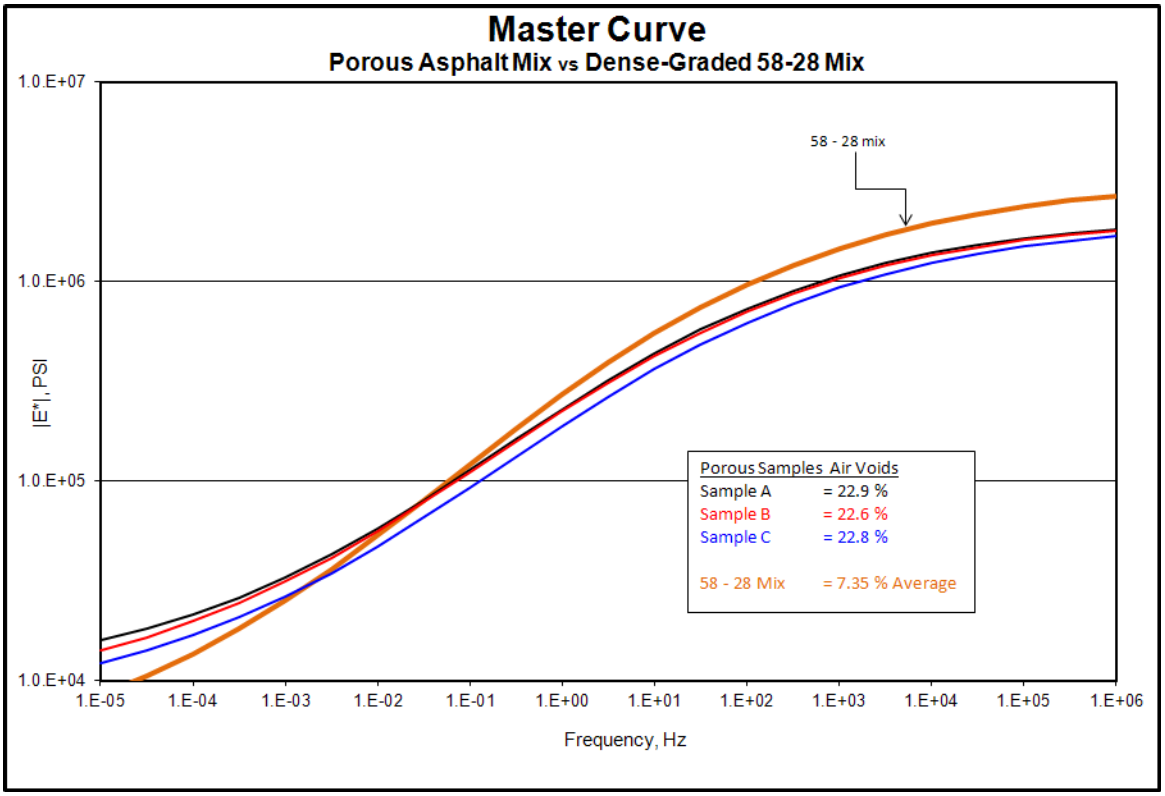


Figure 2.5. Dynamic modulus (E*) test results

2.3.2 Special Freeze-Thaw Testing

In order to study the durability of the porous asphalt mix under cold-climate conditions, it was subjected to freeze-thaw testing, in a laboratory testing protocol (ASTM C1262) normally used for Portland cement concrete (PCC). As this test is valid only for PCC materials, no specification was assigned (or assumed) for successful performance of the PA mix. The goal of the test was simply to acquire information about how this PA mix might respond to freezing conditions in the state of complete saturation.

Several six-inch diameter by six-inch tall specimens of porous asphalt were prepared by gyratory compaction and allowed to cool completely. Six specimens were placed in vessels with a brine solution and subjected to freeze-thaw testing over the course of several months. They were repeatedly tested for more than 170 complete freeze-thaw cycles, (which is normally more than adequate for the destruction of the PCC sample). After completion of the testing, the samples showed no visible damage; either by degradation or distortion of the specimens. Appendix J contains the freeze-thaw testing record for the porous asphalt mixture samples.

3 PAVEMENT STRUCTURE AND INSTRUMENTATION DESIGN

3.1 PAVEMENT STRUCTURAL DESIGN CONSIDERATIONS

The porous asphalt pavement thickness selection was based on its intended installation on a test cell of the MnROAD low-volume test road. The PA project was initially intended to last 2 years – from 2008 to 2010. The project was extended one year (to fall 2011) to capture data for a second winter period. During the study period both pavement performance and environmental aspects were monitored. It was important that the pavement last the duration of the study and at the end of the study be minimally serviceable. Although valuable data is gathered as a pavement deteriorates, premature failure would have also negatively impacted the environmental research. Therefore, the design was not performed strictly based on minimizing the pavement thickness or the cost of the materials.

The design approach initially took into account limiting factors. First, the porous asphalt cells would be built in an “urban design”; two 12-foot lanes with curb and gutter edges. They would also be constructed in conjunction with the pervious concrete project (LRRB INV879). The confined construction area greatly encouraged designing overall thickness of pavement + base to be identical in each of the five test subcells involved. Secondly, the bottom of the crushed stone base (depth of excavation) was set approximately 2 feet from the surface due to site constrictions. Lastly, the stone base thickness and porosity was designed for storage of a five-inch rain event (the largest single rain event recorded at MnROAD in recent history).

Because no recommended PA structural design method was available at the time, the Soil Factor Design method was employed and determined a minimum pavement thickness of 5 inches. The MnROAD loading vehicle applies approximately 18,000 ESALs/year to one lane of the test cells. The other lane is currently unloaded, except for occasional test vehicles. The unloaded lane is used for a control surface and also to provide unloaded (environmental degradation) pavement data. Therefore the pavement thickness was designed to meet specifications for a low-volume road; at least 9 ton @ less than 150 HCADT. See Appendix K for a summary of the Soil Factor Design applied.

3.2 AGGREGATE BASE AND PAVEMENT THICKNESS DESIGN

The aggregate base selected was crushed CA-15 [28]. This aggregate was selected due to its close similarity to AASHTO #5 aggregate, which is recommended as an alternate specification in the National Asphalt Pavement Association (NAPA) Porous Asphalt Pavements guide, Appendix B [8]. It was thought that the smaller top size of the CA-15 aggregate would allow eliminating the filter/choker course. This was desired in order to maintain base material homogeneity for simplification of internal flow modeling and also to prevent localized clogging. It was also thought that a washed concrete aggregate with minimal organic impurities and well-known quality characteristics would be advantageous to the environmental research. It was anticipated that CA-15 suitable for this project would be readily available at the time of construction in the relatively small quantities needed.

The minimum base thickness was determined simply by applying an estimated inplace aggregate porosity of 0.4 (based on previous experience with local CA-15 sources), and allowing for a storage capacity of a five-inch rainfall event. Therefore, 5 inches/0.4 required approximately 12.5 inches of base; twelve inches was determined to be adequate for the pervious concrete cells. This thickness allows the minimum base, pervious concrete thickness, and curb thickness, within a total depth of two feet. As all cells 85 through 89 would be constructed to identical total thickness, the porous asphalt cells would then have (a slightly more than necessary) 14 inches of aggregate base. The pavement surfaces and the bottom of the base then both matched for all cells 85 through 89. The total depth of the pavement/base system was intentionally designed to not extend below the frost depths regularly recorded at the site, in order to induce some measurable freezing for analysis.

An attempt was made to isolate cells from surrounding soils by the use of vertical plastic barriers. The barriers were installed from the top of the pavements to below the bottom of the aggregate base. The aggregate base was also separated from the subgrade by a permeable, type 5 filter fabric, which is common practice in PA to prevent upward migration of fine particles. See cell layouts and cross-sectional details in Appendices A and B. Detailed construction plan drawings are contained in the records of MnROAD Phase II construction; MnDOT State Project #8680-156.

3.3 INSTRUMENTATION TYPES AND LAYOUT

In each pervious cell, each of cells 85 through 89 was separated by a transverse surface drain (emptying into the ditch) for cell isolation and to sample any runoff that occurs. Water sampling standpipes and the piezometer wells recorded water table elevations and allowed water quality sampling. Other sensors utilized are the temperature (thermocouples) and moisture (Echo2) devices installed at increasing depths in the subgrade in a configuration commonly referred to as a “thermocouple tree”. Transverse and longitudinal strain gauges were installed in the pavement, and normal stress (pressure) sensors at the bottom of the base. They were configured and hardwired to automatically upload data to the MnROAD database. There are two local automated weather stations that continuously record ambient conditions. A time-lapse camera was also temporarily installed to compare the snow and ice accumulation and removal process on the control cell versus a porous asphalt cell. Unfortunately several sensors malfunctioned during the study period, and calibration of the moisture sensors could not be completed by the time of this writing. The as-built instrumentation layouts for the porous asphalt and control subcells are shown in Appendix L.

4 CONSTRUCTION OF MNROAD TEST SECTIONS

This section details the process employed and the timeline to construct the porous asphalt test cells and the impervious control cell on the MnROAD LVR. Cells 86 and 88 were constructed with porous asphalt; control Cell 87 with dense-graded Superpave. All are constructed using open-graded (high porosity) CA-15 aggregate base material to collect infiltrated water. All sections included a Type V geotextile fabric (to separate the base and subgrade layers), vertical plastic barriers (to prevent water from flowing into or out of the pavement from the sides), curbing and transverse drains for surface runoff. The only difference between Cells 86 and 88 is that Cell 86 was constructed above a sand subgrade and Cell 88 above a clay subgrade. Cell 87 was constructed with the same base material, but above the transition area between subgrade types - the east end has sand subgrade, the west end has clay, and the DGHMA layer is only 4 inches thick.

4.1 SUBGRADE PREPARATION

Grading on these cells began June 25th, 2008. After preliminary instrumentation work was completed in early August 2008, existing pavement from previous LVR test cells 25 and 26 was removed to prepare for construction of cells 85 through 89. The cells were subcut to the sand and clay subgrades during the second week of September 2008. Plastic sheeting was installed vertically to a 4-foot depth around all four sides of each cell to isolate the water flowing through the pavement structure and prevent lateral flow into the system (figures 4.1 and 4.2).

Figure 4.1. Cell 86 (sand subgrade) installing plastic edge barriers

Figure 4.2. Cell 88 (clay subgrade) with plastic edge barriers installed

The difference between the sand and clay subgrades in gradation and compaction was significant – the sand was very permeable and not compacted, while the clay remained dense and well compacted. No effort was made to disc or loosen the subgrade material after subcutting and leveling, nor was the subgrade rolled or compacted – it was left in the condition an inplace road subgrade would be after normal pavement removal and subcutting.

4.2 BASE MATERIAL AND CURB AND GUTTER CONSTRUCTION

Type V Geotextile fabric was installed (figure 4.3) on top of the prepared subgrade September 15th, 2008 and placement of the planned CA-15 base material was attempted the following week (figure 4.4). The CA-15 obtained by the contractor for cells 85 through 89 demonstrated insufficient stability for supporting construction operations. After on-site attempts at blending and layering other materials, it was decided to replace the top 4 inches of CA-15 base with crushed granite railroad ballast (figure 4.5). On cell 87 the top 4 inches were replaced with crushed iron ore ballast that was leftover from the construction of cell 23. Each lift of base material was lightly rolled to set the material without significant compaction (figure 4.6). The resulting composite base provided an adequate construction platform.

Figure 4.3. Installation of type V geotextile

Figure 4.4. Placement of CA-15 base material

Figure 4.5. Railroad ballast / CA-15 composite base

Figure 4.6. Light rolling to seat base material

Curb and gutter was installed October 1st, 2008 directly over the vertical plastic barriers along the cell edges (figure 4.7). After curbing was sufficiently cured, topsoil was backfilled and seeded behind the curbing and the median was reshaped during the first week of October 2008.

Final grading and light rolling of the base material was then completed in early October 2008. After the necessary sensor installations, the cells were ready for paving.

Figure 4.7. Curbing and shoulder installation

4.3 PLACEMENT OF POROUS ASPHALT

Paving of Cells 86-88 was performed on October 15th, 2008 (figure 4.8). Installation of the standard HMA control Cell 87 went well. However, the contractor experienced difficulties both at the plant and the paver while paving the porous asphalt cells. The aggregates for the mix came to the HMA plant directly off the wash plant from the quarry. Due to the high moisture content, the material would not veil in the mixing drum and almost started the baghouse on fire. The plant operator decided to run each of the aggregate materials through the plant separately to dry them before mixing. By the time that was finished the asphalt binder line had cooled excessively and became plugged. These issues were finally resolved and mix production resumed.

The porous asphalt was initially laid down approximately eight inches thick by the paver in order to obtain the five-inch specified final layer thickness after compaction (the average compacted thickness was later determined by coring to be approximately 6 inches.) The contractor waited about five hours until the surface temperature of the mix was below 100^{o}F before starting the rolling (figure 4.9). Then the pavement mat was rolled once or twice to make it smooth, but no more so as to retain the desired surface porosity. After rolling the pavement appeared to have acceptable smoothness and porosity. This was a learning experience for MnDOT and contractor personnel alike.

Figure 4.8. Porous asphalt paving

Figure 4.9. Porous asphalt rolling

4.4 CONSTRUCTION OF TRANSVERSE DRAINS

After paving was complete, MnROAD staff constructed transverse drains (figure 4.10) to capture any surface water runoff from the down-slope ends (a < 1% slope exists from east to west) of each cell 85-89, and the up-slope end of cell 89 (to prevent water entering from the cell before it). Saw-cut openings were made approximately two feet wide along the transverse joints directly above the transverse plastic barrier sheeting, and the pavement was removed down to the base material. Steel reinforcement was designed and placed in the trenches to support the concrete drains. Wood forms were fabricated to create a sloping trench to the center, and placed prior to the concrete pour. A PVC drainpipe was installed from the roadway centerline (the low point) of the formed trench to a collection tank in the inside ditch. Concrete was then poured and finished to create the drain. Four drains were built in the fall of 2008, and the remaining two were built in the spring of 2009 (figure 4.13).

In August of 2009, collection tanks for the transverse drains were installed. The tanks were equipped with improvised flow meters (figure 4.12) for monitoring surface water runoff. However, due to the low, intermittent flow, the meters malfunctioned and never produced reliable data. Water-sampling standpipes (figure 4.11) were also installed vertically in the concrete transverse drains. Three of them extended down to the bottom of the base material, and one into the groundwater. The groundwater sampling standpipe was used to compare water quality beneath the porous asphalt pavement to water samples taken in the piezometer outside of the cells; however, the standpipes in the base material never had any measureable quantity of water present when checked.

Figure 4.10. Cell-separating transverse drains

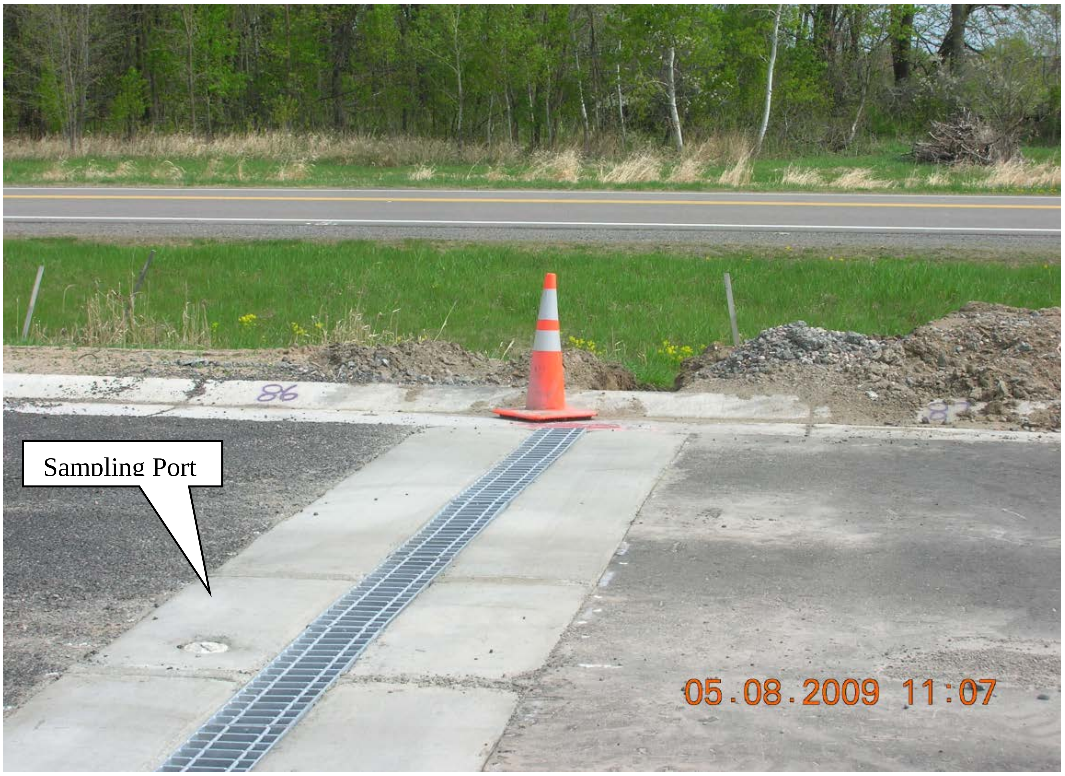


Figure 4.11. Transverse drain with sampling port

Figure 4.12. Collection tank with flow meter

Figure 4.13. Cell 86 looking east, February 2009

4.5 INSTRUMENTATION

An important element of MnROAD is the extensive infrastructure and data storage capacity available to support the instrumentation of pavement sections. Test cells for this project were built with electronic sensors embedded in them to measure the pavement's response to loading and environmental effects.

In late September 2008, MnROAD personnel began installing instrumentation and prepared wring conduits and cabinets for the porous asphalt (cells 86 and 88) and control (cell 87) test cells. Dynamic pressure gauges were installed on Cells 86-88 prior to the base material being placed. Other instrumentation was installed just prior to the pavement paving, during the week of October 15th, 2008.

The pavement gauges installed include thermocouples, water sensors, strain, and pressure gauges. Figure 4.14 shows installation of strain gauges at the bottom of the pavement just prior to paving. Ultimately some sensor malfunctions occurred on the porous asphalt cells – particularity among the strain gauges. However, enough data was collected with the functioning sensors to provide useful conclusions.

Two other parameters of interest were not tested. Lysimeters were planned for installation beneath the base material to capture infiltrated water but were not installed due to constructability issues resulting from the high groundwater elevation. Additionally, no reliable method for monitoring splash and spray could be determined due to the single loading vehicle traveling at low highway speeds (40mph) on the short, mixed test cells. As-built instrumentation layouts are contained in Appendix L.

Figure 4.14. Instrumentation installations

5 PAVEMENT PERFORMANCE MONITORING AND MAINTENANCE

5.1 LOADING APPLIED TO POROUS ASPHALT TEST SECTIONS

MnROAD personnel regularly monitor the test sections to track the changes in pavement performance over time. Various measurements of structural and functional performance are made at certain intervals throughout the year. Other tests are performed on an as-needed basis. This section contains the results of the porous asphalt pavement performance monitoring efforts for this project.

Controlled loading on the LVR is applied by a MnROAD operated vehicle, which is an 18-wheel, 5 axle, tractor/trailer with a specific weight configuration. The MnROAD vehicle normal load configuration has a gross vehicle weight of 80,000 lbs. (Minnesota legal weight limit). The tractor/trailer travels multiple laps each day on the inside lane of the LVR loop. The outside lane (also called the environmental lane) remains unloaded except for lightweight test vehicles.

The equivalent single axle loads (ESALs) on the LVR are determined by the number of laps (averaging 80 laps per day and 6000 laps per year), and the cumulative loading data is recorded in the MnROAD database. Figure 5.1 shows the MnROAD loading vehicle in 2010, with vehicle axle numbers (referred to later in this report) labeled Axle 1 through Axle 5.

Figure 5.1. MnROAD 80kip loading vehicle

MnROAD vehicle loading of the inside (loaded) lane of the porous asphalt test cells 86/88 and "control" cell 87 began on December 16th, 2008. As of November 29th, 2011, after 3 years of operation, the inside lane of cells 86, 87, and 88 received approximately 17,000 laps of the loading vehicle, resulting in approximately 40,000 applied ESALs. The application of loading occurs fairly consistently throughout the year; however the rate may be reduced during spring and summer, when other testing and data collection is intensified on the LVR or when construction or rehabilitation projects block the inside lane (figure 5.2).

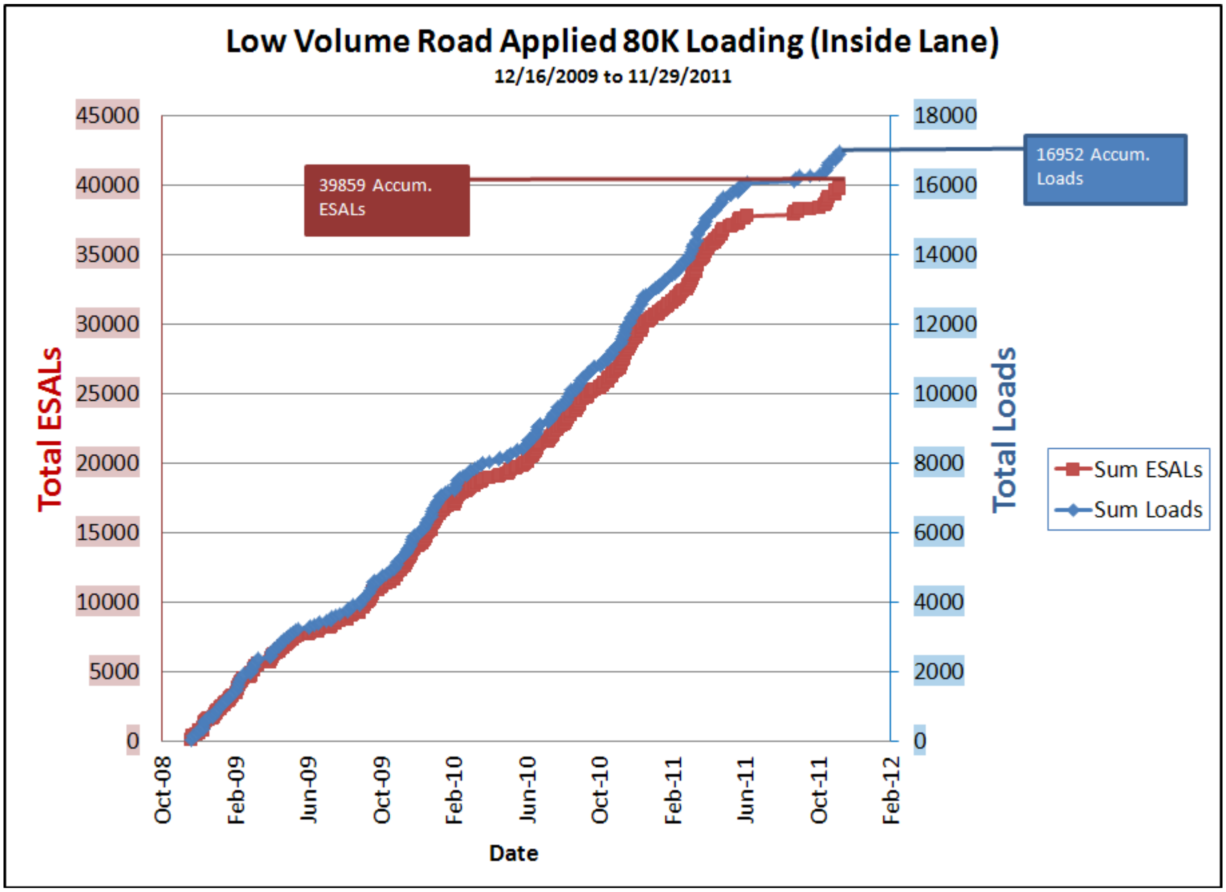


Figure 5.2. LRRB 878 3 years applied loading to LVR

5.2 NUCLEAR BACKSCATTER DENSITY TESTING

Nuclear backscatter density testing has been performed multiple times on the porous asphalt pavement since construction. Cell 87 was also tested in order to compare the porous asphalt density to a typical dense-graded asphalt pavement density. Density is a strong indicator of the percentage of voids in a bituminous pavement, and has been correlated to the structural capacity and lifespan of bituminous pavements.

MnDOT uses the Seaman C-200 Nuclear Density Testing device (figure 5.3) to rapidly and non-destructively measure the in-situ field density of bituminous pavement and granular base materials at the time of construction. The Seaman testing device is capable of making determinations of material densities in the range of 70 to 170 pounds per cubic foot (pcf). The device usually samples pavement to a depth of approximately 2 inches, and it can be adjusted to take measurements of thinner layers. It is assumed that density measurements of the top section of single-layer bituminous pavements that are thicker than 2 inches (such as the porous asphalt) are representative of the material conditions throughout the entire lift thickness.

Figure 5.3. Seaman C-200 nuclear density testing device

The average porous asphalt densities measured were similar in cells 86 and 88 and increased slightly during the testing period. A comparison of the density in loaded-to-unloaded lanes in cells 86 and 88 is listed in table 5.1 and shown in figures 5.4 and 5.5. In the unloaded lane (outside lane) the two cells have had very similar values. In the loaded lane (inside lane), cell 88 has consistently shown density readings of approximately 3% higher than cell 86. Because pavement rolling during began on cell 88, the pavement was likely compacted to a slightly higher density at the time of construction.

Since the first test in June 2009 until March 2010, the inside lane average densities increased 1.3% on cell 86 and decreased 1.0% on cell 88. Since the first test on the outside lane, the densities increased 1.6% on cell 86 and 4.2% on cell 88. However, on both porous cells, the density increased somewhat until 2010 and then decreased in 2011, and are now similar to (but slightly higher than) the initial readings. Therefore, although part of the increase in densities in the loaded lane may coincide with loading, the density in the unloaded lane is also increasing – and at a slightly higher rate. The minor increases observed so far may be due to minor clogging of the surface, and the loading vehicle may produce some tire-induced suction and wind-blown cleaning effects on the loaded lane.

The measured density values were reasonable for this type of asphalt pavement. The density of the porous asphalt in both cells averaged approximately 120 pounds per cubic foot (pcf). Only the cell 87 unloaded lane measured density is available and shown for comparison in figure 5.4. The measured density of cell 87 averaged approximately 142 pcf or about 18% higher than the porous asphalt. The density of cell 87 in the unloaded lane has also increased somewhat since 2009.

Table 5.1. Nuclear device-measured density

Nuclear Device - Measured Density												
Date	Inside Lane						Outside Lane					
	Left Wheel Path			Right Wheel Path			Left Wheel Path			Right Wheel Path		
	86	87	88	86	87	88	86	87	88	86	87	88
6/4/09	116		118	114		120	116		114	118	138	115
8/4/09	116		120	118		120	118		115	118	143	114
3/17/10	119		129	118		121	119		125	120	143	119
4/15/11	119		118	114		117	119		119	119	145	119

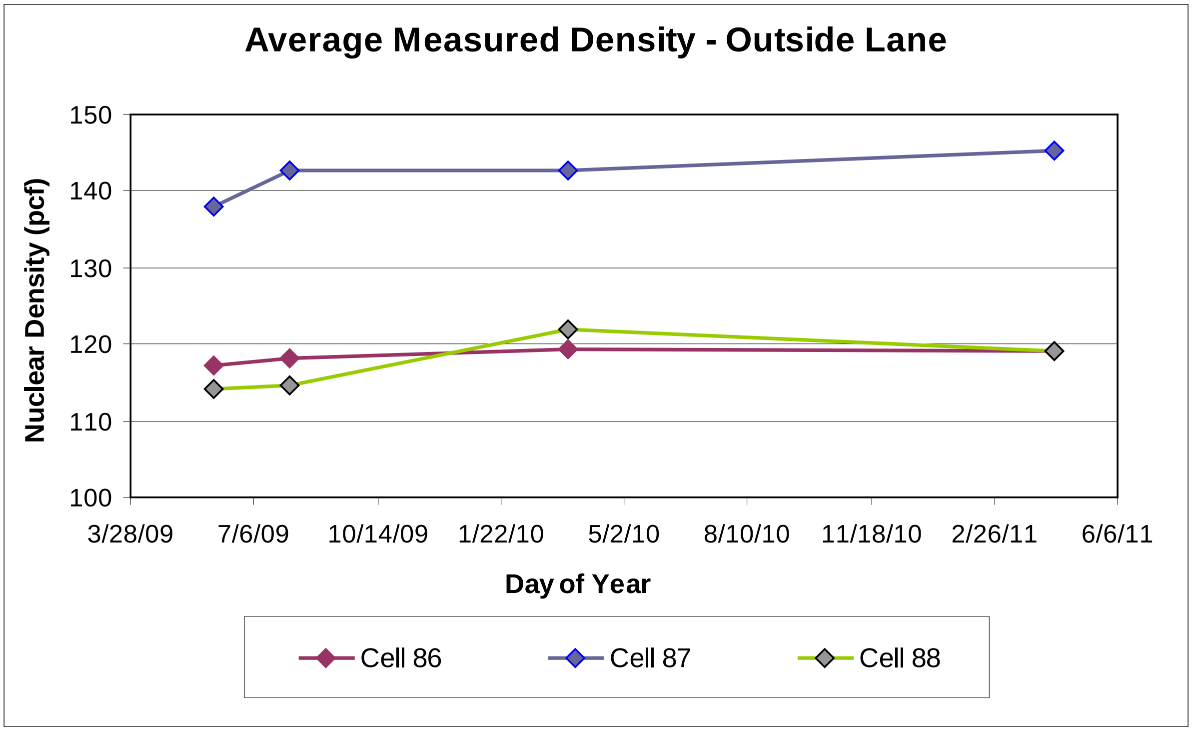


Figure 5.4. Average measured pavement density, outside lane

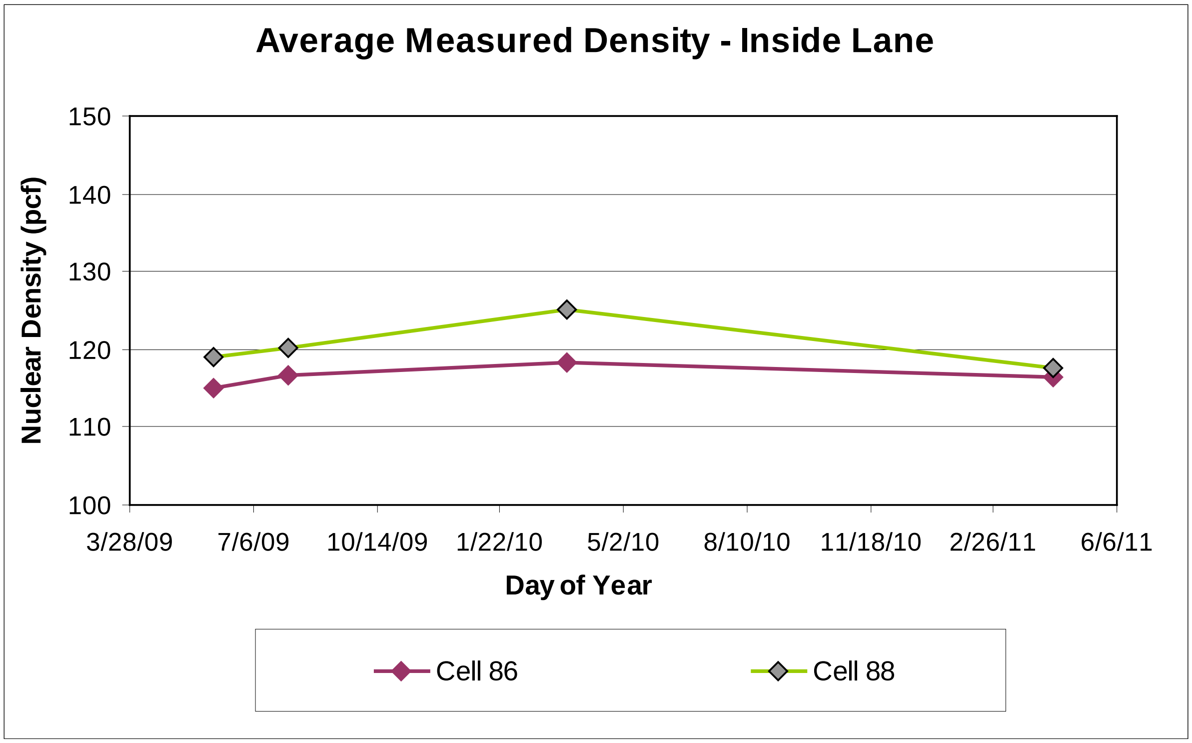


Figure 5.5. Average measured pavement density, inside lane

5.3 PERMEABILITY TESTING

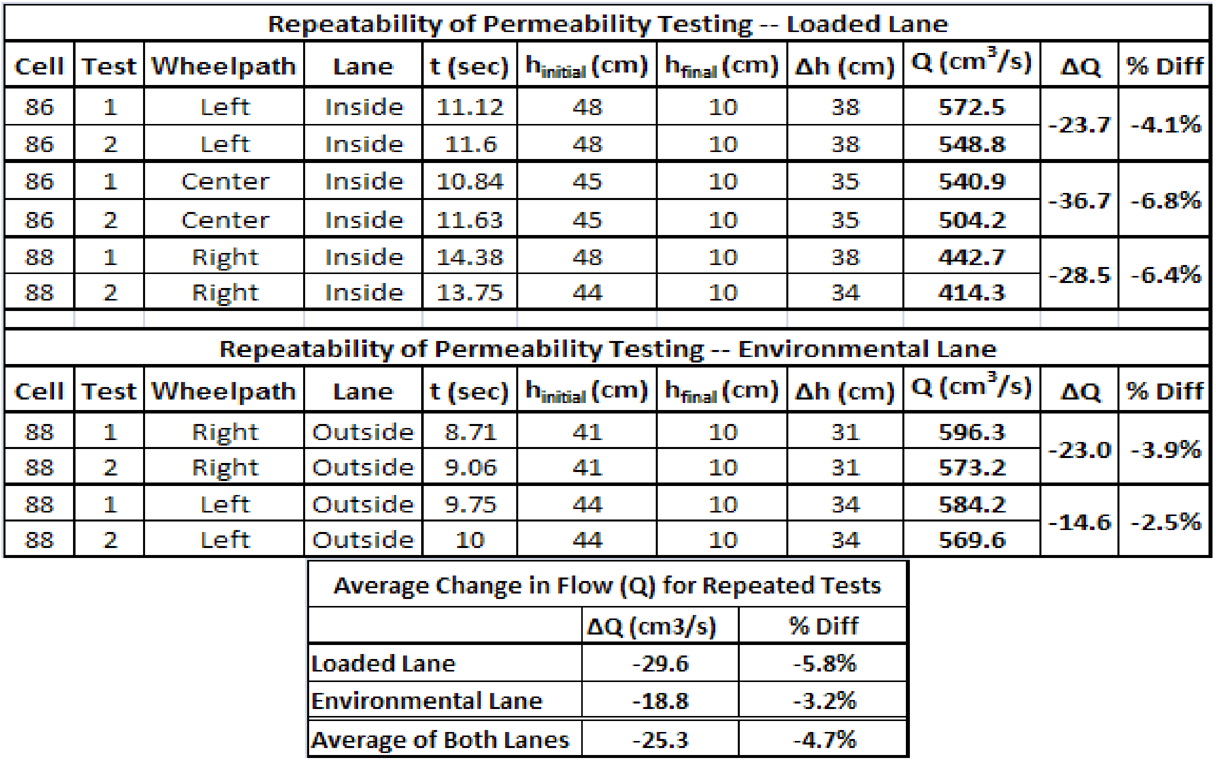
The initial and long-term surface permeability of the porous asphalt pavement is essential to its serviceability and is one of the primary interests of this research study. Permeability testing has been regularly performed by MnROAD personnel on the porous asphalt test sections (86 and 88) since 2009. Test locations for permeability (and other surface characteristic tests) were established in 2009 and permanently marked on cells 86, 87, and 88. The permanent test point locations and additional permeability data are contained in Appendix M.

Due to the rapid rate of surface infiltration in these test sections, and the need to regularly evaluate many test points, a simple falling-head apparatus was developed at MnROAD for permeability testing (figure 5.6). The device is a clear, six-inch outside diameter, graduated cylinder. A flexible seal (electrical sealant) is applied to the bottom of the cylinder, the device is weighted to the pavement, and a stream of water is supplied through a 4-inch tube from a water trailer. The cylinder is quickly filled approximately ¾ full and the time (t) for the cylinder to empty from an initial to a final level (Δh) is recorded. The rate of flow through the pavement surface is then computed by; $Q = (A*\Delta h)/t$, where the area (A) of the pavement surface tested is 167.53 cm^2 (the inside area of the tube). This test is not used to compute a measure of pavement porosity due to the difficulty of modeling the highly variable water flow through the 3 dimensional pavement pore structure. But it is a convenient and repeatable method of monitoring changes in the volume of water permeating through the surface of the pavement over time.

Figure 5.6. MnROAD permeability testing apparatus

In 2010, a series of tests were performed to determine the repeatability of this permeability test procedure. Two consecutive measurements were taken at randomly chosen test points; immediately after the water was done draining from the initial test, the second test was performed. Table 5.2 lists the difference between the two measurements, both in change of flow and the percent difference.

Table 5.2. Repeatability of permeability testing



Repeatability of Permeability Testing -- Loaded Lane

Cell	Test	Wheelpath	Lane	t (sec)	$h_{initial}$ (cm)	h_{final} (cm)	Δh (cm)	Q (cm^3/s)	ΔQ	% Diff
86	1	Left	Inside	11.12	48	10	38	**572.5**	**-23.7**	**-4.1%**
86	2	Left	Inside	11.6	48	10	38	**548.8**		
86	1	Center	Inside	10.84	45	10	35	**540.9**	**-36.7**	**-6.8%**
86	2	Center	Inside	11.63	45	10	35	**504.2**		
88	1	Right	Inside	14.38	48	10	38	**442.7**	**-28.5**	**-6.4%**
88	2	Right	Inside	13.75	44	10	34	**414.3**		

Repeatability of Permeability Testing -- Environmental Lane

Cell	Test	Wheelpath	Lane	t (sec)	$h_{initial}$ (cm)	h_{final} (cm)	Δh (cm)	Q (cm^3/s)	ΔQ	% Diff
88	1	Right	Outside	8.71	41	10	31	**596.3**	**-23.0**	**-3.9%**
88	2	Right	Outside	9.06	41	10	31	**573.2**		
88	1	Left	Outside	9.75	44	10	34	**584.2**	**-14.6**	**-2.5%**
88	2	Left	Outside	10	44	10	34	**569.6**		

Average Change in Flow (Q) for Repeated Tests

	ΔQ (cm3/s)	% Diff
Loaded Lane	-29.6	-5.8%
Environmental Lane	-18.8	-3.2%
Average of Both Lanes	-25.3	-4.7%

The percent difference is computed by; $(\Delta Q/Q_{Test1})$*100. On each repeatability test, the flow rate decreased slightly for the second trial, probably due to the residual water retained within the pore structure. The largest change between consecutive tests was less than -7%, and average percent difference between trials was -4.7%, which indicated acceptable repeatability of this test.

After establishing the procedure to use, and defining the permanent permeability test locations in 2009, surface flow tests were repeatedly performed at certain test points. Other points were tested once a year and some tested at the beginning and end of the project only. The porous cells were vacuumed in November 2009, September 2010, May 4th 2011, June 27th 2011, and November 2nd, 2011; on dates as indicated on the graphs by vertical lines. Cell 86 test points at station 16632 and cell 88 test points at station 17084 were regularly monitored for surface permeability (figures 5.7 and 5.8). From the data, it appears that the both loaded and unloaded lanes in both cells at stations 16632 and 17084 have experienced a gradual decrease in permeability since 2009.

The lowest flow measured during any testing event (figure 5.9) has been tracked as a measure of the minimum functionality of the pavement. An increase in the lowest measured flow measured at any test point was evident after the vacuuming on September 2010, May 2011, and November 2011, particularly on the May 4th, 2011 attempt. However the vacuuming did not result in a significant improvement in all cases and has not prevented (but probably is slowing) a long-term decrease in permeability. Since 2009, the lowest measured surface flow in the wheel paths of the inside lane of cell 86 has decreased 61.7%. The lowest measured flow in the wheel paths of the outside lane of cell 86 has decreased 36.6%.

On Cell 88, the results are unexpected. The lowest measured surface flow in the wheel paths of the inside lane of cell 88 has decreased 25.7%. The lowest measured flow in the wheel paths of the outside lane of cell 86 has actually increased – it was 38.2% less in 2009 than what it was when last measured in 2009. It is not known how this occurred but some soil was spilled on the surface of cell 88 during construction, the first lowest test point may have been temporarily clogged.

Rapid clogging on the test sections was not expected due to them having isolation from normal mixed vehicle traffic, no application of deicing sand, and minimal adjacent vegetation or loose soils. However, the most of the sections of the cells have experienced some clogging as of fall 2011, and the clogging seems to be progressing at a fairly constant rate. The cause of the permeability loss is not known at this time. It may be at least partially due to raveled surface particles embedded in the voids. However, the outside lane of cell 86 has also clogged somewhat, indicating that the clogging process is not directly related to the loading process. It should be noted that the current lowest measured flow [1.5cm/sec (0.6 in/sec) in the 6-inch tube] is still much more than adequate to absorb the largest expected rate of any single rain event at MnROAD.

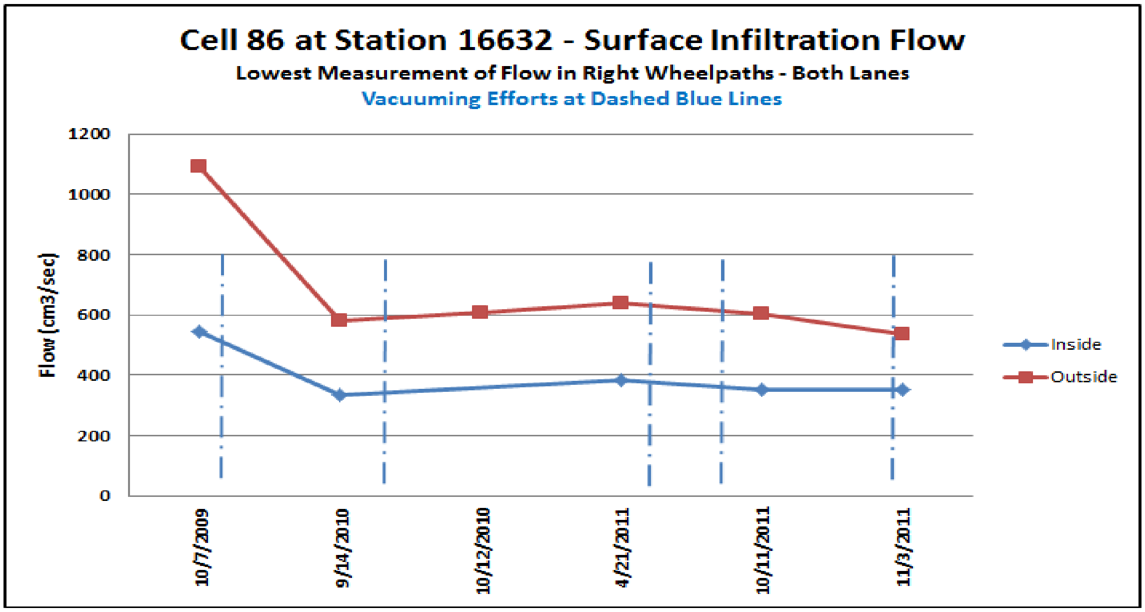


Figure 5.7. Cell 86 surface infiltration flow at station 16632

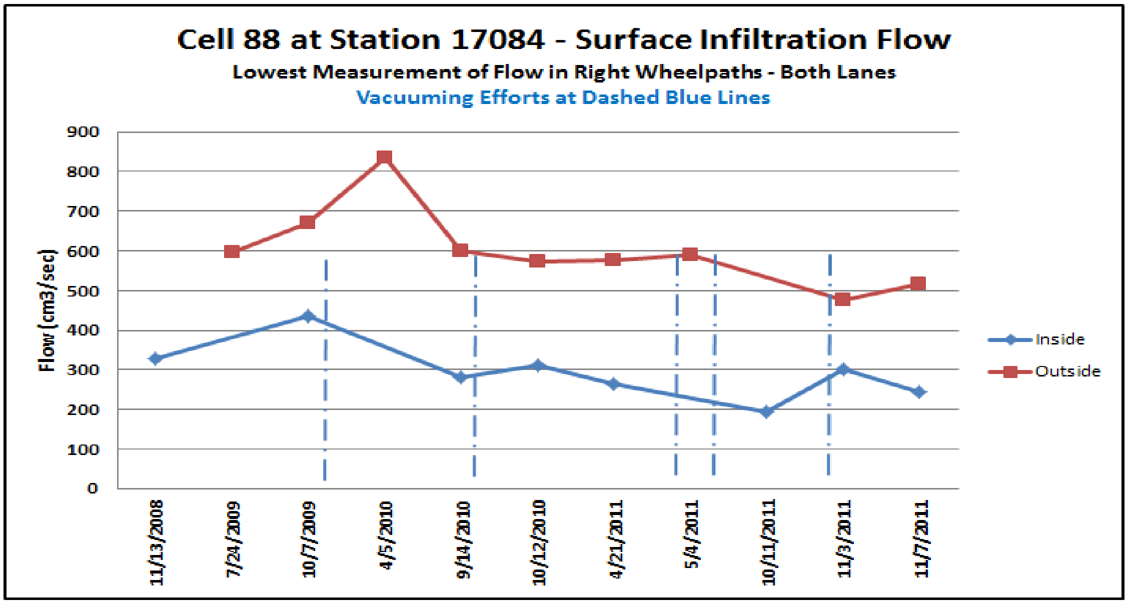


Figure 5.8. Cell 88 surface infiltration flow at station 17084

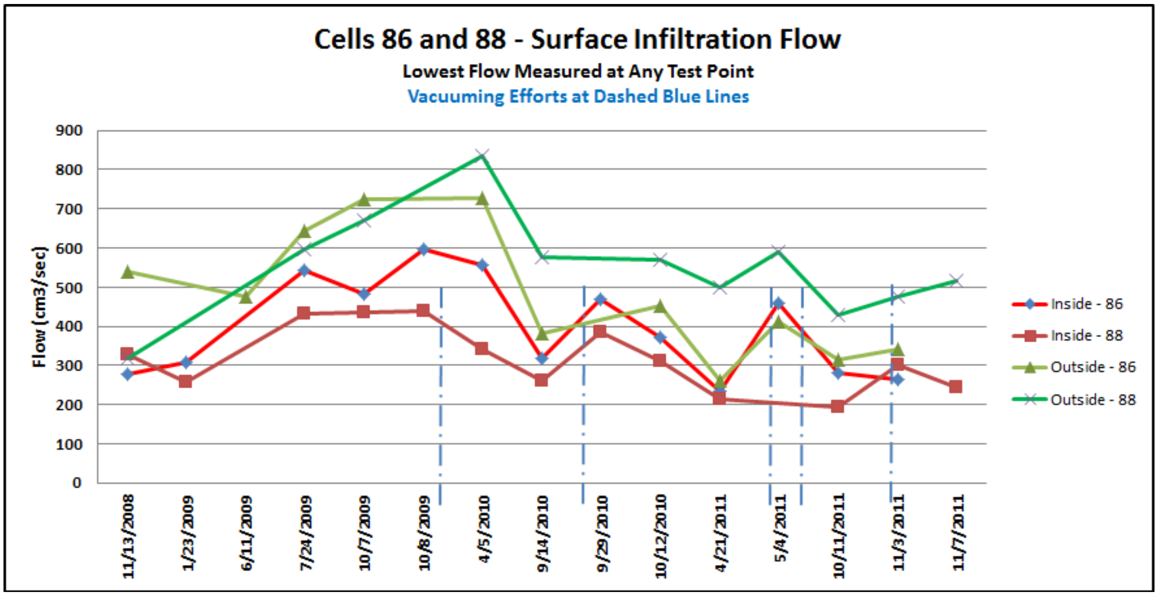


Figure 5.9. Cells 86 and 88 lowest measured flow at any test point

5.4 PERFORMANCE TESTING

5.4.1 Distress Surveys

In early 2009, minor surface raveling was observed on the loaded lane of the porous asphalt test sections. The raveling first appeared in “patches” regularly spaced along the loaded lane of the test sections and was recorded within the initial visual distress survey in January 2009. A photo showing the raveled cell 88 porous asphalt surface in 2009 is shown in figure 5.10. The results of the most recent (October 2011) visual distress survey completed on the porous test cells are attached in Appendix N.

Figure 5.10. Surface raveling, cell 88

Special core testing done in 2009 (Appendix O) showed that the inplace density and voids of the porous asphalt are consistent in both unraveled and raveled areas, and from top to bottom through the pavement. Notably, the air voids measured on these cores was higher than specified – averaging over 23%. The raveling process is difficult to quantify but it appeared to slow somewhat after the first hot days experienced by the pavement in summer 2009. Observations during paving, and analysis of the cored samples did not indicate any binder draindown problems that might have contributed to the raveling. Because the ambient air temperature was low during placement, and the 5-inch lift thickness required a long wait until rolling operations commenced, it is likely that some temperature segregation of the mix occurred. This could have led to localized insufficient compaction that contributed to the surface raveling. The high air voids and improvement after hot weather supports this hypothesis.

While temperature segregation may have been a factor in the initial raveling in “patches”, raveling has progressed on the porous cells to cover much of the loaded lane wheelpaths and small areas of the unloaded lane. The raveling still appears to only affect the top 1 inch (or less) of the pavement. Aggregate particles have been observed to be lost from the surface and deposited on the curbing at a slow, steady rate, and in all seasons.

As of fall 2011, no longitudinal or transverse cracking has been observed anywhere on the porous asphalt test cells. Other than minor raveling and very minor snowplow wear (figure 5.11), no distress is visible in the unloaded (environmental) lane of the porous asphalt test cells. Except for minor surface wear in the loaded wheelpaths, the standard HMA asphalt pavement “control” cell 87 has also not developed any visible cracking, raveling or other distresses to date.

Figure 5.11. Minor snowplow scuffing, cell 86

5.4.2 Rutting Measurements and Pavement Forensic Evaluation

In addition to raveling, pavement rutting has been observed by visible distress surveys and measured with automated data collection methods on porous cells 86/ 88 and also cell 87.

Some rutting is expected given the severity of loading applied to the test sections. Rutting is visible in the wheelpaths of the inside (loaded) lane of each cell, but less so on cell 87. On all cells 86-88, the rutting process appears to be more complicated than what is often observed on a standard dense graded pavement. Figure 5.12 shows the surface of cell 88 (inside lane on the right) in October 2010, with control cell 87 in the background. The porous pavement rutting has been monitored at MnROAD using two different automated methods; "Pathways" Vans and Automated Laser Profiling System (ALPS).

Figure 5.12. Porous cell 88, October 2010

Rutting is measured with the MnDOT Pathways vehicles, by the procedures of ASTM E-950. This vehicle was replaced in 2011 as part of a normal equipment upgrade. The two vans use a similar (but slightly different) laser testing process and the results are usually consistent. [figure 5.13 (old van) and figure 5.14 (new van)]

Figure 5.13. Pathways surface evaluation device, 2009–2010

Figure 5.14. Pathways surface evaluation device, 2011–present

The most recent Pathways rutting measurements were recorded in November 2011. As presented in the Pathways rutting data (figure 5.15) the average measured rutting on the loaded lane of the porous asphalt sections is significant, with current values of approximately 0.45 inches on cell 86, and 0.45 inches on cell 88. Rutting on the loaded lane of the standard pavement on cell 87 is less than 0.15 inch.

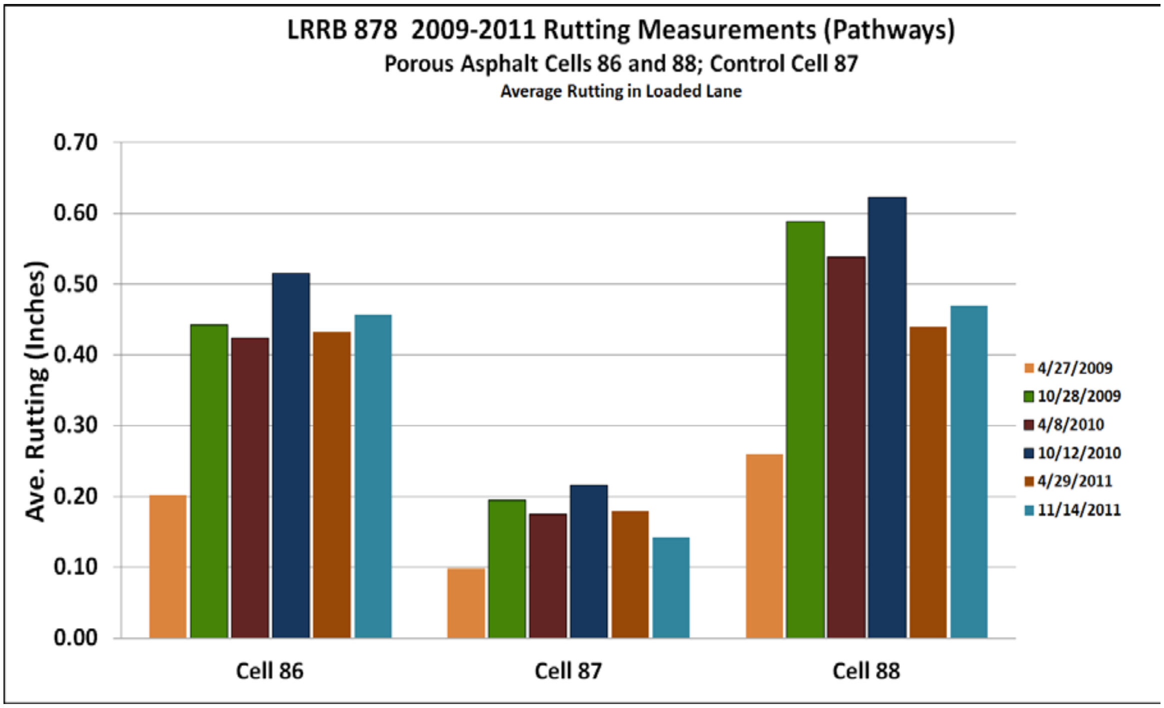


Figure 5.15. Rutting measurements (pathways)

As can be seen from the Pathways data, the measured rutting has not progressed linearly.

Permanent deformation of bituminous pavements usually increases faster during the warmest periods but usually doesn't decline, so a more thorough analysis of the rutting measurements was indicated. The spring and fall measured cross slopes of the surfaces of cells 86-88 were extracted from the Pathways data for comparison. Figures 5.16 and 5.17 show the transverse profile of the same station on cell 88 in spring and fall 2011. The cross slope data shows that the pavements (of all three cells) are experiencing seasonal vertical distortion. The cause could be a combination of the heavy vehicle loading, movement of the open graded base material, and seasonal (frost/moisture) influences. The measured rutting decreased at this location in the fall and the lane profile also changed noticeably. These images also show how the Pathways measurement is made; rutting is measured in the wheelpaths, from a theoretical horizontal line. A pavement experiencing distortion across the entire lane could fall outside normal testing parameters.

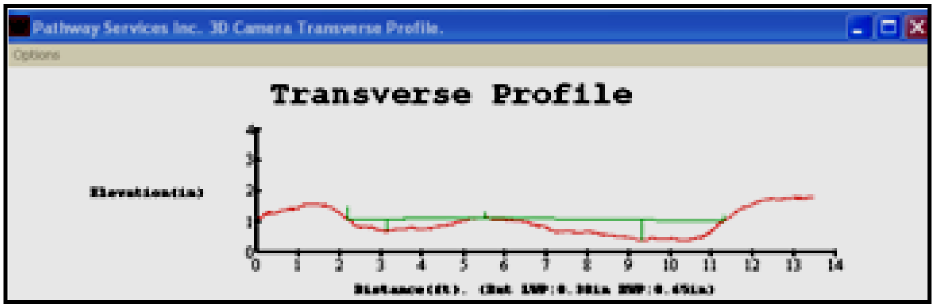


Figure 5.16. Cell 88 spring 2011 transverse surface profile

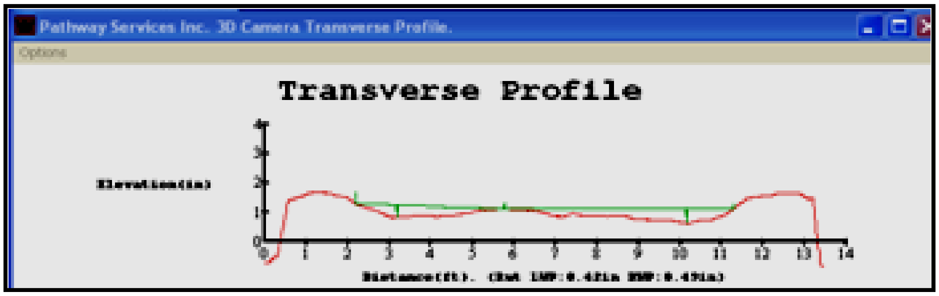


Figure 5.17. Cell 88 fall 2011 transverse surface profile

Rutting is also at MnROAD using the Automated Laser Profiling System (ALPS) shown in figure 5.18. The most recent ALPS rutting measurements were recorded in September 2011. As presented in the ALPS rutting data (figure 5.19) the average measured rutting on the loaded lane of the porous asphalt sections is similar to the Pathways data, with current values of approximately 0.50 inches on cell 86, and 0.60 inches on cell 88. Rutting on the loaded lane of the standard pavement on cell 87 is less than 0.15 inch.

Figure 5.18. Automated laser profiling system (ALPS)

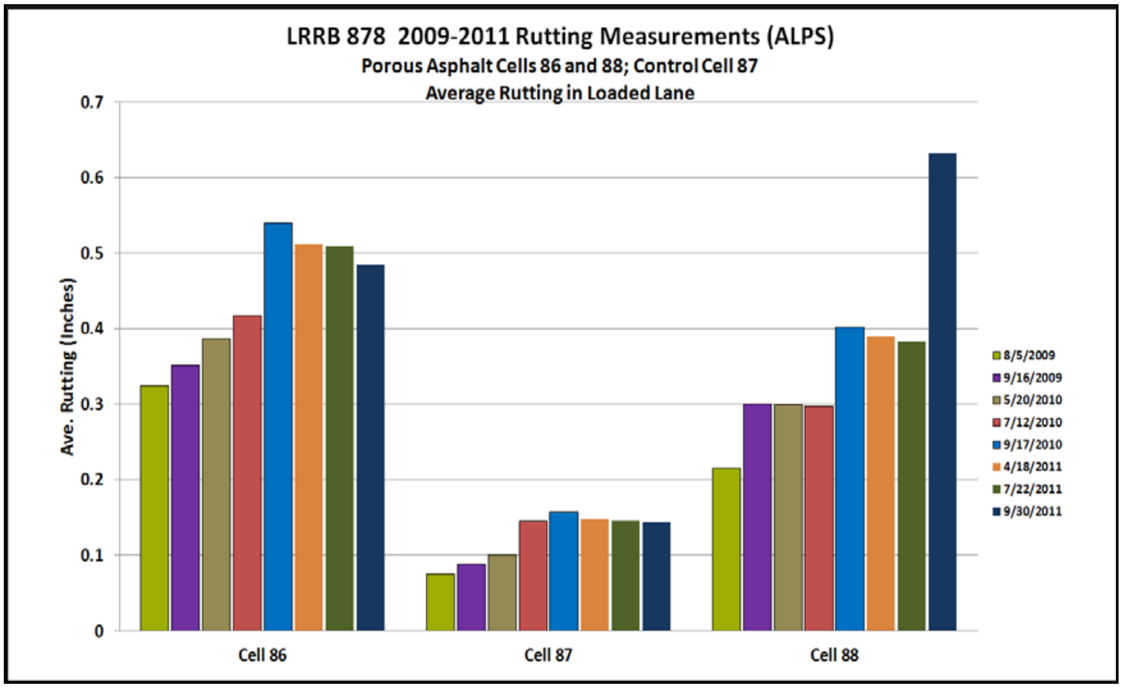


Figure 5.19. Rutting measurements (ALPS)

The ALPS rutting data also appeared unusually non-linear, with some apparent decreasing values. After declining on cell 88 for almost a year, rutting inexplicably increased ¼ inch. MnROAD personnel also noted that the pavements in all cells 86-88 appeared to vertically shift or heave seasonally. A forensic examination of the pavement was performed on cell 88 in October 2011 in order to gain more information about the rutting irregularities and subsurface condition. The pavement was sawcut and removed across the right wheelpath of the loaded (inside) lane, at a location with evident rutting. Figure 5.20 shows the 2 ft. wide by 7 ft. long section of porous pavement removed for forensic evaluation.

Figure 5.20. Forensic pavement section removed

The pavement section that was removed and the surrounding pavement (and base) appeared sound – no top or bottom cracking was visible, but the surface was raveled. A stringline was placed on top of the pavement at the centerline of the LVR and the other end placed on the front edge of curb (figure 5.21.) Measurements were made from the stringline to the pavement surface (and to the bottom of PA) at six-inch intervals; starting 6 ft. from the centerline to the edge of curb 13 ft. from the centerline. The results of the east stringline measurements are summarized in the chart in figure 5.22.

It appears from the data that the entire transverse profile of the lane has settled approximately 1 inch at the center of lane – and is probably negatively influencing the automated rutting measurements. The pavement cross-slope appeared flat after construction; however detailed elevation measurements were not made or tracked on the porous cells. It should be noted that the porous pavement appears to have sufficient flexibility to accommodate the distortion without cracking. The distortion does not appear to be caused primarily by pavement shoving. The cause of the settlement cannot be ascertained without the complete removal of the pavement and base material, which is not immediately planned.

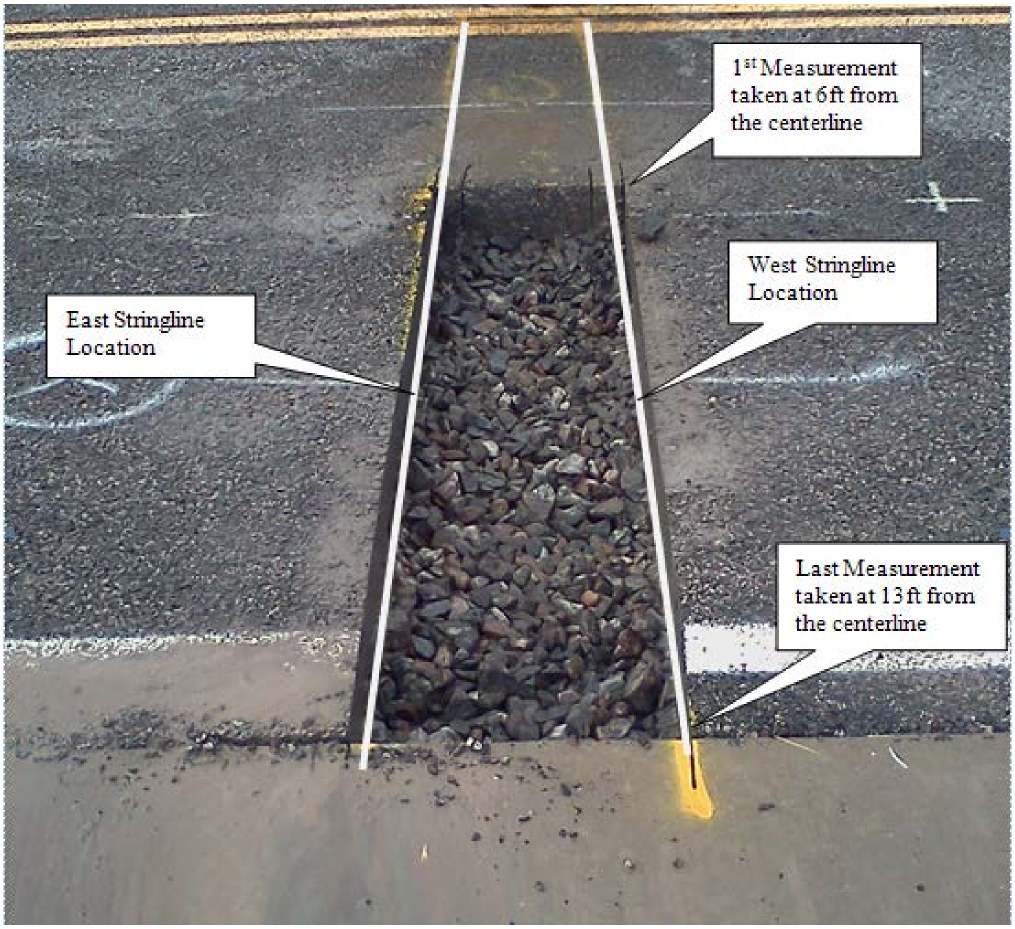


Figure 5.21. Pavement forensic evaluation method

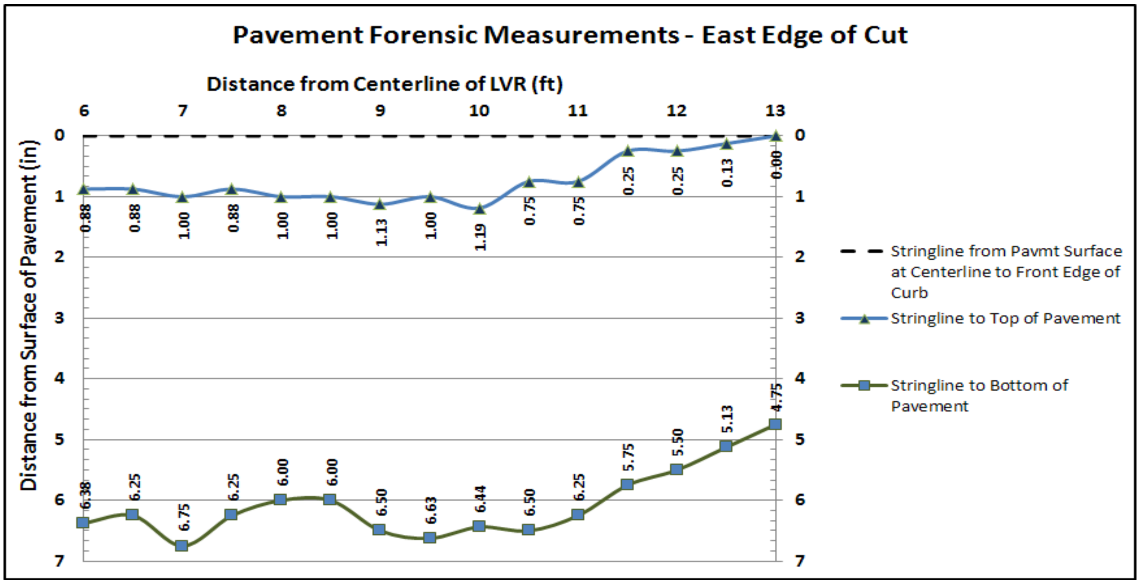


Figure 5.22. Rutting measurements from forensic evaluation

5.4.3 Ride Measurement

The international roughness index (IRI) is used to quantify irregularities of the longitudinal profile of a roadway wheelpath, and is used by MnDOT as a standard roughness measurement (ASTM E-950). The IRI is based on the average rectified slope (ARS), which is a ratio of a standard vehicle's accumulated suspension motion, divided by the distance traveled by the vehicle during the measurement. The IRI has been regularly measured since 2009 for the porous asphalt cells and cell 87 with the Lightweight Interval Surface Analyzer (LISA) (Figure 5.23).

Figure 5.23. Lightweight interval surface analyzer (LISA)

The initial roughness on these test sections is higher than expected for normal new road construction due to the special requirements for test-cell construction practices on the relatively short (226 foot) MnROAD cells. As can be seen from the charted IRI data (figures 5.24 and 5.25), longitudinal roughness on each cell has changed very little since construction, but it did increase somewhat faster in 2011. On the inside lane of cells 86, 87 and 88, IRI has increased approximately 20% - on cell 88 it is approaching 200 in/mi. On the outside lanes cells 86 and 87 have remained flat but cell 88 has increased approximately 15%,

Cell 87 IRI has consistently demonstrated the least roughness of the three cells. Cell 88 consistently has a somewhat higher IRI than cell 86. As previously described in the construction report, rolling operations began on cell 88 and roller marks may have contributed to initial roughness there.

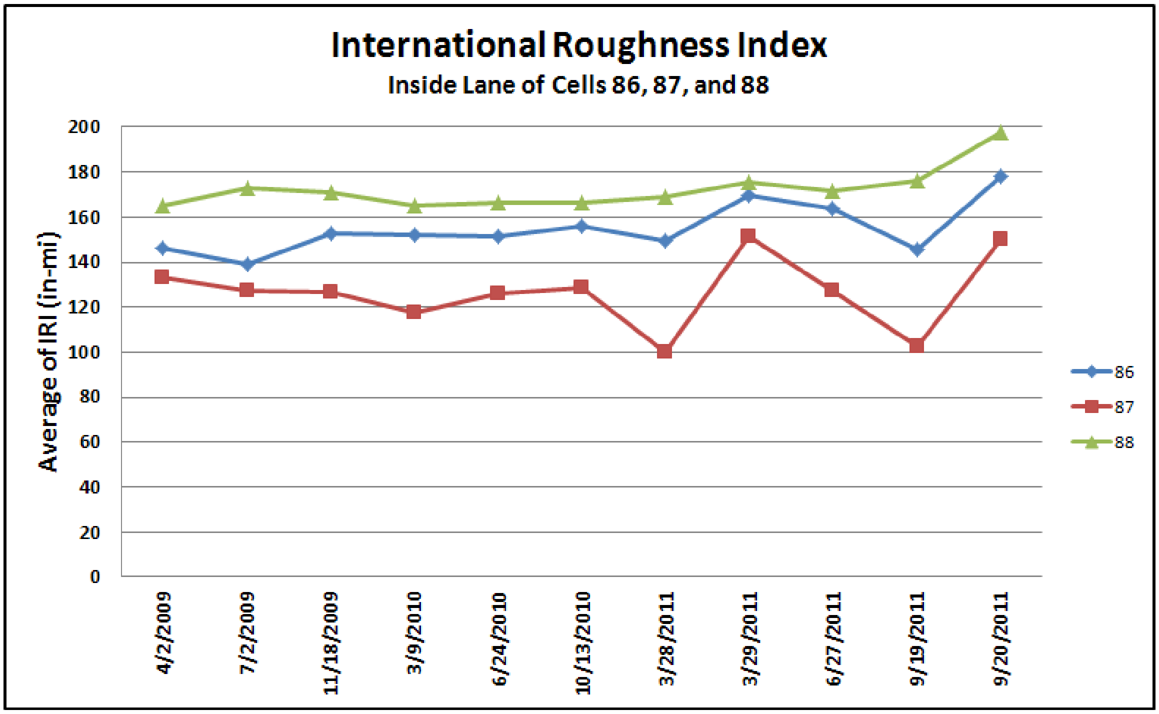


Figure 5.24. International roughness index (IRI) inside lane

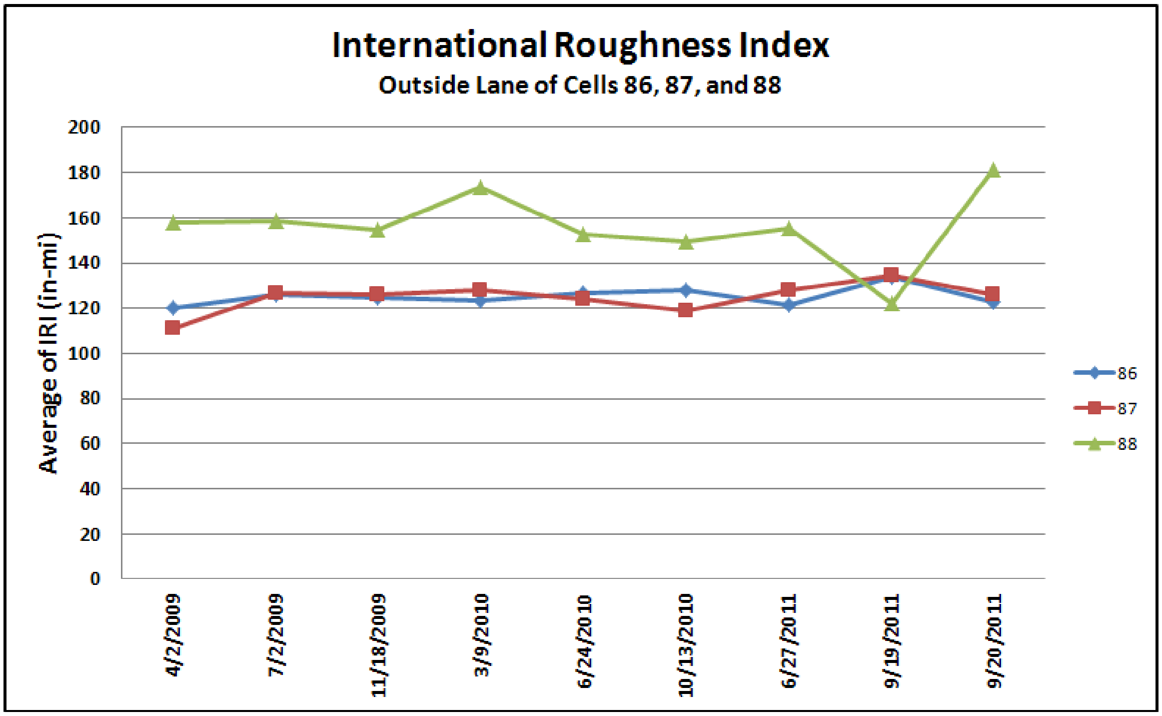


Figure 5.25. International roughness index (IRI) outside lane

5.4.4 Falling Weight Deflectometer Testing

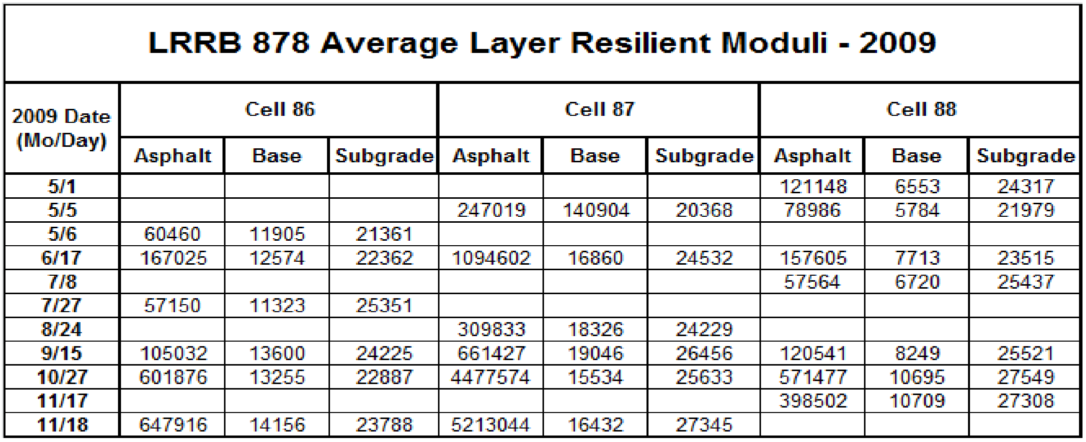
The Falling Weight Deflectometer (FWD) is a non-destructive testing device that applies dynamic loads to the pavement surface, simulating a single heavy wheel load. The response of the pavement system is measured in terms of deflection over a given area. The “deflection basin” caused by the controlled loading, combined with layer thickness information, can be used to calculate the in-situ resilient elastic moduli (stiffness) of a pavement structure. The results can then be used to estimate remaining life, determine the bearing capacity, and suggest rehabilitation strategies over a design period.

Falling Weight Deflectometer (FWD) data was collected on cells 86 through 88 on multiple dates in 2009 through 2011. Testing is not always performed on the same day for all three cells due to staffing and equipment requirements, but an effort is made to regularly test all cells to monitor seasonal changes in stiffness. The data was collected during the spring, summer, and fall of 2009, 2010, and 2011. This allowed for the calculation of layer moduli values over wide ranges of subsurface moisture and pavement temperature. These two variables have a major influence on the stiffness of the unbound (base & subgrade) and bound (asphalt) materials. A trailer mounted FWD testing vehicle used at MnROAD is shown in figure 5.26.

Figure 5.26. MnDOT FWD testing vehicle

The FWD data was analyzed using ELMOD software. Reasonable resilient moduli values for the pavement, base and subgrade on cells 86, 87, and 88 were obtained. The summary of the back-calculated 2009 moduli values is shown in table 5.3. The 2010 moduli values are shown in table 5.4, the 2011 values are shown in table 5.5. The back-calculated moduli for each lane and wheel paths of all cells 86 through 88 are contained in Appendix P.

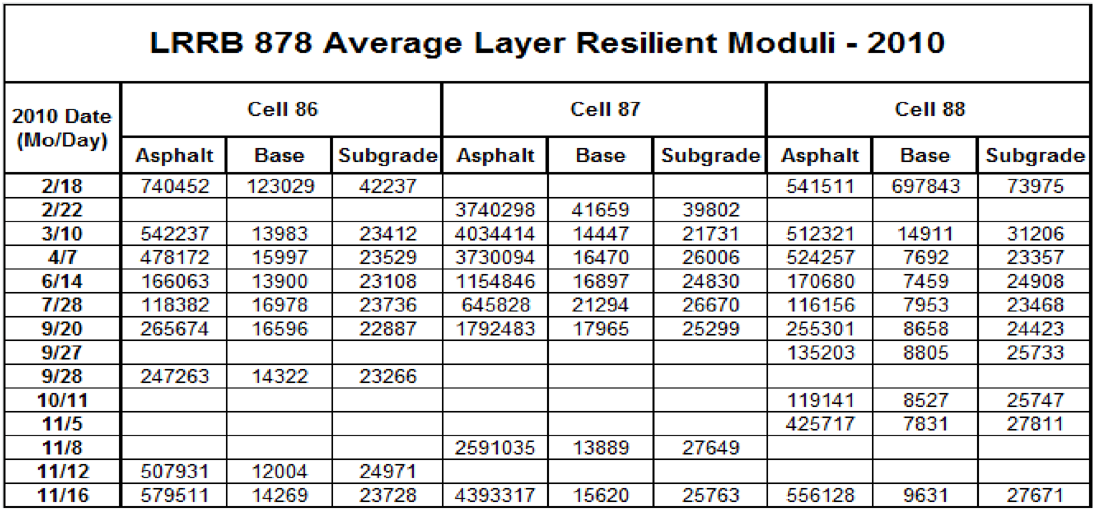
Table 5.3. Average back-calculated resilient moduli, 2009



LRRB 878 Average Layer Resilient Moduli - 2009

2009 Date (Mo/Day)	Cell 86			Cell 87			Cell 88		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
5/1							121148	6553	24317
5/5				247019	140904	20368	78986	5784	21979
5/6	60460	11905	21361						
6/17	167025	12574	22362	1094602	16860	24532	157605	7713	23515
7/8							57564	6720	25437
7/27	57150	11323	25351						
8/24				309833	18326	24229			
9/15	105032	13600	24225	661427	19046	26456	120541	8249	25521
10/27	601876	13255	22887	4477574	15534	25633	571477	10695	27549
11/17							398502	10709	27308
11/18	647916	14156	23788	5213044	16432	27345			

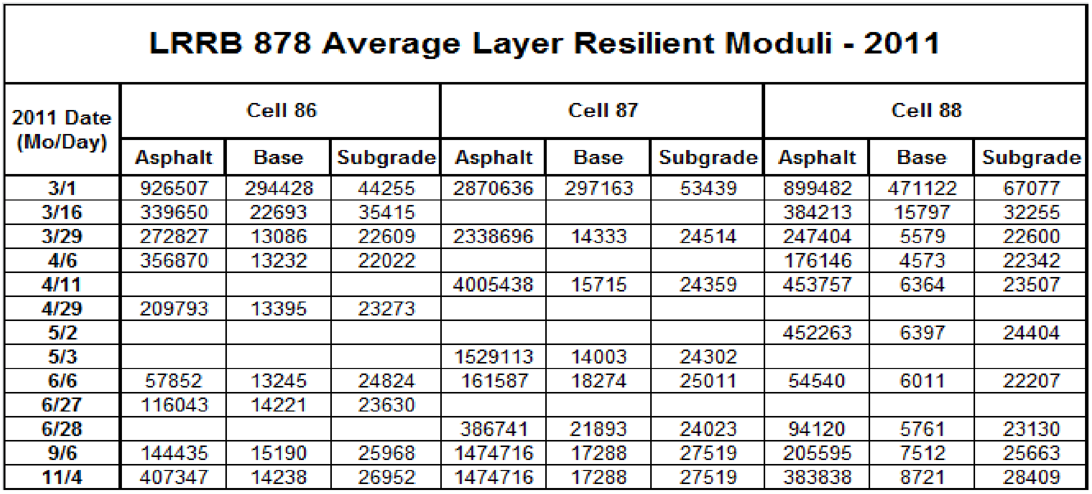
Table 5.4. Average back-calculated resilient moduli, 2010



LRRB 878 Average Layer Resilient Moduli - 2010

2010 Date (Mo/Day)	Cell 86			Cell 87			Cell 88		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
2/18	740452	123029	42237				541511	697843	73975
2/22				3740298	41659	39802			
3/10	542237	13983	23412	4034414	14447	21731	512321	14911	31206
4/7	478172	15997	23529	3730094	16470	26006	524257	7692	23357
6/14	166063	13900	23108	1154846	16897	24830	170680	7459	24908
7/28	118382	16978	23736	645828	21294	26670	116156	7953	23468
9/20	265674	16596	22887	1792483	17965	25299	255301	8658	24423
9/27							135203	8805	25733
9/28	247263	14322	23266						
10/11							119141	8527	25747
11/5							425717	7831	27811
11/8				2591035	13889	27649			
11/12	507931	12004	24971						
11/16	579511	14269	23728	4393317	15620	25763	556128	9631	27671

Table 5.5. Average back-calculated resilient moduli, 2011



LRRB 878 Average Layer Resilient Moduli - 2011

2011 Date (Mo/Day)	Cell 86			Cell 87			Cell 88		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
3/1	926507	294428	44255	2870636	297163	53439	899482	471122	67077
3/16	339650	22693	35415				384213	15797	32255
3/29	272827	13086	22609	2338696	14333	24514	247404	5579	22600
4/6	356870	13232	22022				176146	4573	22342
4/11				4005438	15715	24359	453757	6364	23507
4/29	209793	13395	23273						
5/2							452263	6397	24404
5/3				1529113	14003	24302			
6/6	57852	13245	24824	161587	18274	25011	54540	6011	22207
6/27	116043	14221	23630						
6/28				386741	21893	24023	94120	5761	23130
9/6	144435	15190	25968	1474716	17288	27519	205595	7512	25663
11/4	407347	14238	26952	1474716	17288	27519	383838	8721	28409

As presented in the summary data and figures 5.27 through 5.29, the average resilient modulus of cell 87 (dense-graded) asphalt containing the PG 58-28 binder remains considerably higher than the porous asphalt containing the PG 70-28 binder (cells 86 and 88). This difference remains throughout the range of pavement surface temperatures but is least pronounced during midsummer. The higher stiffness of the dense-graded asphalt on Cell 87 is expected. However it was unexpected that both porous asphalt cells experienced moduli of less than 60000 psi during the hottest summer months.

It is also observed in this data that the porous asphalt seems to develop increased stiffness later in the fall than cell 87 HMA. Additionally, in the spring of 2010, it appears that the porous asphalt reduced stiffness earlier than cell 87 HMA; suggesting an earlier thawing of the pavement/base structure, as observed previously in MnROAD pervious pavements [40].

The moduli of both the porous asphalt cells and cell 87 are charted versus temperature at mid-depth in figure 5.30. It can be observed that the porous asphalt moduli seem to have a more direct relationship to internal pavement temperatures than the cell 87 pavement. Although the overall stiffness of the porous asphalt is markedly lower, it apparently has been adequate to support the extensive loading without extreme deformation. Additionally, the reduced stiffness of the porous pavement is probably an important factor in the lack of cracking observed to-date.

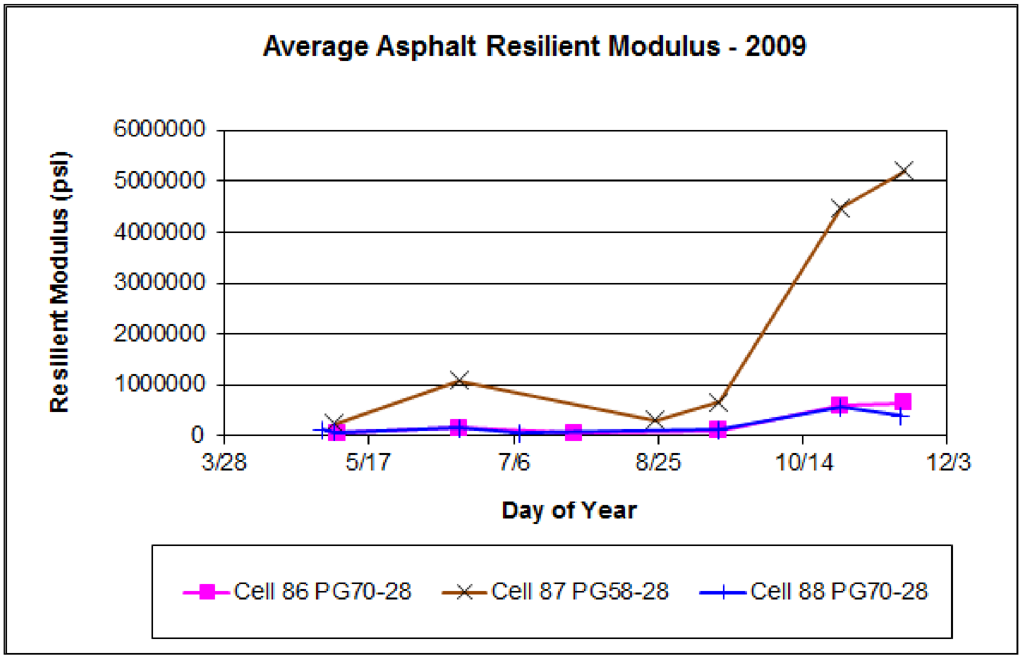


Figure 5.27. Average back-calculated asphalt pavement resilient moduli, 2009

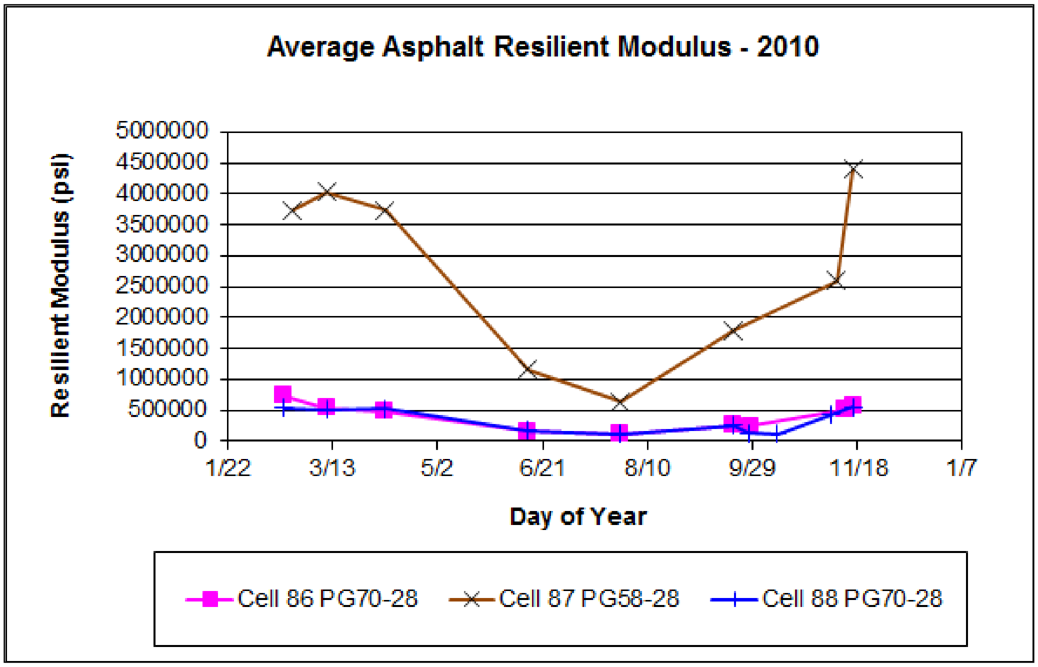


Figure 5.28. Average back-calculated asphalt pavement resilient moduli, 2010

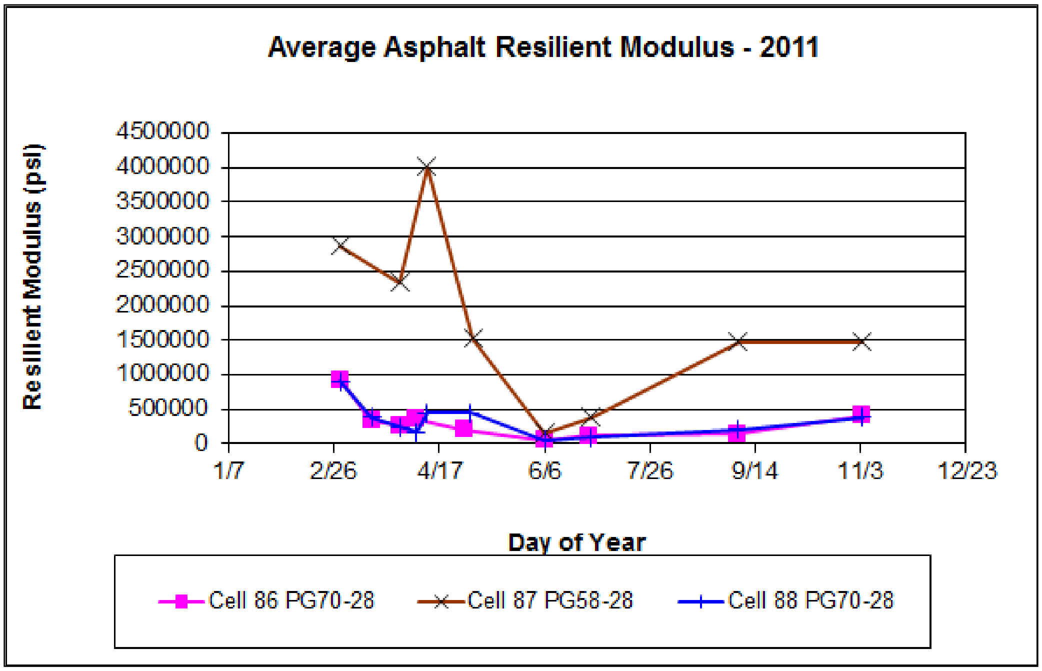


Figure 5.29. Average back-calculated asphalt pavement resilient moduli, 2011

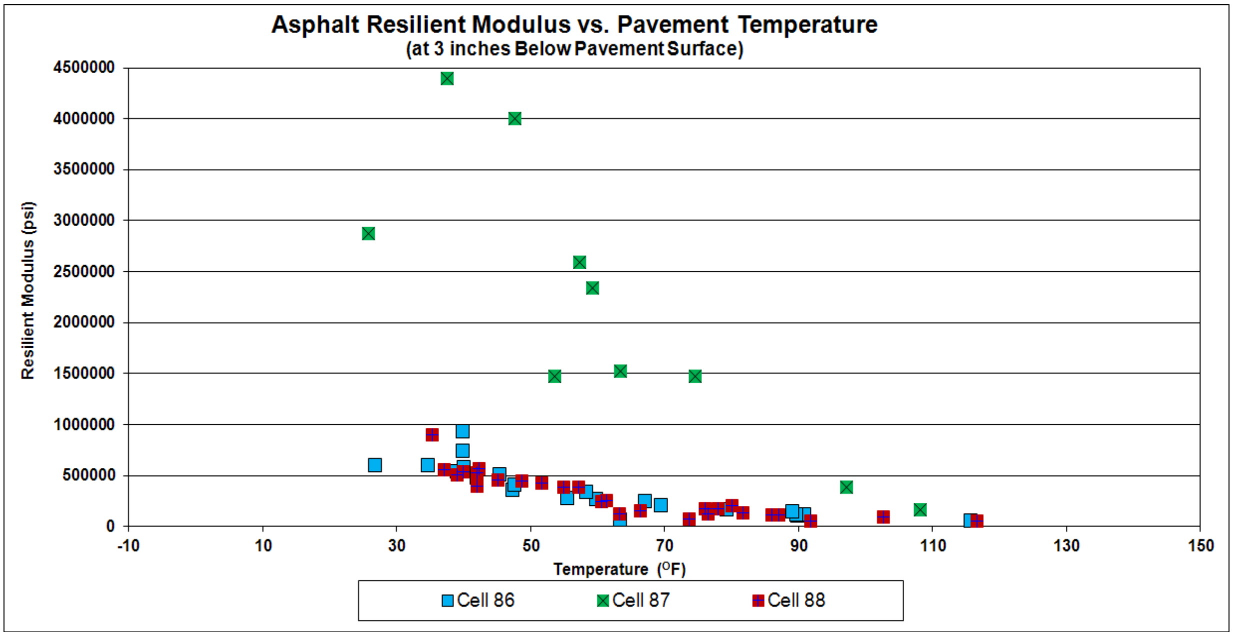


Figure 5.30. Porous asphalt resilient moduli versus temperature 2009-2011

An analysis of the base material moduli (figures 5.31 through 5.33) indicates that the base in cell 88 (above the clay subgrade) has consistently less stiffness than in cell 86 (above the sand subgrade). As the pavement and base materials are identical in cells 86 and 88, the data suggests that the clay subgrade is having a negative effect on the base stiffness. This could be caused by less effective drainage in cell 88; also, the moisture in the base could remain higher, and for longer periods after rain events. It is also possible the clay particles may be clogging the geotextile fabric at the bottom of the base, and the clay could be providing less support to the bottom of the base. The data suggests additional forensic testing may be beneficial after the project is complete.

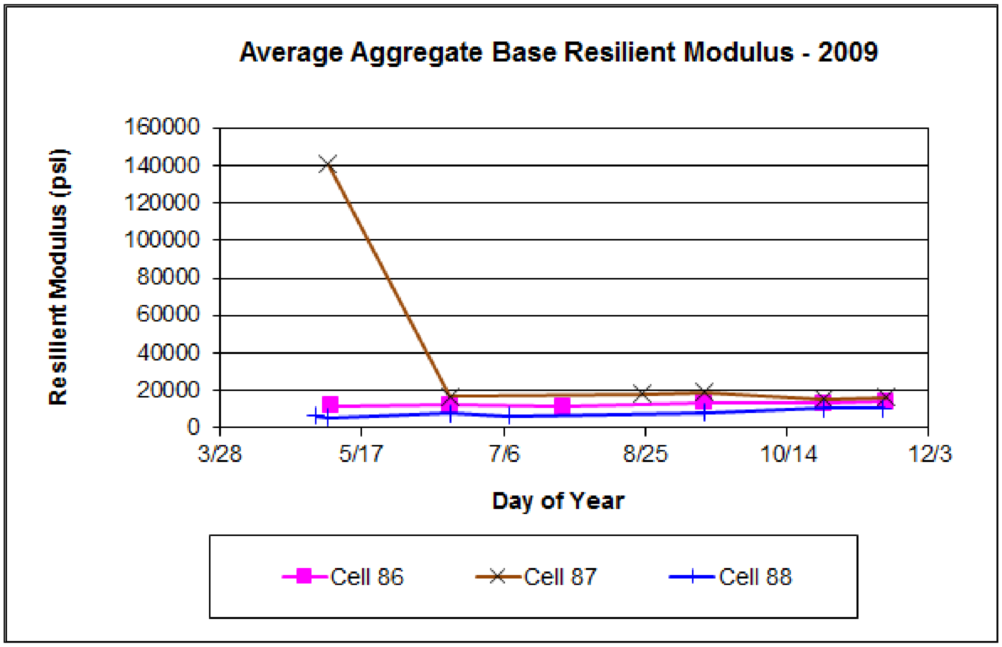


Figure 5.31. Average back-calculated base resilient moduli, 2009

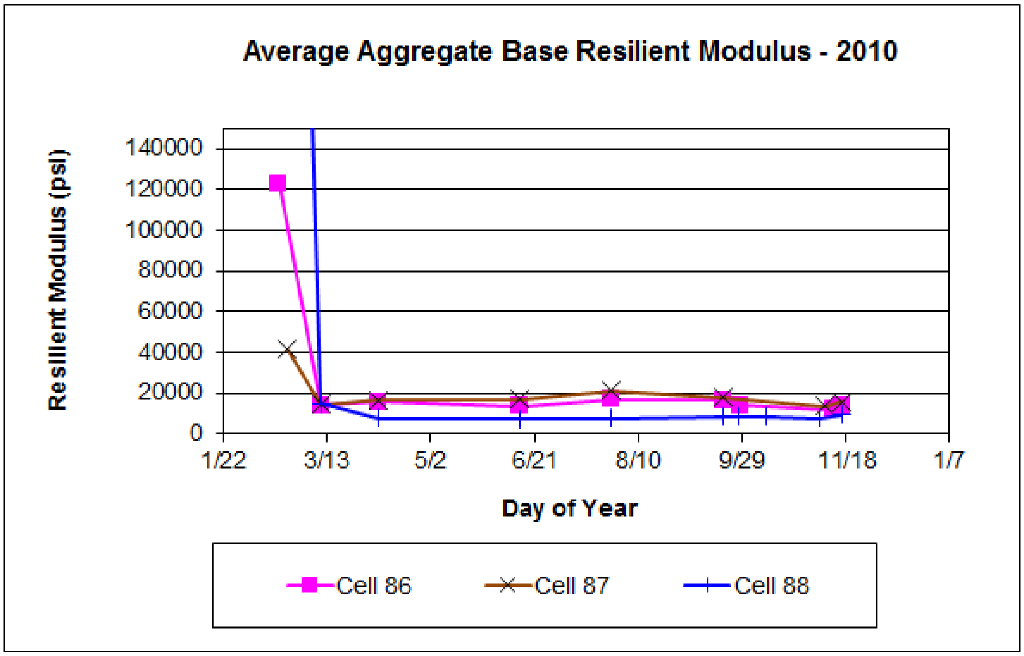


Figure 5.32. Average back-calculated base resilient moduli, 2010

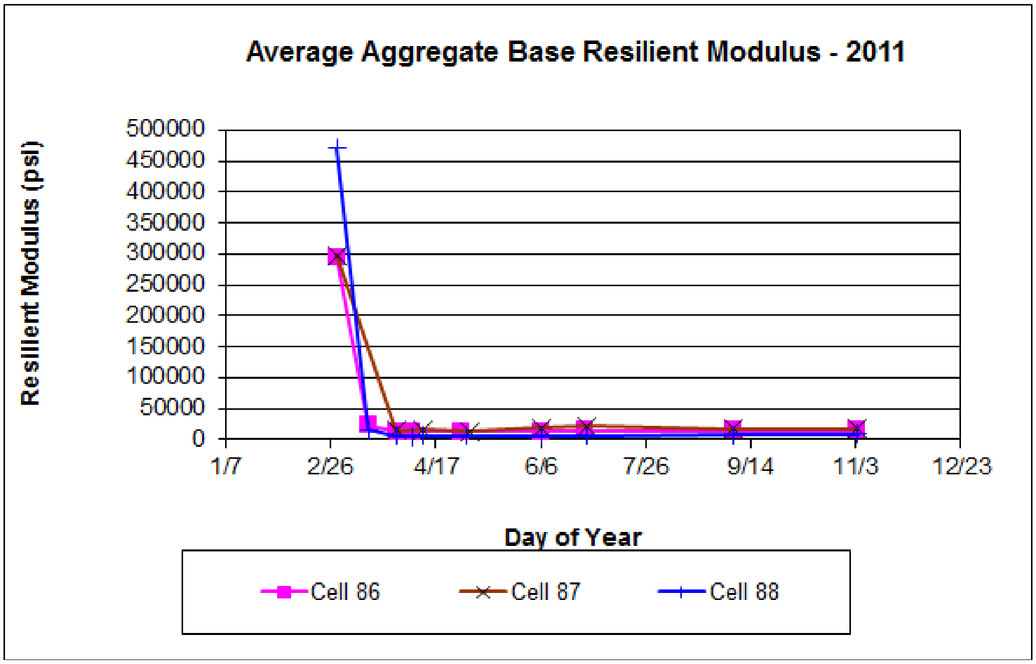


Figure 5.33. Average back-calculated base resilient moduli, 2011

The subgrade modulus data appears generally as expected (figures 5.34 through 5.35). The sand subgrade in cell 86 is similar in stiffness to the clay in spring and summer. The clay subgrade gains higher stiffness in late fall and winter, when the clay would benefit more from the drier conditions, and, if frozen, solidify better than sand. As expected, the subgrade stiffness in cell 87, which is the subgrade transition area from sand to clay, generally falls in a range between cells 86 and 88, but has exceeded them at times – possibly due to being dryer.

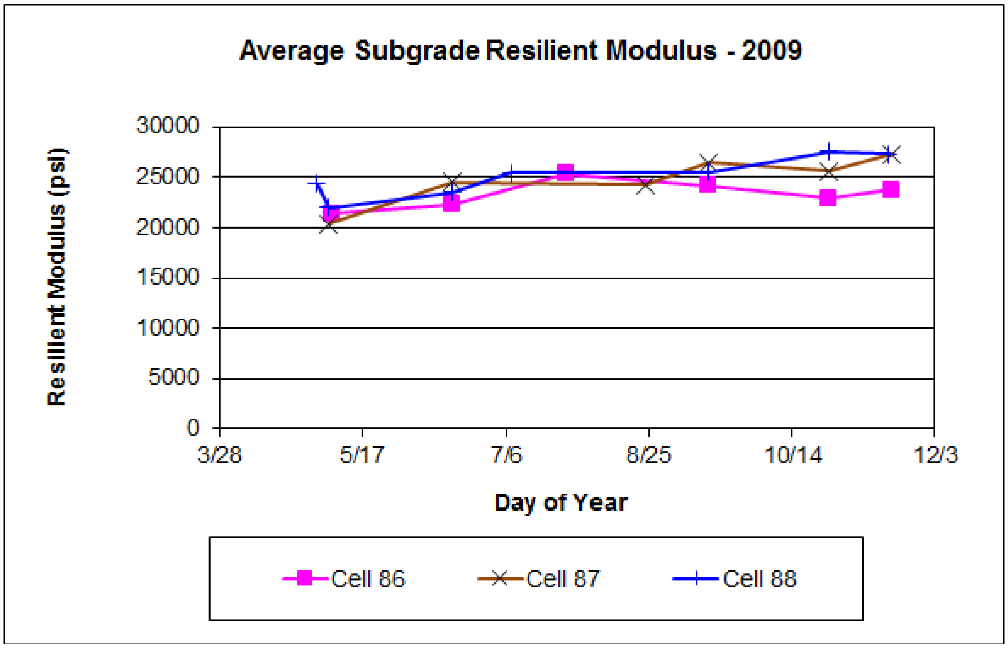


Figure 5.34. Average back-calculated subgrade resilient moduli, 2009

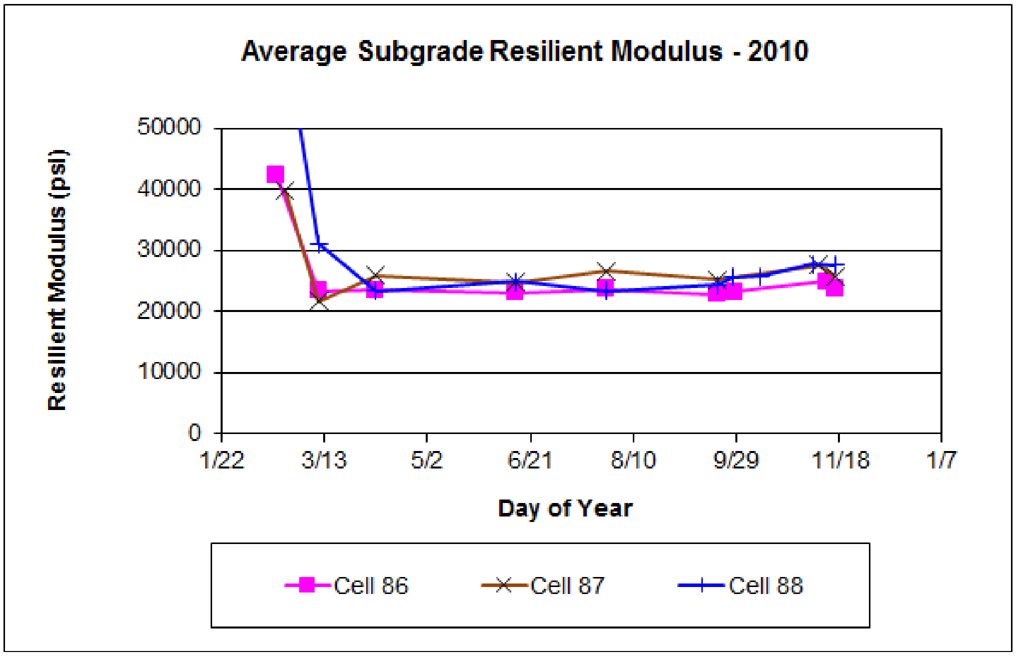


Figure 5.35. Average back-calculated subgrade resilient moduli, 2010

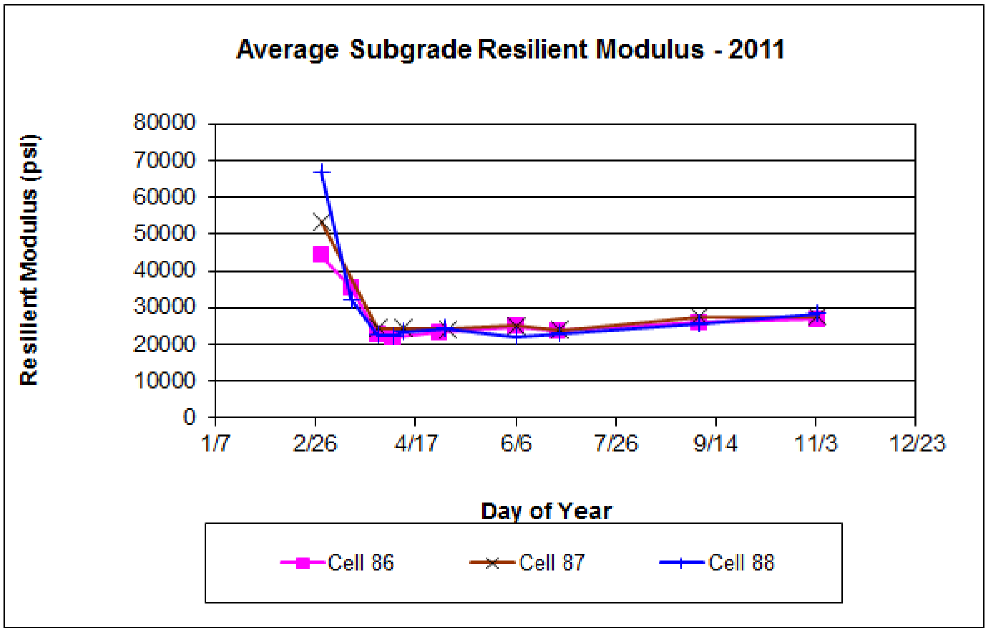


Figure 5.36. Average back-calculated subgrade resilient moduli, 2011

The base and subgrade moduli at both ends of cell 87 were graphed (figures 5.37 and 5.38) in order to corroborate the results. Cell 87 does not experience the effects of water filtering through the porous pavement, and has similar, although slightly higher, base and subgrade stiffness values. The data confirms that the base material above the clay remains considerably less stiff, except in cooler, drier periods. More detailed FWD backcalculation results, for each cell and each lane, are contained in Appendix P.

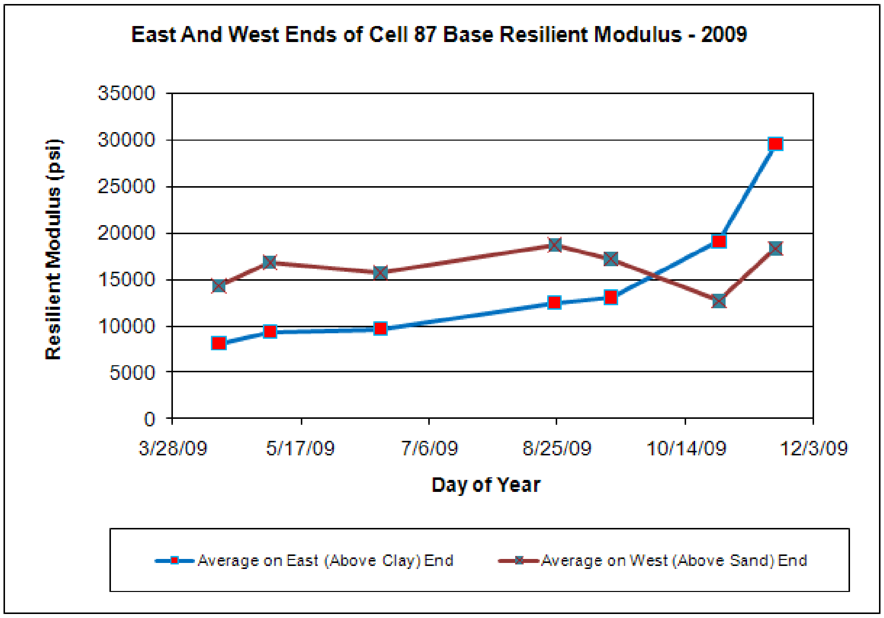


Figure 5.37. Cell 87 base resilient moduli at cell ends

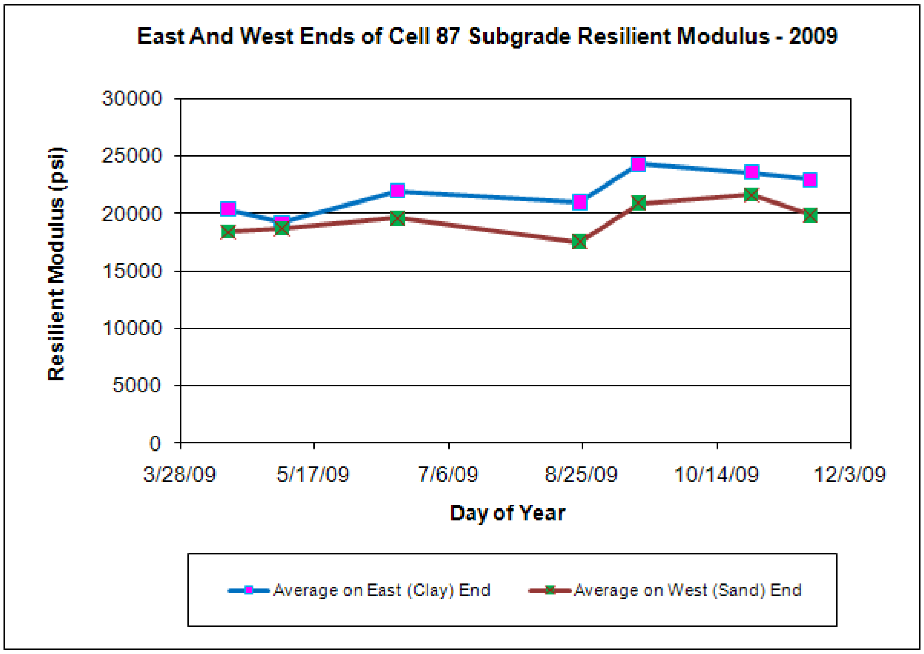


Figure 5.38. Cell 87 subgrade resilient moduli at cell ends

5.4.5 Pavement Strain

Dynamic load testing was performed on MnROAD cells 23, 86, and 88 in 2011 to assist in quantifying differences in pavement strain responses between the conventional, dense-graded asphalt pavement and porous asphalt pavement. This testing usually consists of activating pavement strain sensors with the MnROAD loading vehicle and recording the responses. The vehicle tests consist of "high speed" (40 mph) and "low speed" (5 mph) runs with the MnROAD loading vehicle. The loading vehicle weighs 80,000 lbs. (Minnesota highway legal limit) for this test – the same configuration used for regular daily LVR loading.

Because there are no strain gauge-instrumented cells located in the LVR that would provide a good comparison (including cell 87), MnROAD mainline cell 23 was selected for comparison with porous cells 86 and 88. Cell 23 was constructed with 5 inches of dense-graded asphalt pavement over a 12-inch, open-graded railroad ballast base. Due to the volume of testing and time restraints, testing is usually conducted on separate days, with somewhat different environmental conditions. In order to eliminate (or at least significantly reduce) these variations, special accommodations were made and testing was conducted on all cells on April 18th, 2011.

Strain gauges are oriented in the longitudinal (same direction as traffic) and transverse directions, to measure horizontal strain (X and Y) strain at the bottom of the asphalt layer. Peak-Pick software was used to determine the maximum strain responses and produce time series plots of the dynamic load test data. The program finds the maximum strain associated with each axle that passes over a strain gauge. One pass of the MnROAD truck (figure 5.1) produces five “peaks” or measurements - one for each axle. For this analysis, ten passes, five at high speed, five at low speed, were made on cells 23, 86, and 88. Unfortunately, strain gauges oriented in the longitudinal direction in cell 23 were not operating properly, and thus a direct comparison of longitudinal strain in cells 23 and 86/88 could not be made. Also of note, strain gauges oriented in the transverse direction in cell 88 were not working properly, and transverse gauges for cell 86 only reported several measurements. Hence, a full comparison of strain in all directions amongst all the three cells under consideration was not possible. Nevertheless, some meaningful comparisons were made.

Strain response charts for longitudinal strain in cells 86 and 88 at high (figure 5.39) and low speeds (figure 5.40) were created to illustrate the responses associated with each axle of five passes over the sensors (note that scales are identical). The distinction between axles was made because the axles do not apply equal loads.

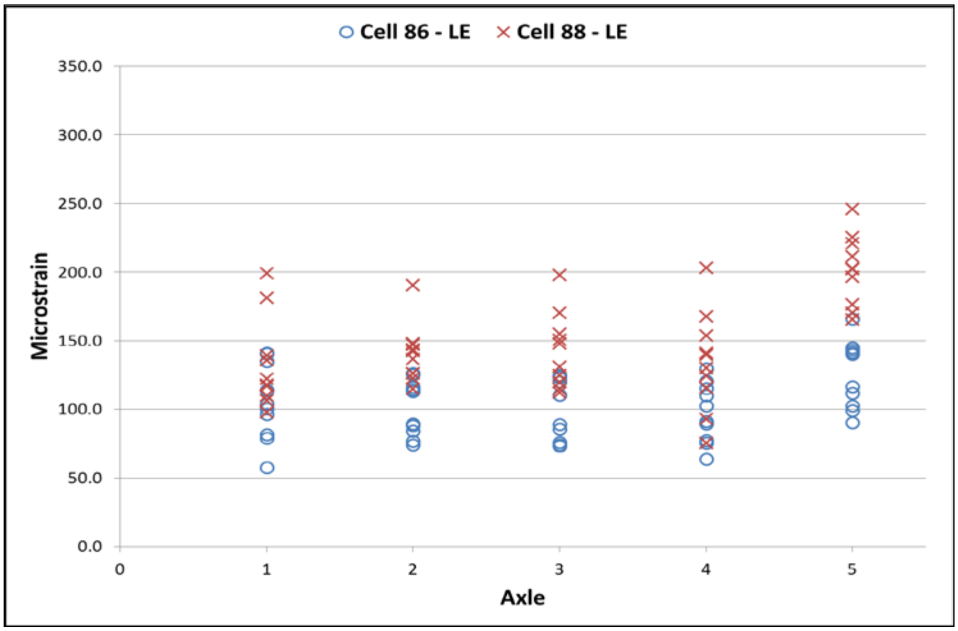


Figure 5.39. Longitudinal strain response in cells 86 and 88, high speed testing

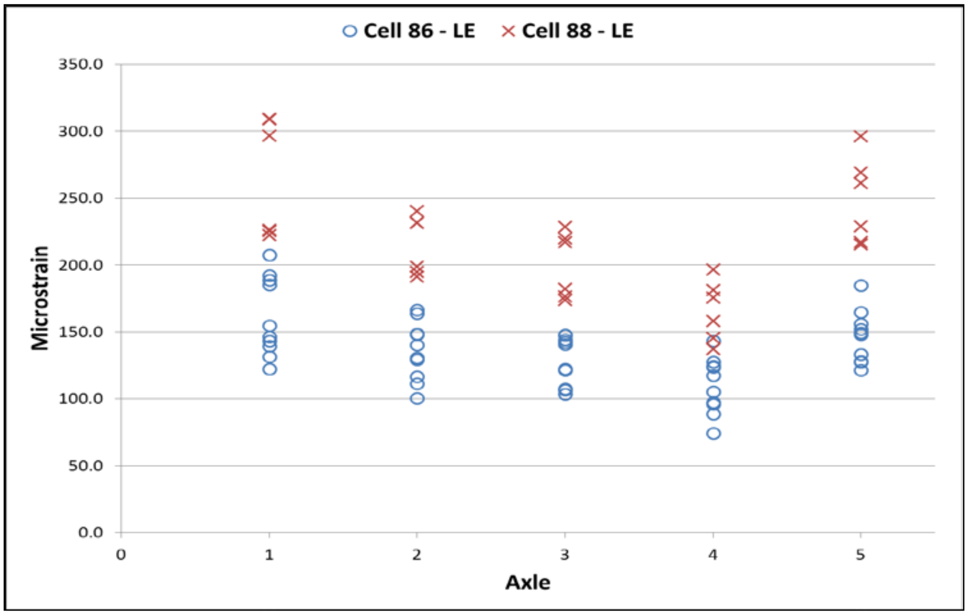


Figure 5.40. Longitudinal strain response in cells 86 and 88, low speed testing

Figures 5.39 and 5.40 show that the longitudinal strain responses in the porous pavements were markedly higher for the porous section built over a clay subgrade (cell 88). It is noted that this behavior was consistent at both high and low speeds, with higher responses in both cells occurring during low speed testing. Asphalt mixtures are viscous materials, therefore strain can be higher at low speeds as the loading time is longer than when high speed loading. Wheel wander and small fluctuations in speed between runs are responsible for the variations recorded on different passes.

Transverse strain measurements from cell 23 and 86 (cell 88 transverse sensors were not functioning) are presented in figures 5.41 (high speed) and 5.42 (low speed).

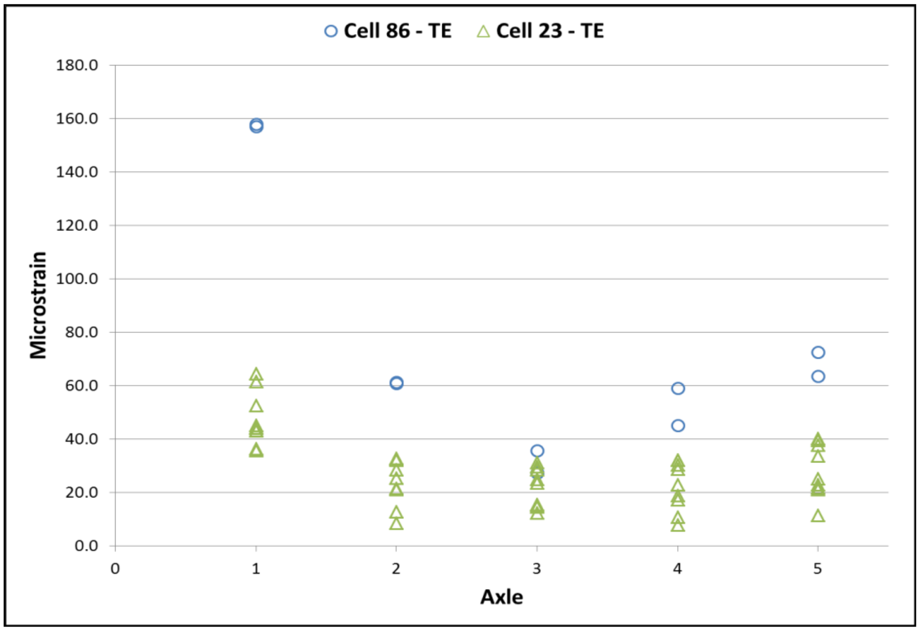


Figure 5.41. Transverse strain response in cells 23 and 86, high speed testing

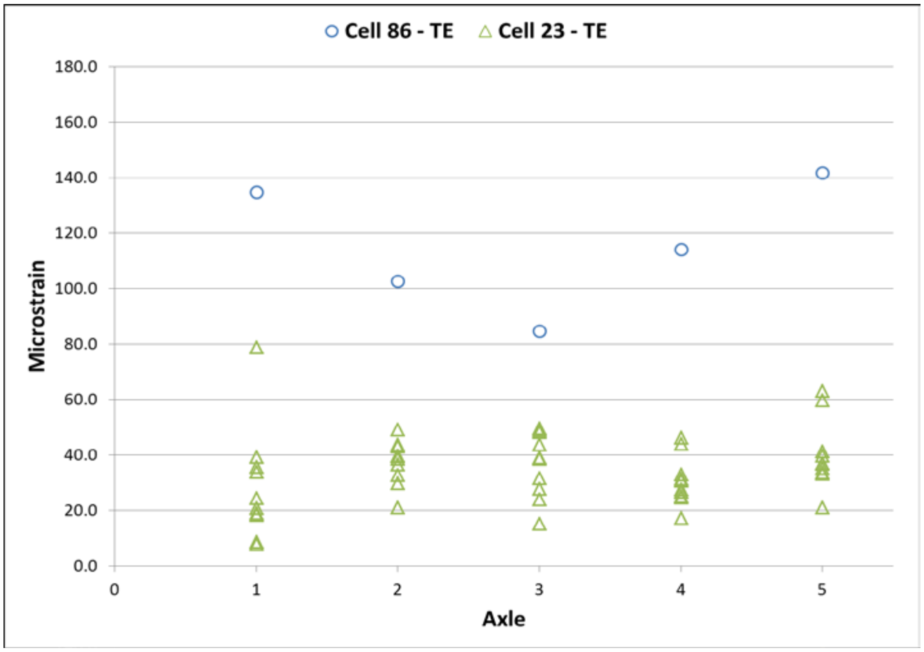


Figure 5.42. Transverse strain response in cells 23 and 86, low speed testing

Figures 5.41 and 5.42 indicate that transverse strains at the bottom of the porous asphalt section on top of a sand subgrade were greater than those at the bottom of a comparable dense-graded section. Because the transverse sensors in cell 88 were not operating properly, exact values of transverse strain at the bottom of cell 88 (clay subgrade) is unknown. However, the researchers suspect that transverse strain values from cell 88 would follow a similar pattern, i.e. higher transverse strain values than cell 23, and in all likelihood higher than cell 86 also (given that longitudinal strain was distinctly higher in 88 than 86).

Tensile strains in the horizontal directions at the bottom of a typical dense graded asphalt layer are responsible for bottom-up fatigue cracking. However, the fatigue resistance of the less stiff porous asphalt could be offsetting the higher strains it is experiencing, so it is not possible to predict cracking with the available strain data. At the time of this writing, no cracking is present in either porous asphalt section; however the cells will continue to be monitored for distress until they are removed.

5.5 SURFACE CHARACTERISTICS

5.5.1 On-Board Sound Intensity (OBSI)

On-board sound intensity (OBSI) is a near-field method that measures the sound intensity caused by Tire-Pavement Interaction Noise (TPIN). The MnROAD equipment consists of a 2004 Chevrolet Impala, a Standard Reference Test Tire (SRTT), a mounting apparatus, intensity meters connected via communication cables to a Brüel & Kjær front-end collector, and a laptop computer.

OBSI measurements report a decibel value for the TPIN as recorded by a set of microphones positioned near the tire (figure 5.43). The sound is recorded for five seconds while the vehicle is traveling at a constant speed of 60 miles per hour, thus averaging the OBSI over a 440 foot section. The data is later parsed to separate out the porous asphalt readings.

The OBSI is measured at MnROAD according to AASHTO TP 76-08. The test is performed at 60 mph because freeway speeds are typically above the crossover speeds for all vehicle types, where the tire pavement noise is the dominant traffic noise source, much higher than the aerodynamic source and the stack source [41]. OBSI was measured on both porous asphalt cells in 2009, 2010, and 2011.

Figure 5.43. MnDOT on-board sound intensity microphones

Figures 5.44 and 5.45 show the charted sound intensity (dBA) data of both the inside and the outside lanes of both porous asphalt cells. As expected, the porous/pervious sections are relatively quiet pavements; for comparison, the OBSI-measured sound intensity of MnROAD cell 40 on the LVR (transverse-tined concrete pavement) registered greater than 103.5 dBA.

The sound intensity decreases somewhat during warmer periods, possibly due to softening of the asphalt or higher moisture in the pavement voids. After 2 years of non-increasing measured values, a slight uptick is evident in 2011 – in both cells and in both lanes.

Research performed under LRRB INV 879 (Pervious Concrete) showed a correlation between pavement clogging and an increase in sound intensity [42]. The recent increase in measured OBSI likely corresponds to the minor clogging taking place. As clogging progresses on the porous cells, OBSI will continue to be monitored and is expected to increase as sound absorption decreases.

Figure 5.46 is a summary of OBSI runs on the south side of the LVR, measured in 2009. It can be seen from the chart that the porous cells produce the lowest on-board sound intensity on the MnROAD LVR – with values similar to a high quality new bituminous pavement.

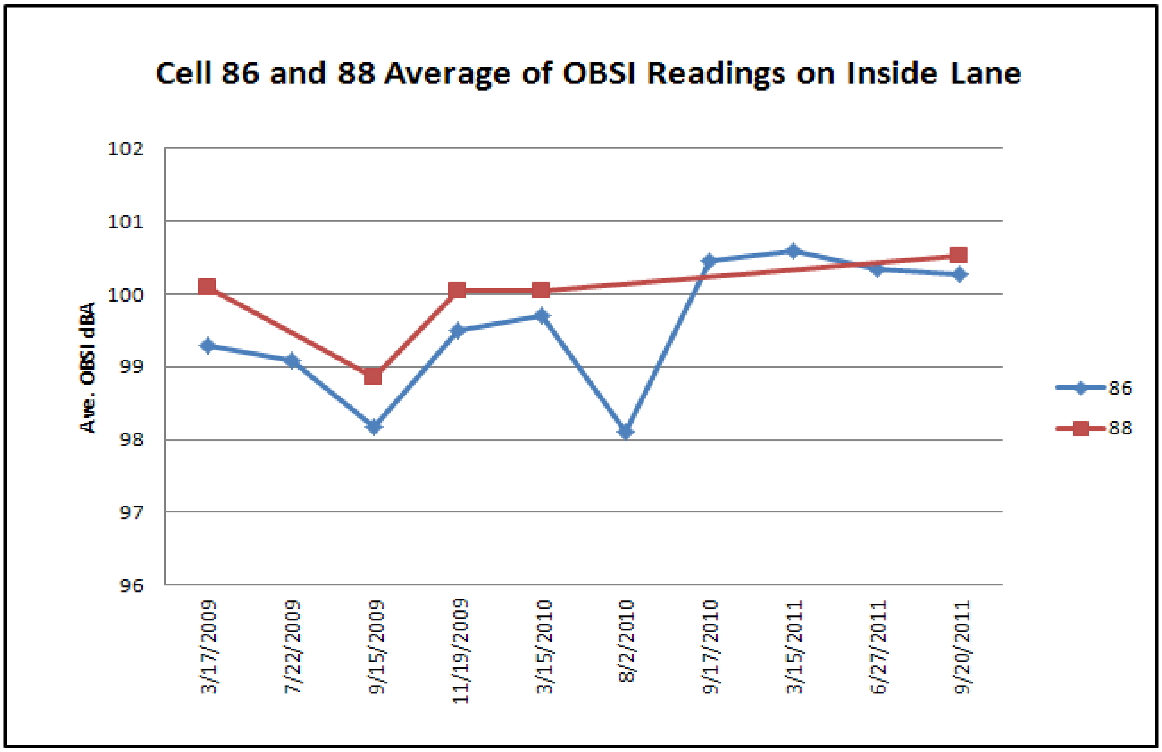


Figure 5.44. Sound intensity (dBA) – inside lane

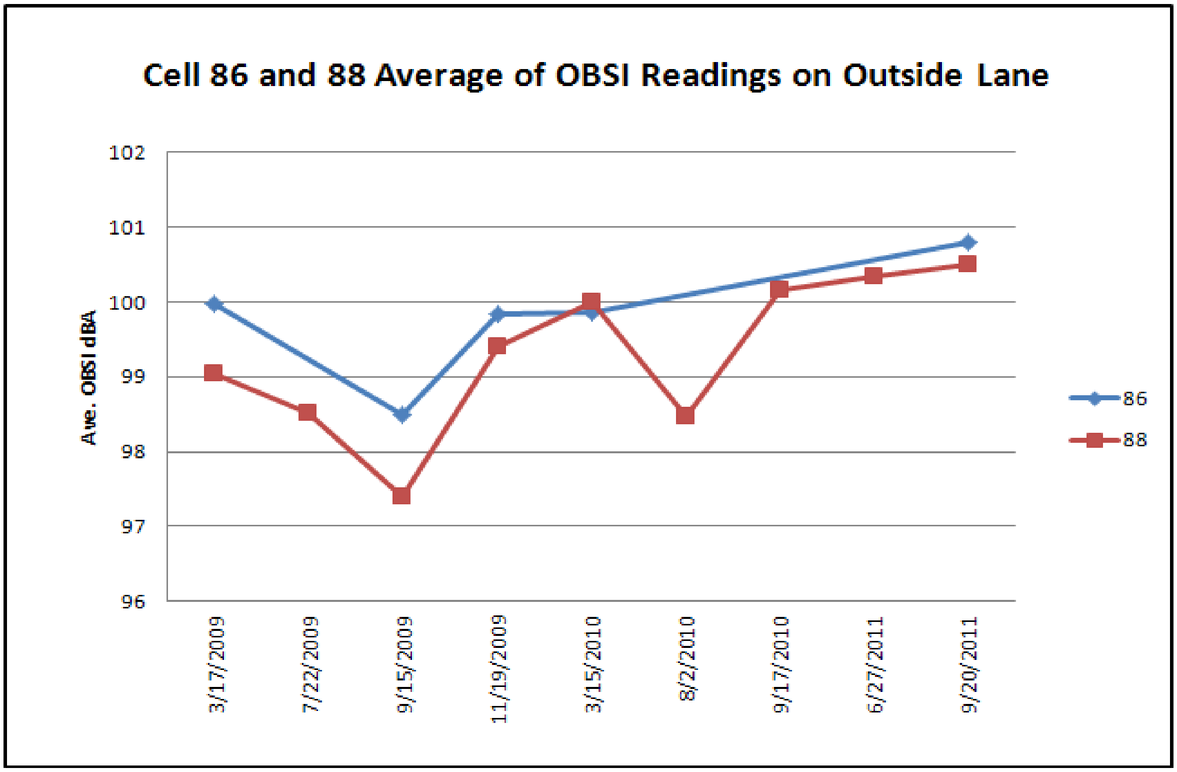


Figure 5.45. Sound intensity (dBA) – outside lane

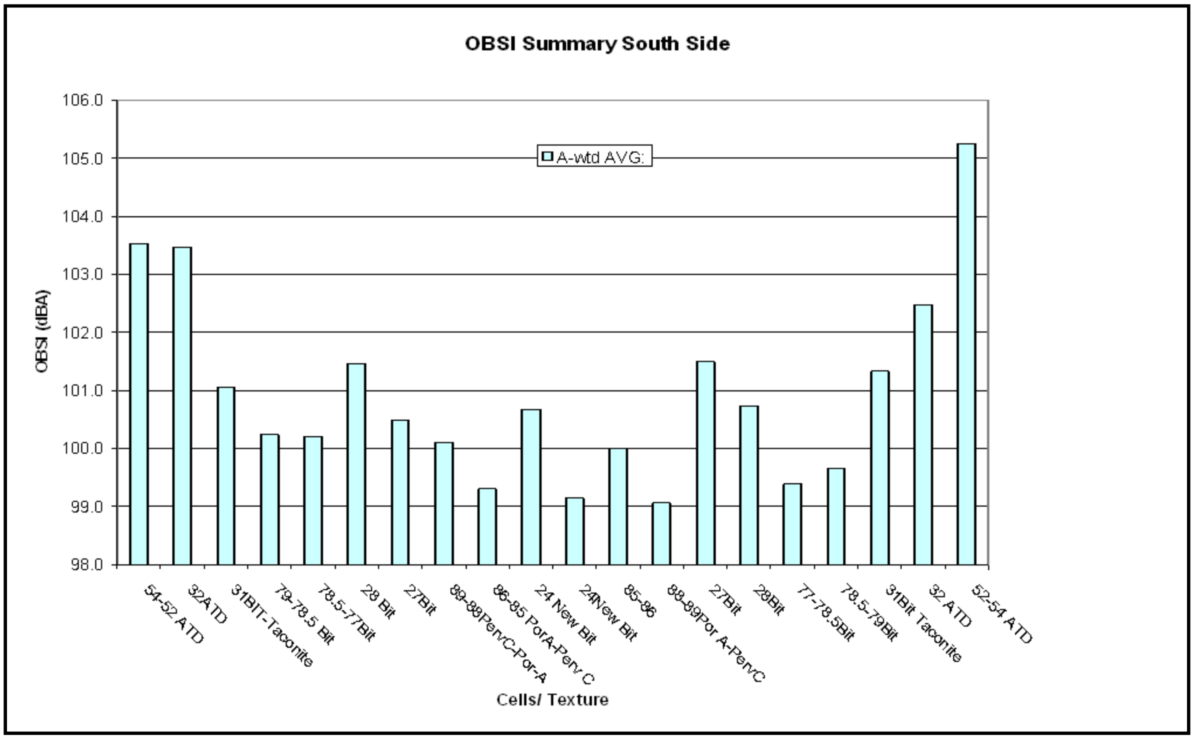


Figure 5.46. OBSI summary on LVR

5.5.2 Sound Absorption and Attenuation

The sound absorption test is a process that measures the characteristic of a pavement surface to “take in” or absorb ambient noise. Sound absorption (attenuation) is measured at MnROAD using a MnDOT BSWA 435 device and following a modified ASTM E-1050. Unlike OBSI, the sound analyzed is not generated by the interaction of the rolling tire with pavement surface, but by a “white noise” source. White noise is a random audio signal with a flat power spectral density that contains noise at the same power at all frequencies.

The MnDOT sound absorption measuring device (figure 5.47) consists mainly of a rigid impedance tube, capped by a white noise source, supported on a steady base and equipped with two microphones. The tube provides insulation from exterior sound sources when the white noise source sends signals to the pavement surface. The two microphones in the lower end of the tube are connected to a frequency analyzer that identifies and records the actual reflection or absorption of each frequency from zero to 2000 Hz. The absorption ratio for 315, 400 500, 750, 1000, 1250, and 1650 Hertz frequencies are then isolated for a broadband analysis and plotted against frequency [41]. Sound absorption is reported as a percentage; the higher the absorption coefficient, the more sound is being absorbed by the material. With this information, the porous surfaces can be analyzed to evaluate acoustical properties. It can also be used on other surfaces for an overall evaluation of surface parameters affecting tire–pavement noise. LRRB investigation 879 showed sound absorption is related to the porosity of pervious pavements, but more research is needed to determine how it relates to OBSI and circular track texture meter (CTM) measurements [42].

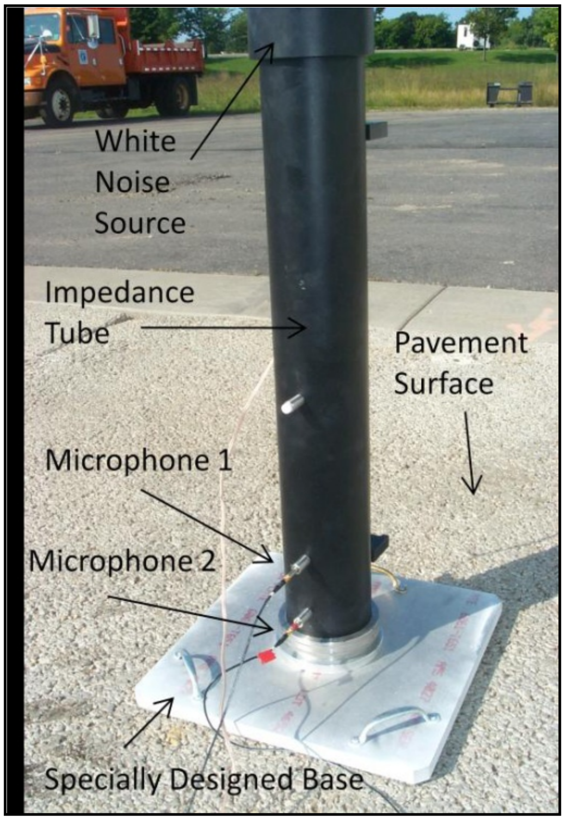


Figure 5.47. MnDOT sound absorption apparatus

Sound Absorption Coefficients measured for cells 86 and 88 are shown in figures 5.48 and 5.49. The sound absorption of the porous cells is over 5 times higher than the dense graded cell 87 pavement, indicating that the porous asphalt absorbs significantly more noise.

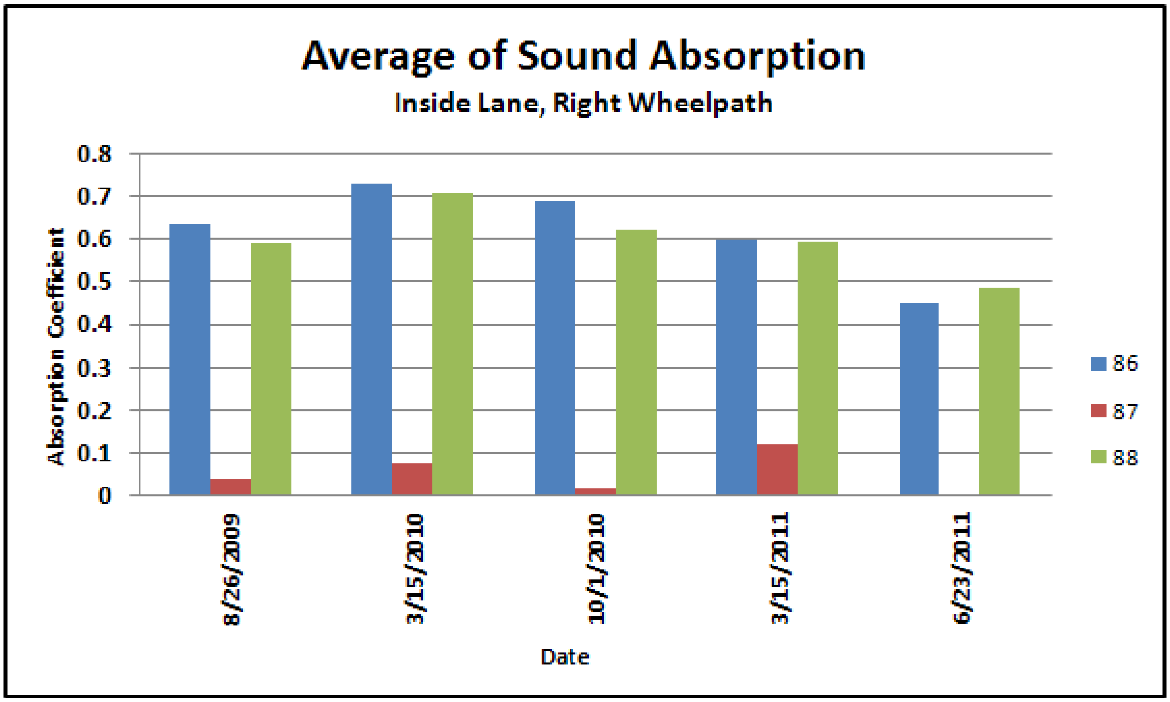


Figure 5.48. Cell 86 sound absorption coefficients

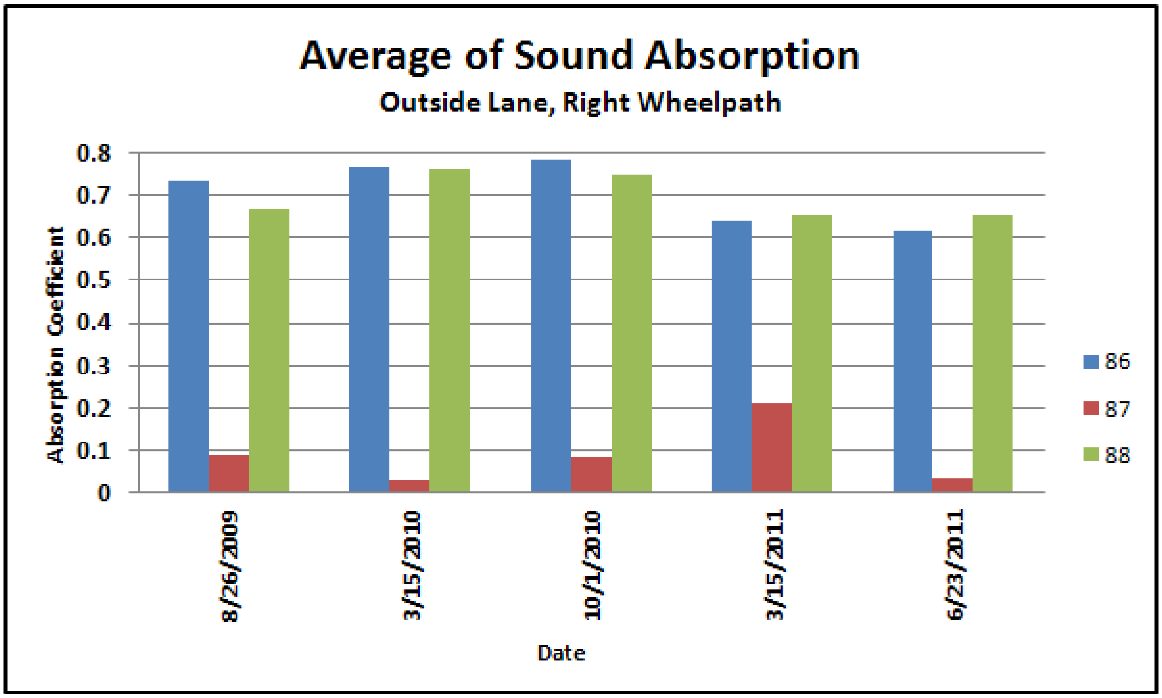


Figure 5.49. Cell 88 sound absorption coefficients

A comparison of several different types of MnROAD pavements is shown in figure 5.50, and the chart shows that porous/pervious pavements provide significantly better sound absorption than dense graded pavements at all frequencies [41].

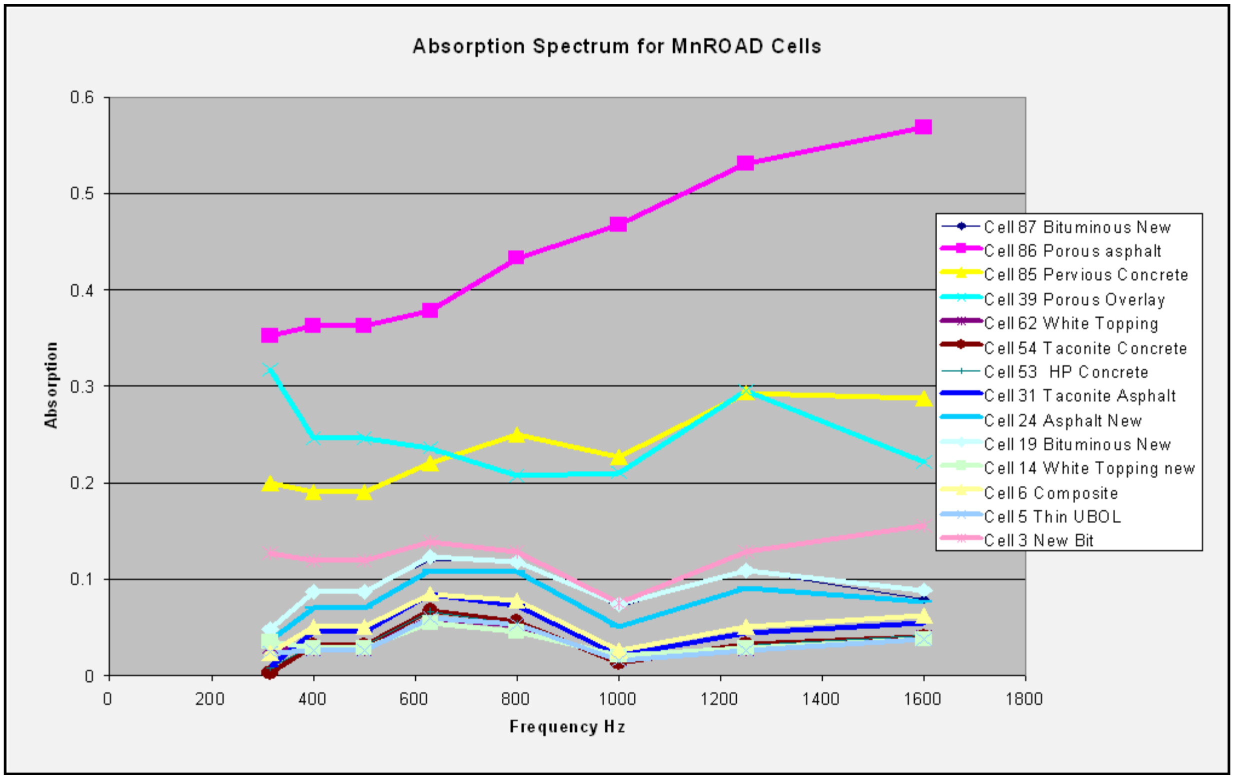


Figure 5.50. Comparison of sound absorption coefficients

5.5.3 Circular Track Texture Meter

The Circular Track Texture Meter (CT Meter) is being used on the porous pavements at MnROAD to measure clogging of the porous asphalt voids. Measurements are made according to procedures of ASTM E 2157. The CT meter (figure 5.51) uses a laser to measure the profile of a circle 11.2 inches in diameter or 35 inches in circumference. The profile is divided into eight segments of 4.4 inches. The average mean profile depth (MPD) is determined for each of the segments of the circle. The reported MPD (mm) is the average of all eight segment depths for 3 measurements. Temperature, surface moisture, and distress observed at the test locations at the time of measurement are also noted.

Figure 5.51. Circular texture meter

Porous asphalt cells 86 and 88 were tested with the CT meter in 2009, 2010 and 2011. On the outside lane MPD has increased slightly on all three cells (figure 5.52 and 5.53). The increase in MPD in the loaded lane is likely due to surface wear (raveling and rutting) caused by the loading vehicle. A significant increase in MPD (from low initial levels) was also observed on cell 87, which has less visible surface distress. The increase in MPD on cell 87 is occurring in both lanes, but at a higher rate on the loaded lane. As the porous cells initially had a very open texture, the raveling did not produce a large change in overall texture. However, the initially smoother surface of dense graded cell 87 shows a bigger change with surface wear.

The mean measured profile depth in the outside (unloaded) lane on both cells 86 and 88 has remained essentially the same since 2009, which is expected due to the minimal changes to the surface there. The MPD has increased more rapidly on cell 87 in the outside (unloaded) lane, with no immediately apparent reason. The cell 87 pavement on the inside lane has very little visible wear to date.

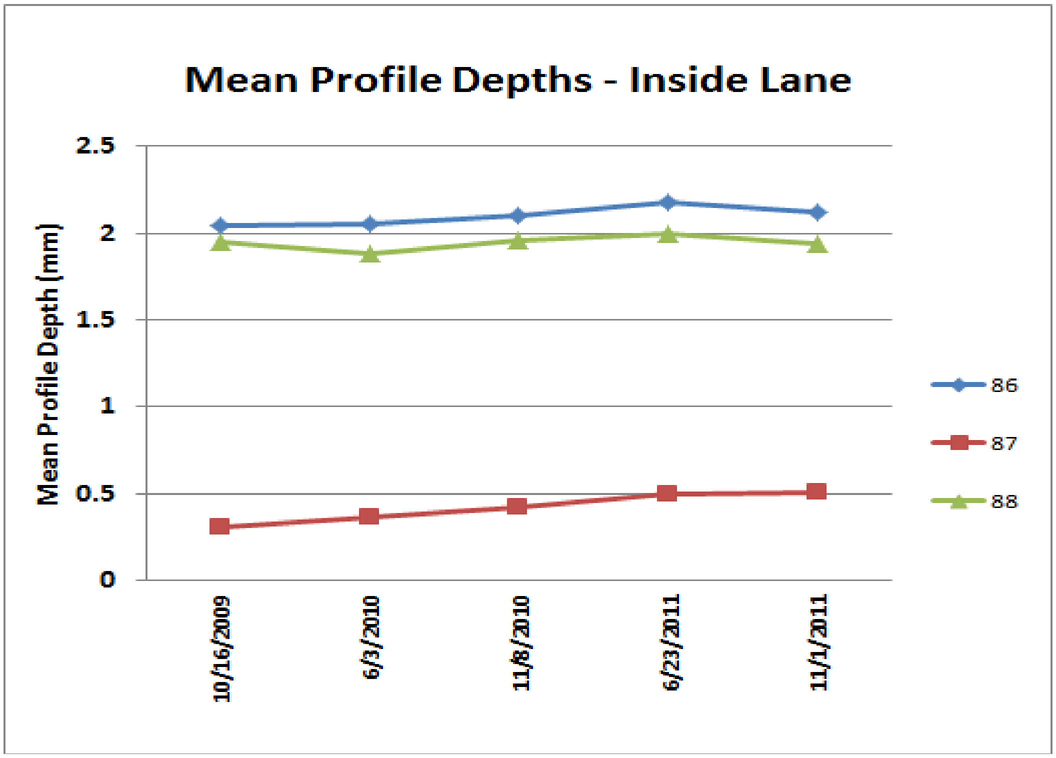


Figure 5.52. Mean profile depths (mm) – inside lane

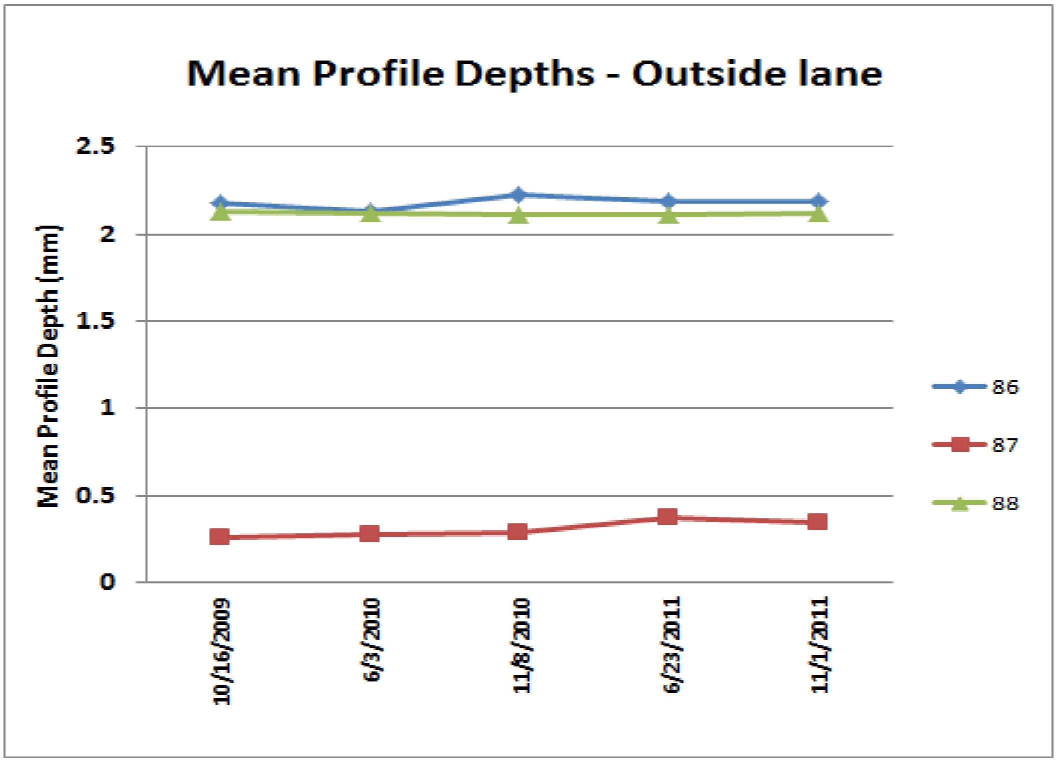


Figure 5.53. Mean profile depths (mm) – outside lane

5.5.4 Skid Resistance Testing

Skid resistance is the force developed when a tire that is prevented from rotating slides along the pavement surface. Pavement surface friction, as inferred from the skid resistance testing, is an important parameter because inadequate skid resistance can lead to a higher incidence of skid related crashes. Pavement skid resistance is also a useful way to characterize pavement texture or compare various pavement types and construction practices. The skid resistance testing at MnROAD is performed using the KJ Law (Dynatest 1295) Friction Trailer (figure 5.54), according to ASTM E-274.

The skid tester truck-trailer has a means to transport water and to deliver it in front of the skidding wheel at test speed. The standardized skid-test tire is defined by AASHTO M 261 or ASTM E 501. The different standard test tires (smooth and ribbed) were developed in order to eliminate the variables of tire type and design in the measurements of pavement skid resistance. During testing, the friction trailer is pulled behind the truck at approximately 40 mph. Water is injected directly to the tire-pavement interface, and a brake applied which causes the wheel to lock. Drag and load (horizontal and vertical forces) are measured by sensors at the wheel.

A Friction Number (FN) is calculated as the average coefficient of friction across the lane and can range from 0-100. A FN above 25 on a smooth tire denotes adequate friction, and a FN below 15 indicates that the pavement may need remediation.

Figure 5.54. MnDOT locked wheel skid tester

Both the ribbed and smooth “standard” tires were used to take the friction measurements in both wheel paths of the inner and outer lanes of the porous asphalt cells in years 2009-2011. The porous cells 86 and 88 demonstrated very good skid resistance (figures 5.55 - 5.58) with both the smooth and the ribbed tire test, with an overall average FN of approximately 50. The absorption of water in the porous cells contributes to skid resistance, and is highlighted in the smooth tire test results. Although increasing somewhat as the pavement surface has started wearing, the cell 87 smooth tire - loaded lane FN is only 50-60 % that of the smooth tire FN on cells 86 and 88 (figure 5.58).

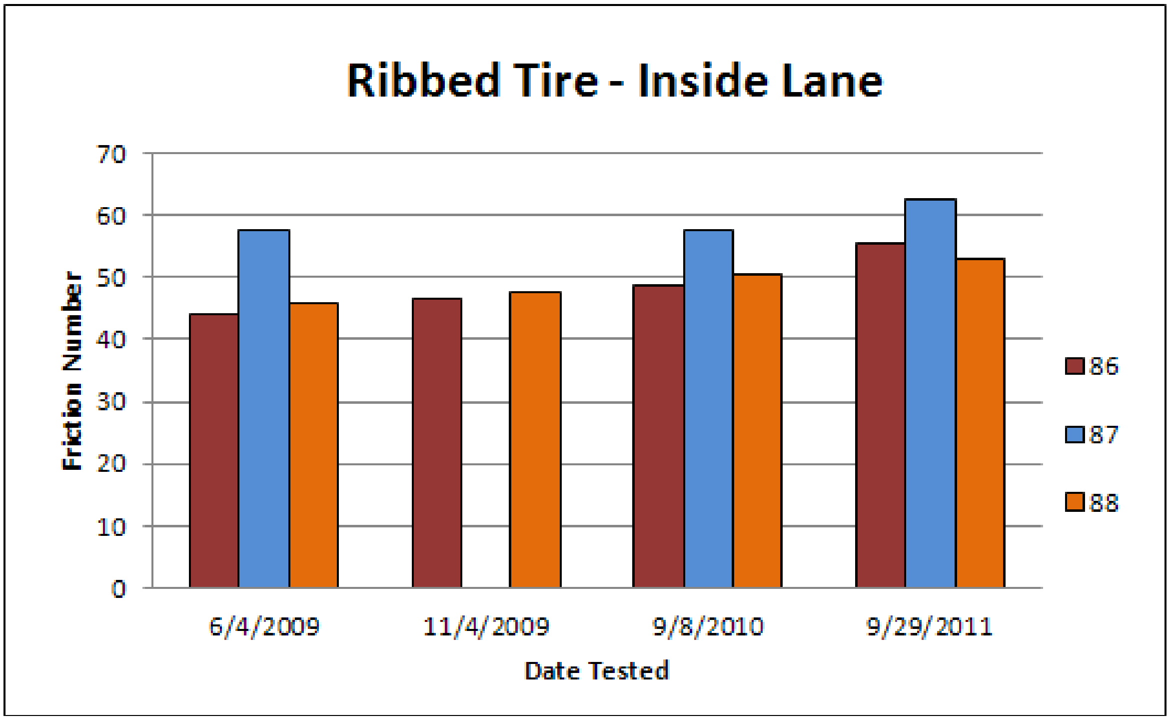


Figure 5.55. Cells 86-88 friction number (ribbed tire, inside lane)

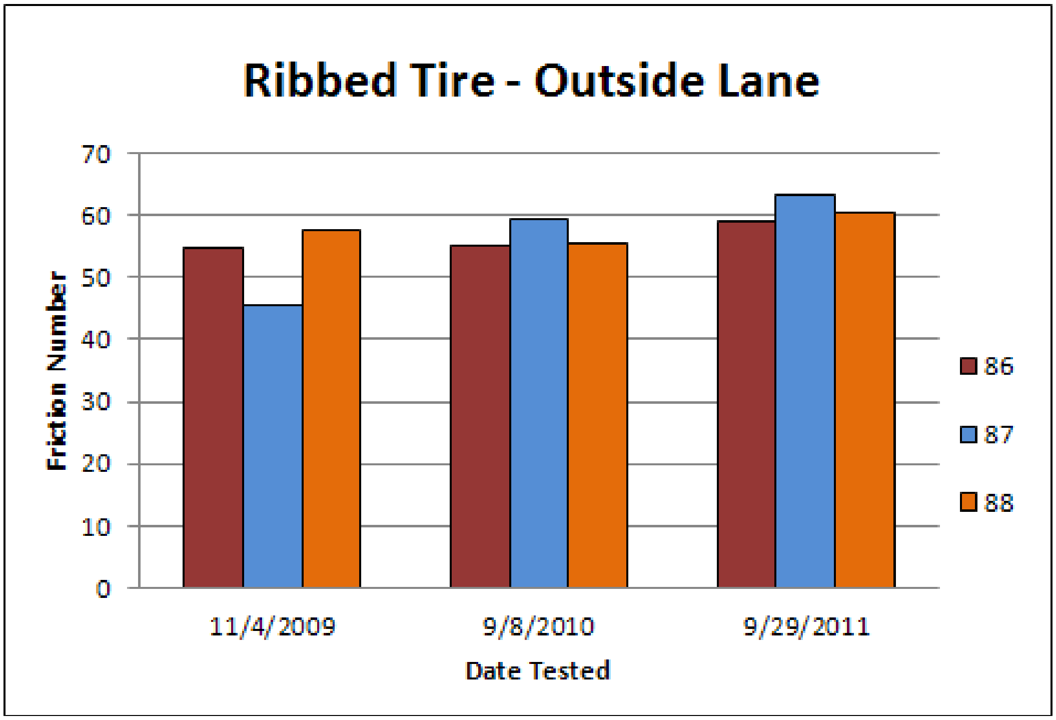


Figure 5.56. Cells 86-88 friction number (ribbed tire, outside lane)

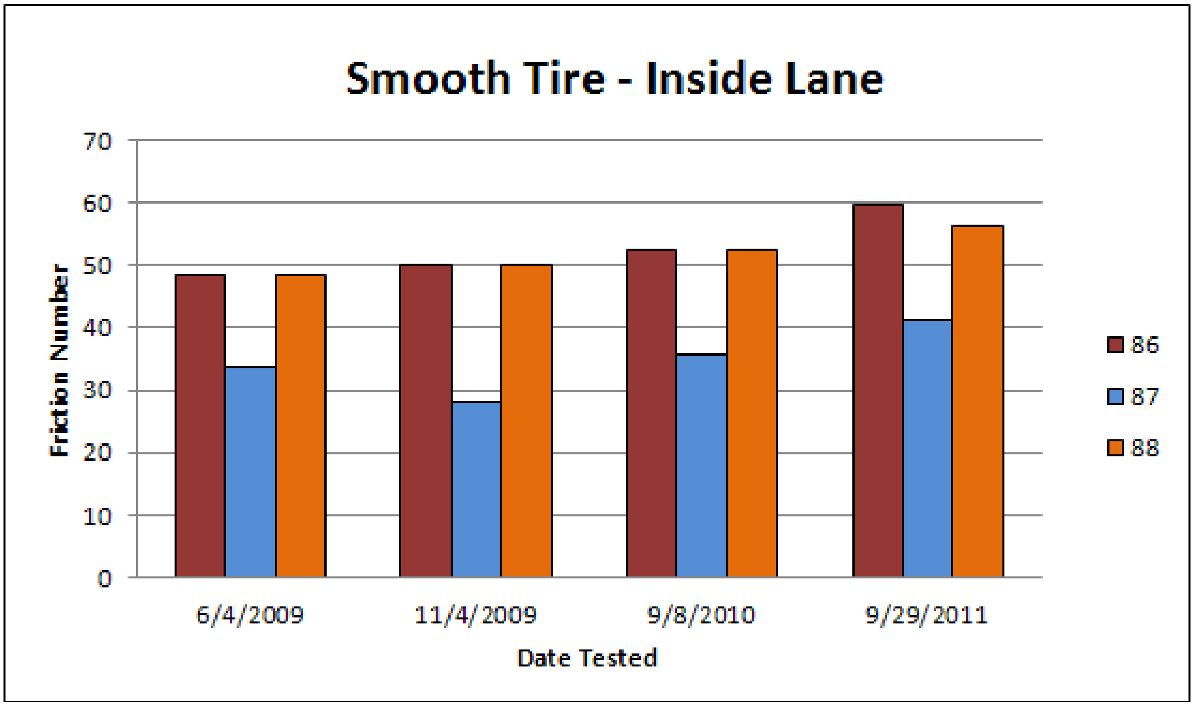


Figure 5.57. Cells 86-88 friction number (smooth tire, inside lane)

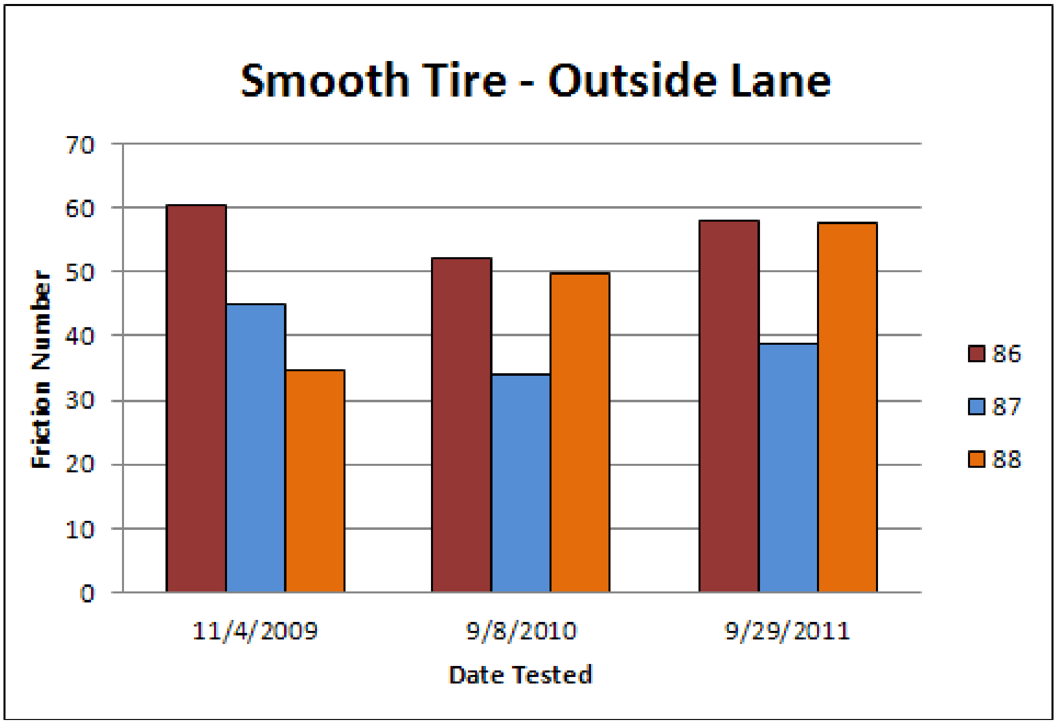


Figure 5.58. Cells 86-88 friction number (smooth tire, outside lane)

5.6 MAINTENANCE

5.6.1 Vacuum Testing

Demonstrations of porous asphalt pavement vacuuming were performed on November 9th, 2009, September 6th, 2010 and May 4th, 2011, June 27th, 2011, and November 2nd, 2011. A Reliakor vacuum truck was employed each time to attempt to clean the porous pavement and determine possible changes in the pavement's hydraulic permeability. The brush on the vacuum truck was not used as to avoid introducing additional material into the pore structure. Figure 5.59 shows the Reliakor Vacuum Truck in operation on cell 88.

Figure 5.59. Reliakor vacuuming

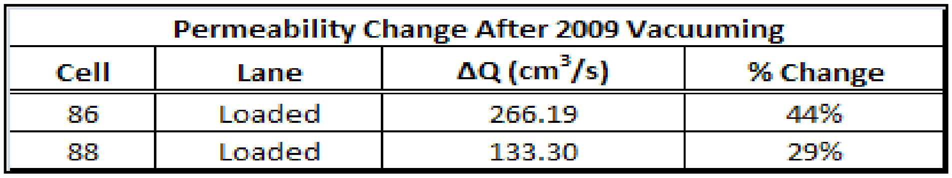
The porous pavement was approximately one year old at the time of the first vacuuming test in 2009. Except for the isolated areas of surface raveling, the pavement was in generally good condition. No pavement cracks, debris on the surface, or other distress was evident. During all the tests a small quantity of loose, fine aggregate particles (less than 1 ft^3) was removed from each porous cell (figure 5.60). Almost no aggregate were observed to be removed from cell 87 during any of the vacuuming tests.

Figure 5.60. Debris removed by vacuuming, 2009

Permeability tests were performed using the MnDOT falling head permeability device before, and immediately after the vacuuming on the porous test cells. In 2009 (table 5.6), there was a 30% and 23% decrease in infiltration flow times in cells 86 and 88, respectively. This indicates a fairly significant increase in permeability after vacuuming. However, after vacuuming in 2010 (table 5.7), an unexplained decrease in surface permeability was recorded, particularly in cell 88 where the flow decreased 15% in the loaded lane test. The only section to record an increase in flow in 2010 was the environmental lane of cell 88. Although vacuuming did not appear to be having a consistent influence on the overall permeability of the porous cells in 2009 and 2010, the relatively new pavement was probably still very clean and in actuality vacuuming was probably not having much of an effect. The extreme variability in the before/after testing results is likely due to the difficulty in reinstalling the permeability device in exactly the same location; the repeatability testing described in section 5.3 was performed without removing the device between tests. A small change in location with the six-inch diameter device could have a significant effect in repeatability; therefore using a larger diameter apparatus may be beneficial.

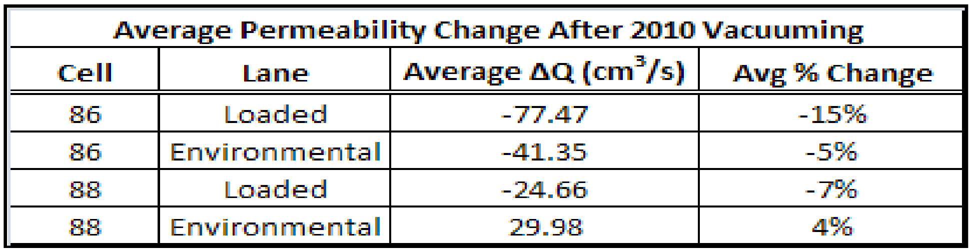
MnDOT vacuumed three times and monitored permeability changes twice in 2011 (tables 5.8 and 5.9) to clarify results. As in previous years, the 2011 data shows that the cleaning did not generally improve the permeability on the loaded lane; however, it seems to consistently have some beneficial effect on the environmental lane. As the overall permeability (as well as OBSI and CTM data) data suggests that some clogging is now occurring on both lanes, it is expected the vacuuming would produce some increase in permeability. The apparent decrease in permeability after vacuuming the loaded lane is not understood at this time; raveled aggregate particles embedded in the void structure may be playing a role. Future forensic investigation of the clogging mechanism in the pavement may provide more information.

Table 5.6. Permeability changes after November 4th, 2009 vacuuming



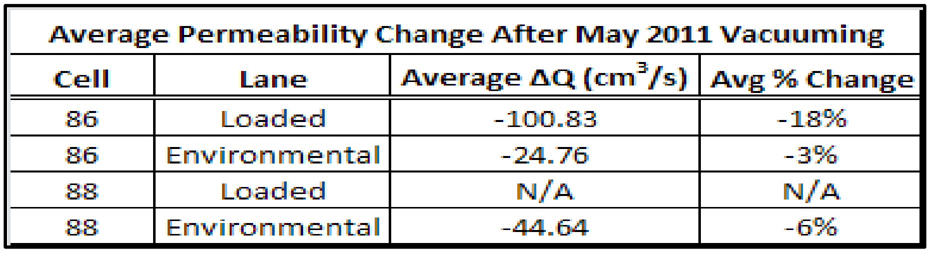
Permeability Change After 2009 Vacuuming			
Cell	Lane	ΔQ (cm^3/s)	% Change
86	Loaded	266.19	44%
88	Loaded	133.30	29%

Table 5.7. Permeability changes after September 6th, 2010 vacuuming



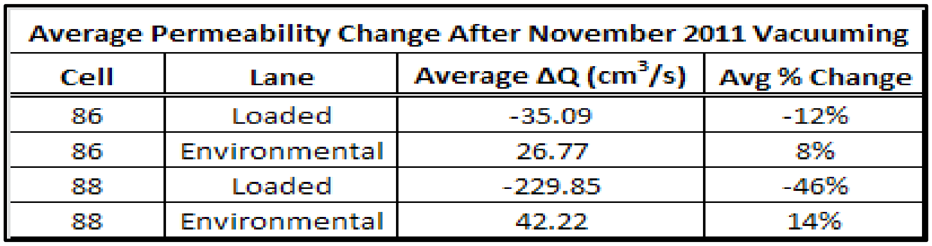
Average Permeability Change After 2010 Vacuuming			
Cell	Lane	Average ΔQ (cm^3/s)	Avg % Change
86	Loaded	-77.47	-15%
86	Environmental	-41.35	-5%
88	Loaded	-24.66	-7%
88	Environmental	29.98	4%

Table 5.8. Permeability changes after May 4th, 2011 vacuuming



Average Permeability Change After May 2011 Vacuuming			
Cell	**Lane**	**Average ΔQ (cm^3/s)**	**Avg % Change**
86	Loaded	-100.83	-18%
86	Environmental	-24.76	-3%
88	Loaded	N/A	N/A
88	Environmental	-44.64	-6%

Table 5.9. Permeability changes after November 2nd, 2011 vacuuming



Average Permeability Change After November 2011 Vacuuming			
Cell	**Lane**	**Average ΔQ (cm^3/s)**	**Avg % Change**
86	Loaded	-35.09	-12%
86	Environmental	26.77	8%
88	Loaded	-229.85	-46%
88	Environmental	42.22	14%

Small amounts of soil and base material was dropped on the porous pavement during construction of the transverse drains in 2009, and it was swept and vacuumed as good as practicable by MnROAD personnel soon after. No other pavement maintenance (besides Reliakor vacuuming) or any other repairs have been performed (or needed) on the porous cells 86 & 88 or control cell 87 at the time of this writing in fall, 2011.

5.6.2 Pavement Surface Monitoring

Regular snow and ice removal operations are performed on the LVR after each significant snow event. However, little salt (and no sand) has been applied to the porous asphalt sections since pavement installation, and no salt has been applied since 2009. The porous cells are plowed in the same manner, and at the same time as all other cells on the LVR. One goal of this research was to monitor the porous pavements in terms of the rate of snow accumulation and melting, and differences were observed in certain conditions (figure 5.61).

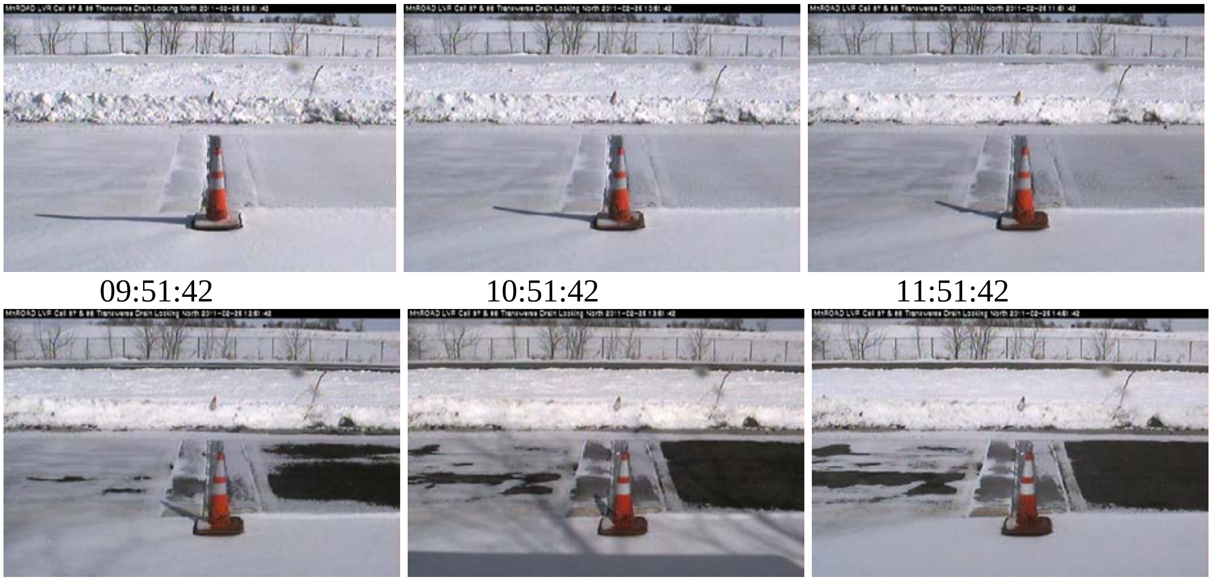
Figure 5.61. Cell 86, 87, and 88 wheelpaths of loaded lane 01/30/2012

It was observed that a faster rate of melting or sublimation was occurring on the porous cells, particularly when a small amount of snow (< 2 inches) was on the surface of the pavement and in periods of sunny weather. The faster melting on the porous cells also occurred when the pavement was in a frozen condition and in low ambient temperatures. In order to accurately quantify any differences in snow accumulation and melting, a camera trailer was employed in 2011 (figure 5.62). It was installed at the transverse drain between cell 87 and 88 and configured to simultaneously record time-lapse images of the surface of the two pavement types; with cell 87 on the left side of the image and cell 88 on the right.

Problems with this system became immediately apparent. First, the trailer itself caused some unusual snow drifting on the surface of both pavements. Secondly, the location was not ideal in terms of correlating data – the subsurface thermocouples were located some distance from the camera. Lastly, the presence of the massive concrete transverse drain probably affected the snow melting rate to some extent. However, the time-lapse camera functioned well, and in late winter after the drifting subsided some interesting images and data were obtained.

Figure 5.62. Camera trailer at junction of cell 87 and 88, February 2011

An example series of time-lapse images from February 25th, 2011 are shown below (figure 5.63). Snowfall of less than ¼ inch occurred before sunrise, average air temperature was 8^{o}F, light winds, and sunny skies. The porous asphalt cell (on the right) cleared faster than cell 87. An analysis of the air and subsurface temperatures measured at increasing depths below the surface on both cells (at the thermocouple trees) is shown in figures 5.63 and 5.64. Interestingly, the three pavement sensors recorded that the porous pavement rose above freezing, while the denser asphalt of cell 87 remained well below freezing all day. The precise mechanism for the faster melt rate is not known, and research is ongoing at MnROAD with additional cameras and a more rigorous methodology to determine more about the phenomenon.


09:51:42 10:51:42 11:51:42

12:51:42 13:51:42 14:51:42

Figure 5.63. Time lapse series 9:51AM to 14:51PM on 02/25/2011 (cell 87 on the left and cell 88 on the right)

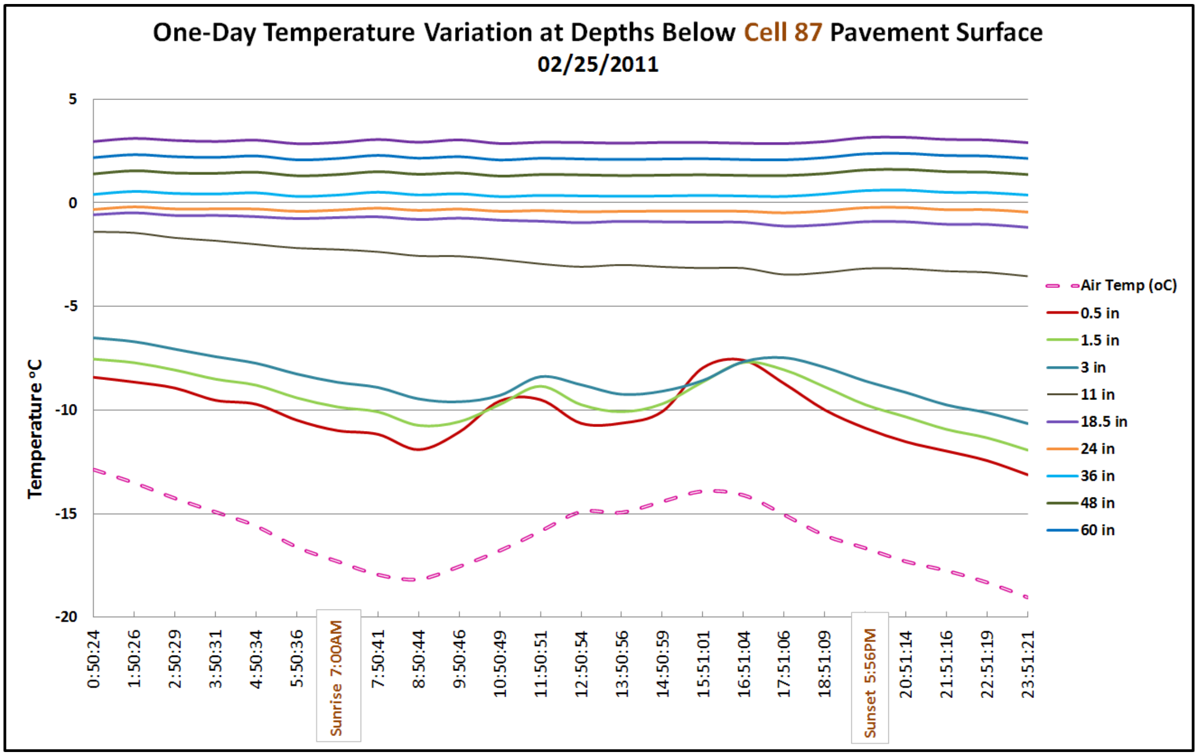


Figure 5.64. Cell 87 subsurface temperature variation 02/25/2011

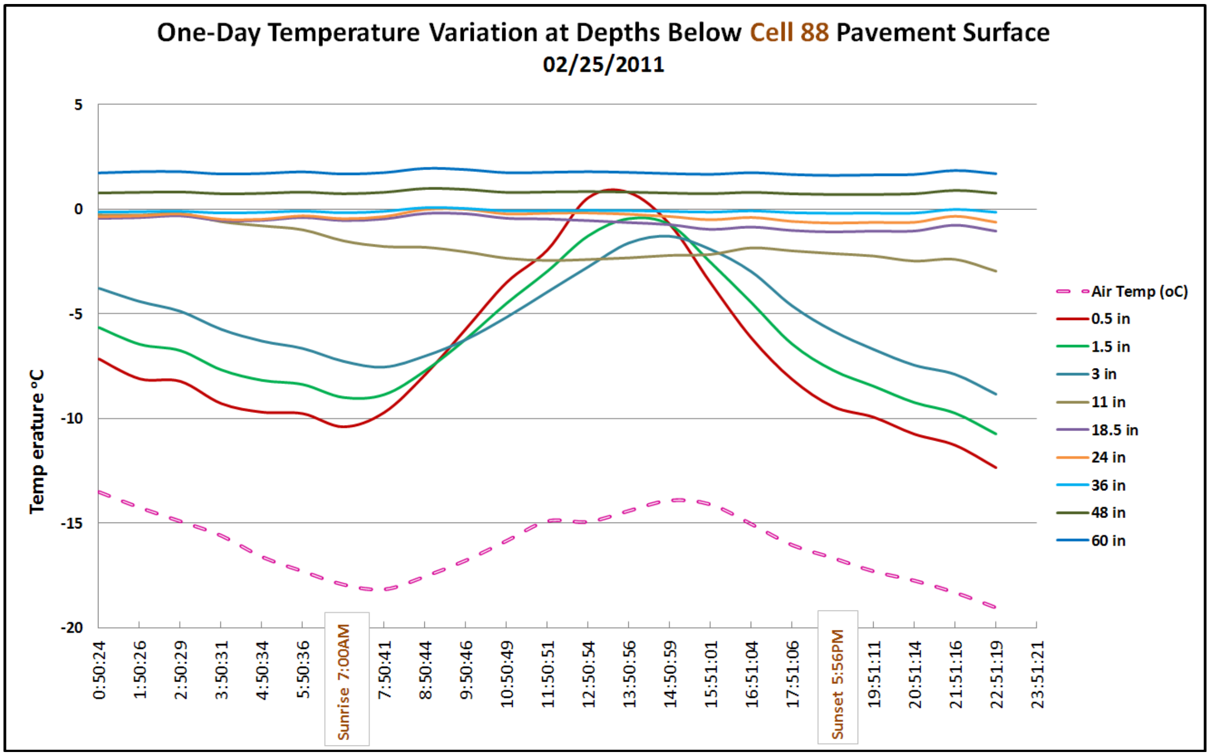


Figure 5.65. Cell 88 subsurface temperature variation 02/25/2011

5.7 SUBSURFACE DATA

5.7.1 Pavement Subsurface Freezing Data

The time-lapse camera data indicated a need for a more thorough analysis of subsurface temperatures. Each day's temperature variation form 11/01/2010 through 04/01/201 is charted at increasing subsurface depths in both porous cells and cell 87 (figures 5.66 - 5.68.) A few interesting elements are visible in the data. First, the porous asphalt internal pavement temperatures rise above freezing several times during the winter (reiterating the camera observation). The porous asphalt temperatures also rise much faster in the spring (and are more variable) than the dense graded HMA.

Differences are also found in the subgrade temperatures. For example, cell 86 at 24 inches below the surface (orange line), slightly exceeds the freezing (0^oC) line all winter. Cell 88 at 24 inches drops below freezing in late December, and the 36 inch deep sensor also drops well below 0^oC. On both cells 88 and 86 the 24 inch sensor (orange line) seems to follow the changes in pavement temperatures much more closely than on cell 87. The porous pavements experience more internal heating and provide better heat transfer between the pavement and deeper subsurface layers. The precise mechanism of the heat transfer is not known at this time, the ongoing monitoring on these cells should help to clarify the issue. On cell 87, the internal pavement temperatures almost always remain lower than the base material, and a longer term change in internal pavement temperature is needed to influence the temperatures deeper beneath the pavement.

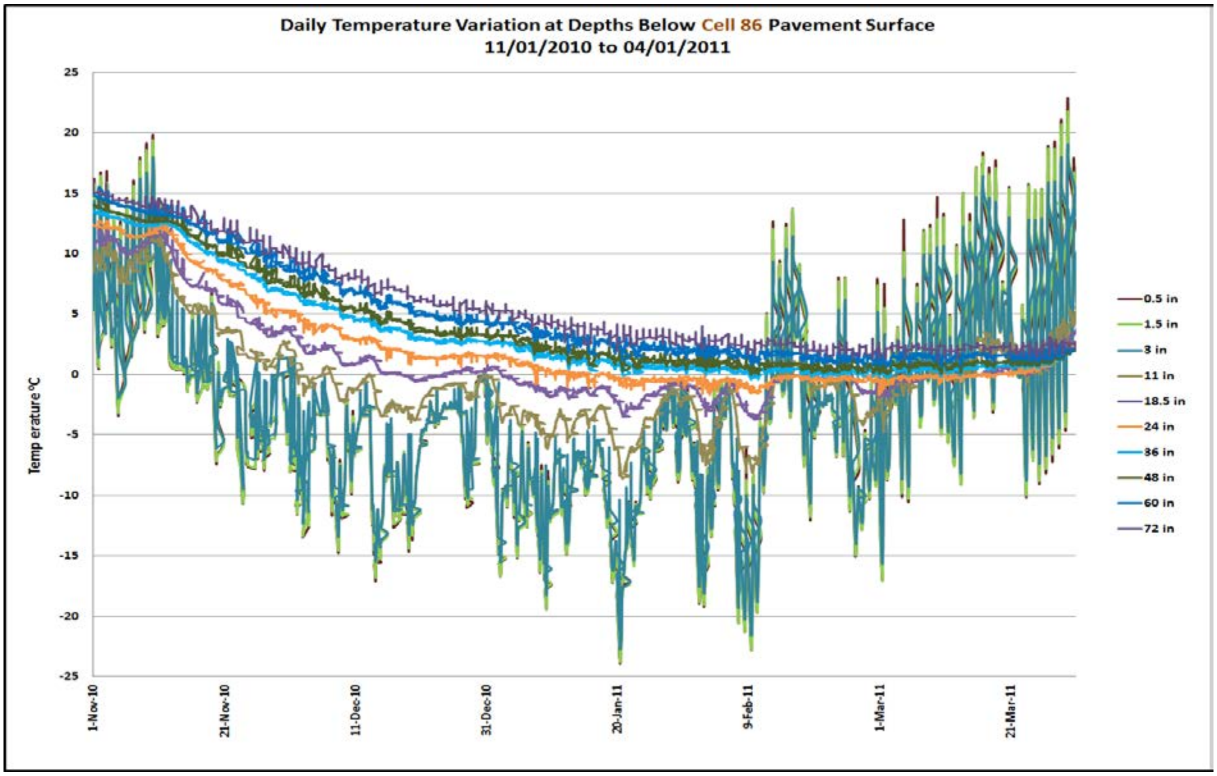


Figure 5.66. Cell 86 subsurface temperatures 11/01/2010 to 04/01/2011

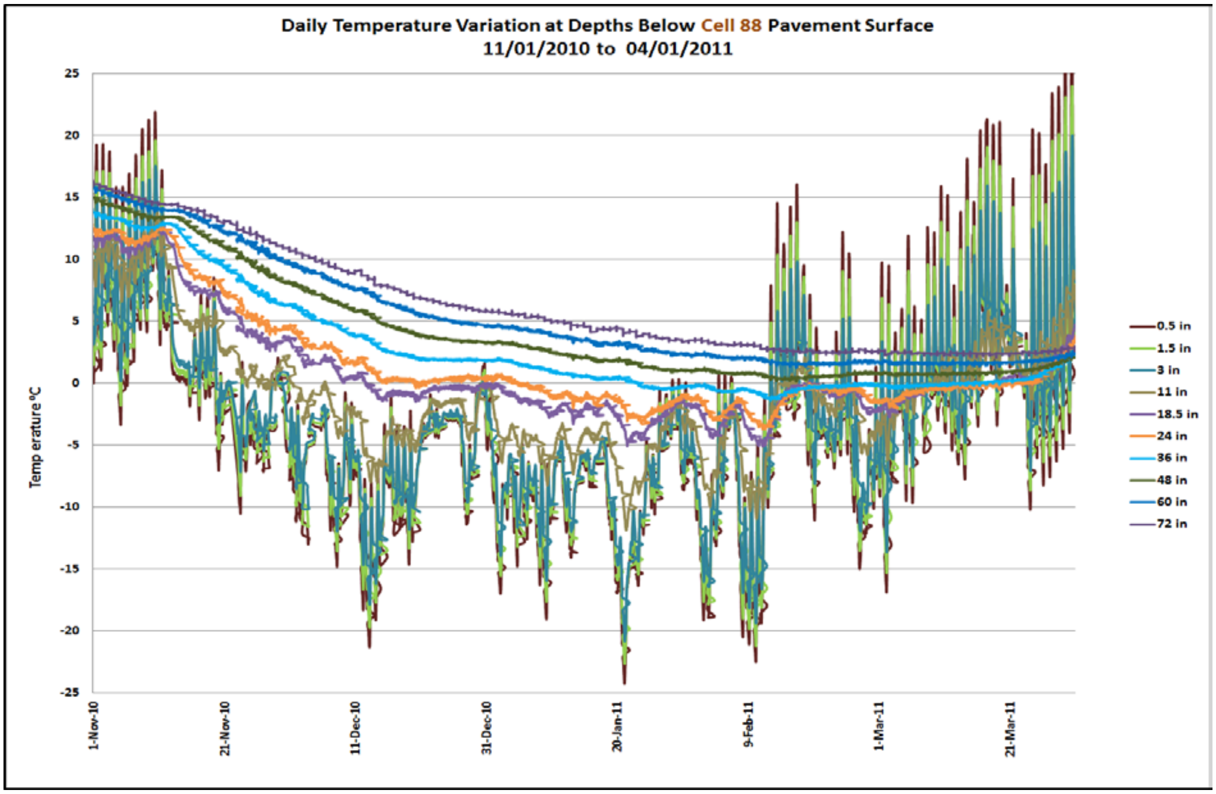


Figure 5.67. Cell 88 subsurface temperatures 11/01/2010 to 04/01/2011

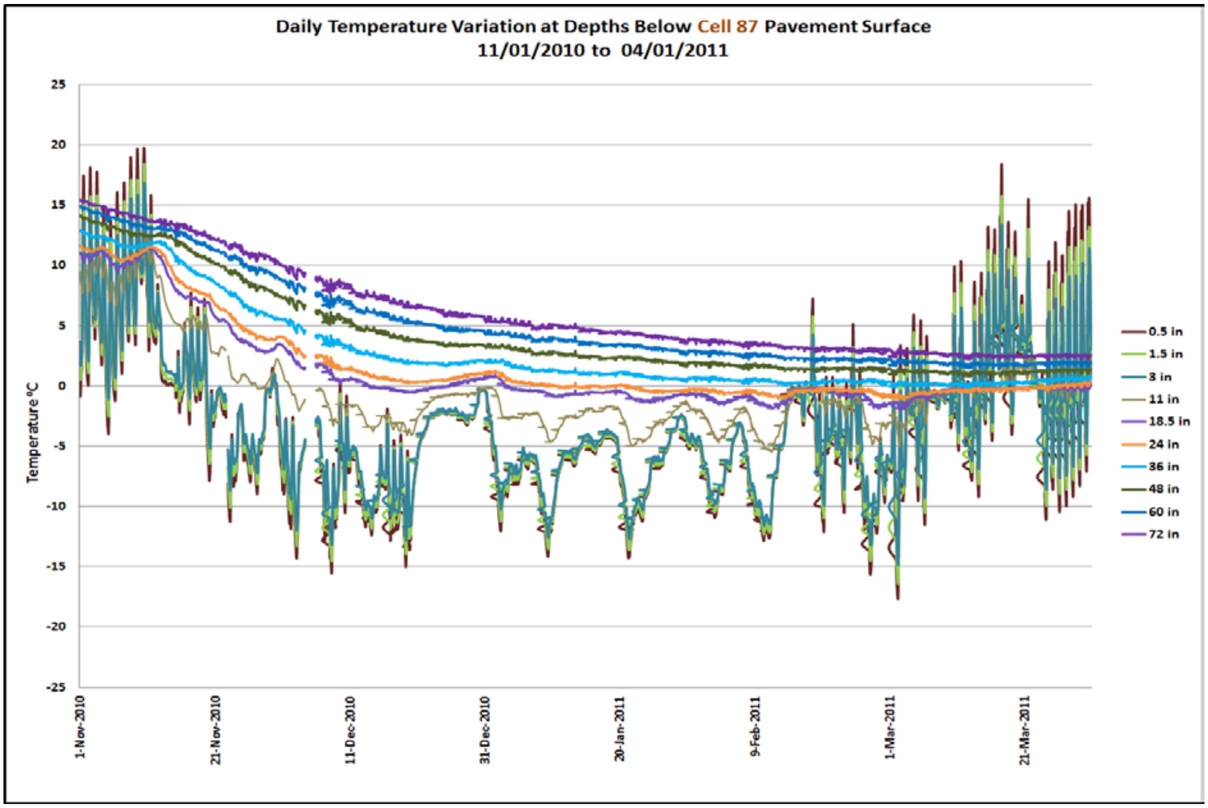


Figure 5.68. Cell 87 subsurface temperatures 11/01/2010 to 04/01/2011

5.7.2 Pavement Subsurface Temperature Changes due to Infiltration

An analysis was made of the subsurface temperatures on cells 88 during and after a significant rain event on October 6, 2009. This event produced 1.4 inches of rain over the course of approximately 14 hours (figure 5.69). The rain fell continuously during the period but never exceeded a rate of 0.25 inches per hour in any 15 minute period.

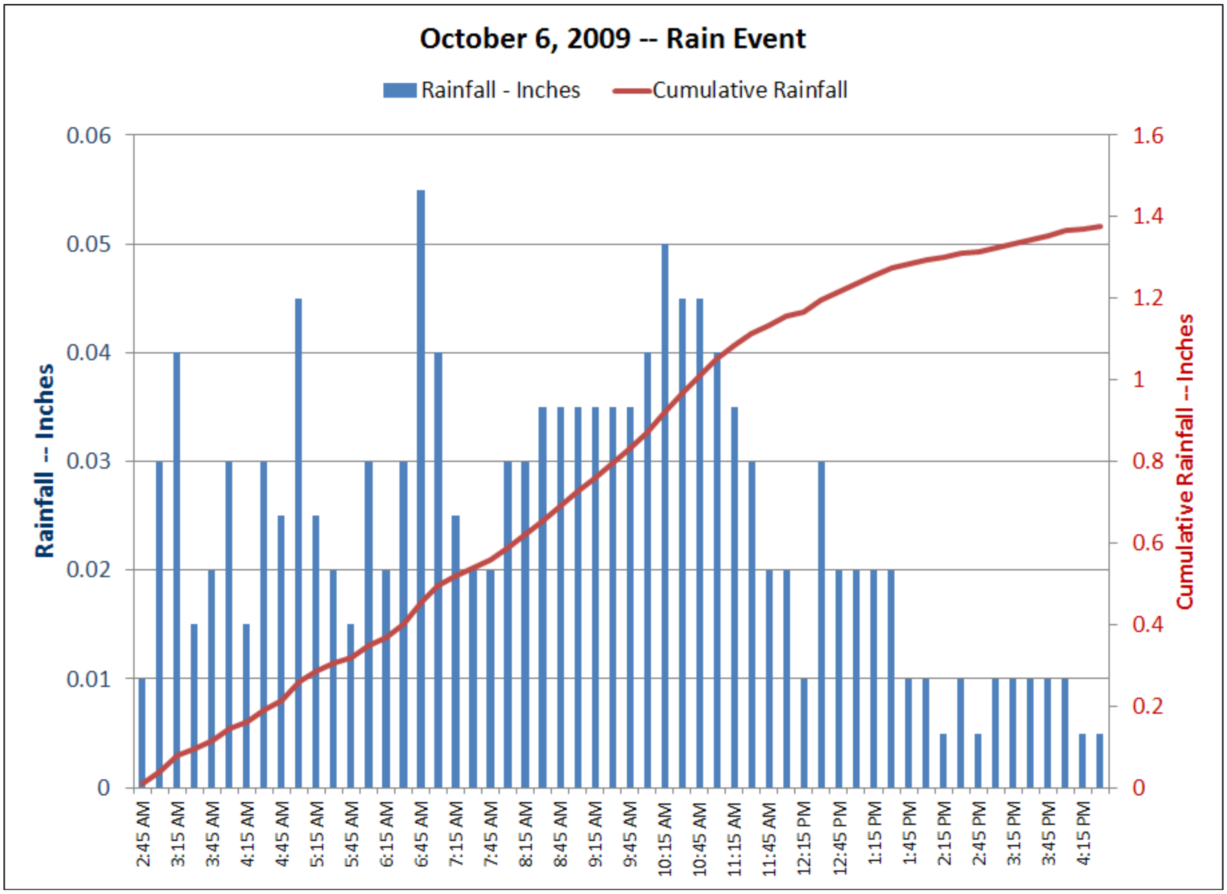


Figure 5.69. Rainfall event 10/06/2009

Subsurface thermocouple air temperature data recorded during the rain event is charted in figure 5.70. The air during the event was cool - approximately 5^{o}C (40^{o}F), and generally declined throughout the day. It is difficult to draw conclusions about the effect of rainwater on the subsurface temperatures from this data set. It appears that the pavement and base temperatures closely follow the air temperature variation. It does not appear that the influx of rainwater has an immediate effect on the subsurface temperatures. However, the rainwater temperature is not known and it may be similar to the air temperature. It does appear that the moisture has more of an effect on the temperatures at greater depths – both the 24 inch and 36 inch sensors are shown to decline during this day – with a relatively small change in air temperature.

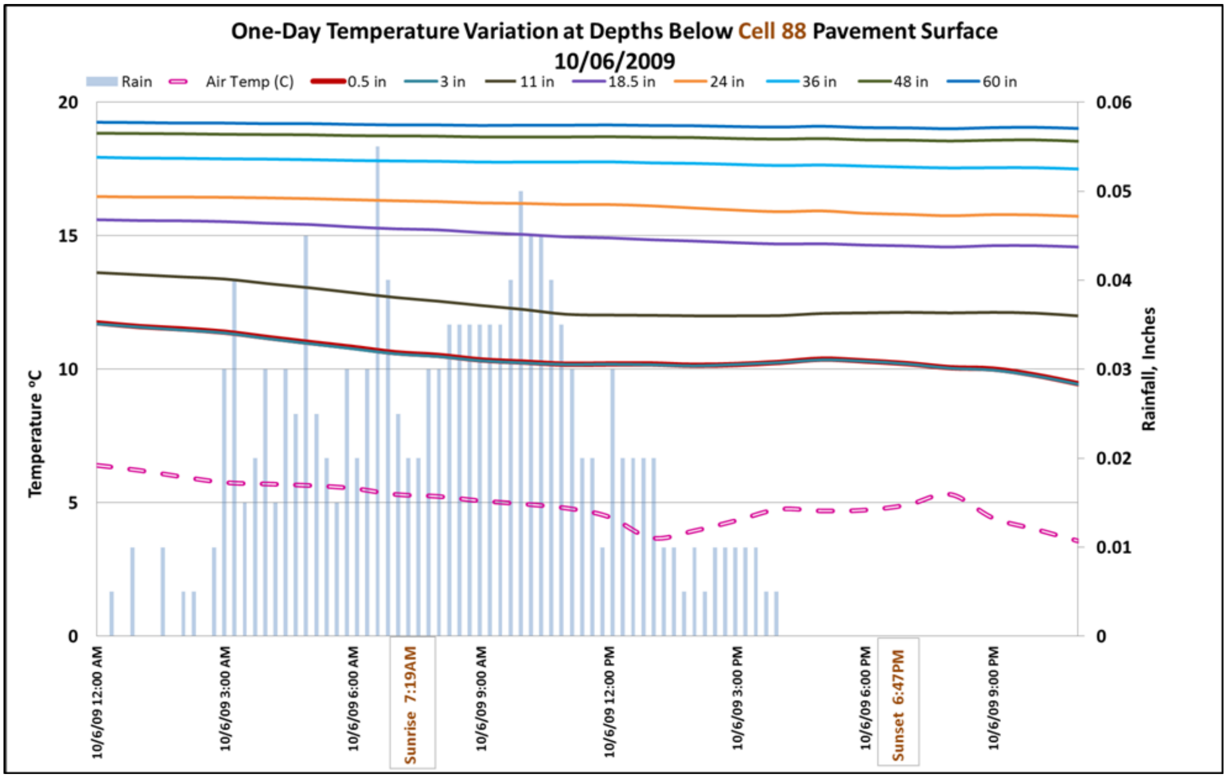


Figure 5.70. Cell 88 subsurface temperatures 10/06/2009

5.7.3 Pavement Subsurface Moisture Data

Subsurface moisture sensors designed to indicate volumetric moisture content were acquired for installation in the porous asphalt cells at the time of construction. MnROAD personnel determined that they would not function properly inside the pavement or CA-15 base, so they were only installed below the geotextile in the subgrade material of each cell. The particular sensor installed requires a complicated and involved calibration process which has not been completed at the time of this writing. After the gauge calibration factor has been obtained, precise volumetric moisture contents of the subgrade materials should be available from the MnROAD database.

Although at this time the data cannot be calibrated to provide an accurate volumetric moisture measurement, the change in the value measured by the sensors can be used for qualitative illustration. An example of the change in subsurface qualitative moisture level at two depths below cell 88 is shown in figures 5.73 and 5.74. It can be seen from the data that the process of moisture accumulation and drainage in the clay subgrade can be delayed significantly after rain events. After completion of the sensor calibration, more extensive data analysis will be performed on the long-term changes in the subgrade moisture on the test cells.

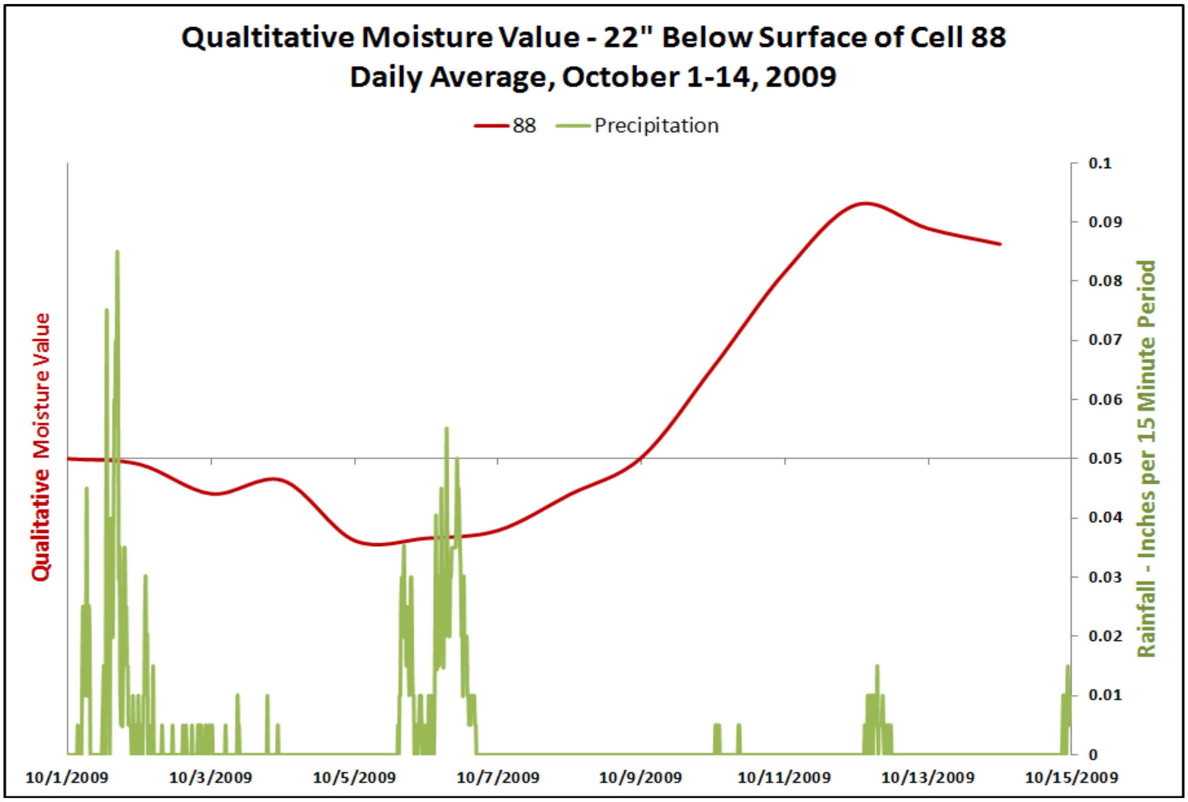


Figure 5.71. Cell 88 subsurface moisture at 22 inches October 1-14, 2009

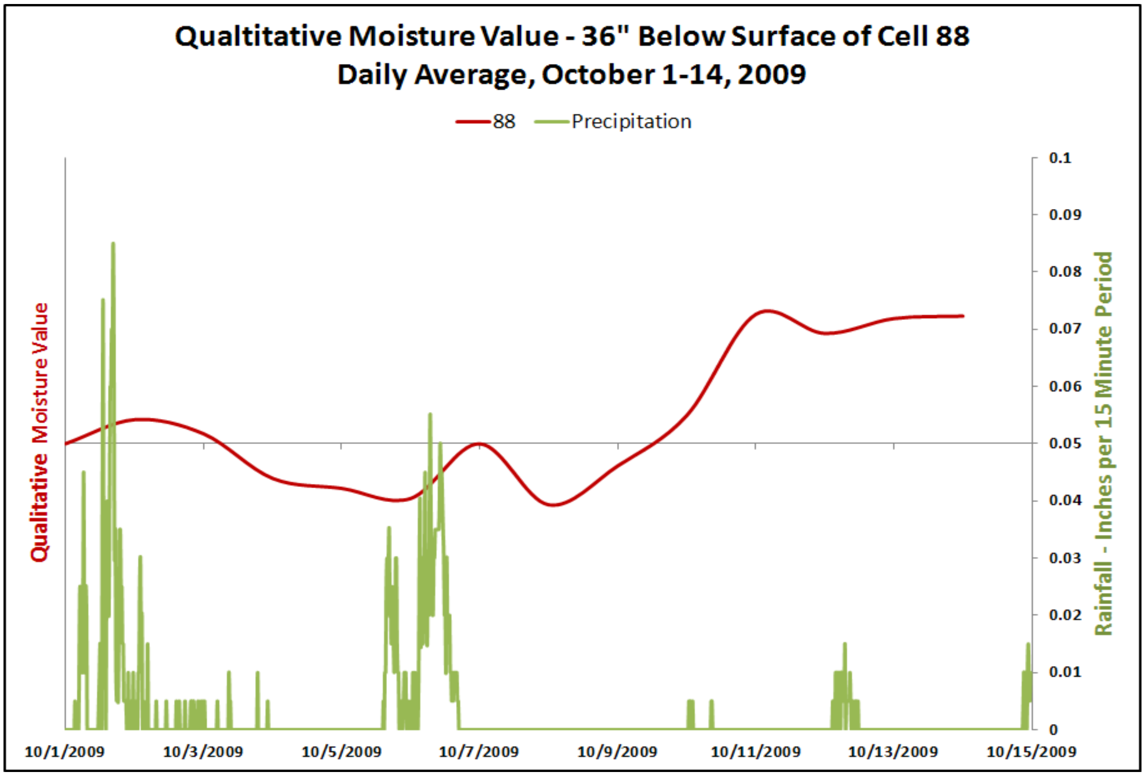


Figure 5.72. Cell 88 subsurface moisture at 36 inches October 1-14, 2009

6 HYDROLOGICAL AND ENVIRONMENTAL REPORT

6.1 INTRODUCTION

Data obtained from research at the MN/Road facility provided us opportunities to review the environmental benefits of porous pavement. To compare the existing environmental conditions at the facility and results of the porous pavement test sections for runoff reduction and water quality the initial intent for the research should be analyzed.

The instrument setup and measurement plan was to measure runoff from the two porous asphalt test sections and the DGHMA control section. The results would provide information when the porous sections begin to clog and require maintenance. Piezometers would be used to periodically test the groundwater and monitor groundwater flow and depth. These results were used to monitor contamination in the surface water runoff, how the porous pavement system filters these contaminants and if, or how, they impact the groundwater levels. During construction of the pavements instruments that measured and captured water as if flowed through the pavement were not installed. While additional monitoring ports were installed to provide substitute information they did not provide the necessary information to determine, filtering capabilities, infiltration rates and clogging tendencies. Groundwater samples and overland flow samples of the pavement sections were taken to make comparisons to water quality standards for lakes and streams in general. Also data was gathered to determine if porous pavements were actually able to cool storm water as it flowed thru the profile.

6.2 ENVIRONMENTAL CONDITIONS

Total rainfall for 2009 was 26.5 inches, for 2010 the rainfall total was 27.7 inches, and for 2011 the rainfall total was 29.8. Rain events of 1 inch or greater in a 24 hour period were taken from the rainfall data. The date and rainfall amounts were used for this report. During the 3 year period there were 22 events that met this criterion. The rainfall gages are 1 mile from the test sections and the actual rainfall at the site may vary from the gages. Table 6.1 shows all events that had 1.0 or more inches of rain in a 24 hour period.

Table 6.1. Rainfall events 1 inch or greater

Rainfall Events		
DAY	Temp DEG F	Rainfall
6/8/2009	47	1.41
7/21/2009	63	1.14
8/8/2009	62	1.02
8/19/2009	62	2.67
10/1/2009	50	1.41
10/6/2009	43	1.69
6/11/2010	63	1.05
6/25/2010	70	1.01
7/17/2010	70	1.12
8/13/2010	68	1.28
9/2/2010	66	1.34
9/15/2010	55	2.51
9/23/2010	62	1.12
3/22/2011	36	2.14
5/21/2011	70	1.06
5/30/2011	74	1.0
6/22/2011	80	1.06
7/5/2011	93	1.50
7/10/2011	87	1.17
7/14/2011	70	1.75
7/15/2011	80	1.48
8/16/2011	81	1.41

Storm water runoff from each test section was captured using tipping buckets. The runoff volumes were measured from the surface area of each test section, including the control section which is an impervious dense graded bituminous surface. Table 6.2 shows the area of each cell, both porous and non-porous. The capacity of the tipping buckets was 16 gallons. The tipping bucket data for each of the storm events was also generated but due to inconsistencies after 2008 this data was determined to be unreliable information.

Table 6.2. Cell areas

Cell Areas								
AREA (ft^2)				Percentage Area		Acreage		
Cell	Porous	Non Porous	Total	Porous	Non Porous	Porous	Non Porous	Total
86	5720	1320	7040	81.25%	18.75%	.1313	0.0303	0.1616
87	0	7040	7040	0.0%	100.0%	0.0000	0.1616	0.1616
88	5720	1320	7040	81.25%	18.75%	0.1313	0.0303	0.1616

Appendix Q shows the tipping bucket volumes. Too many inconsistencies with the equipment occurred to obtain accurate data regarding infiltration rates and clogging. Runoff from the cells 86 and 88 was from the non-porous portions of the cells which were the gutters and the end capture drain. From times that the tipping buckets were working, which was early in the research, showed that the porous sections do provide a benefit for reduction in overland flow.

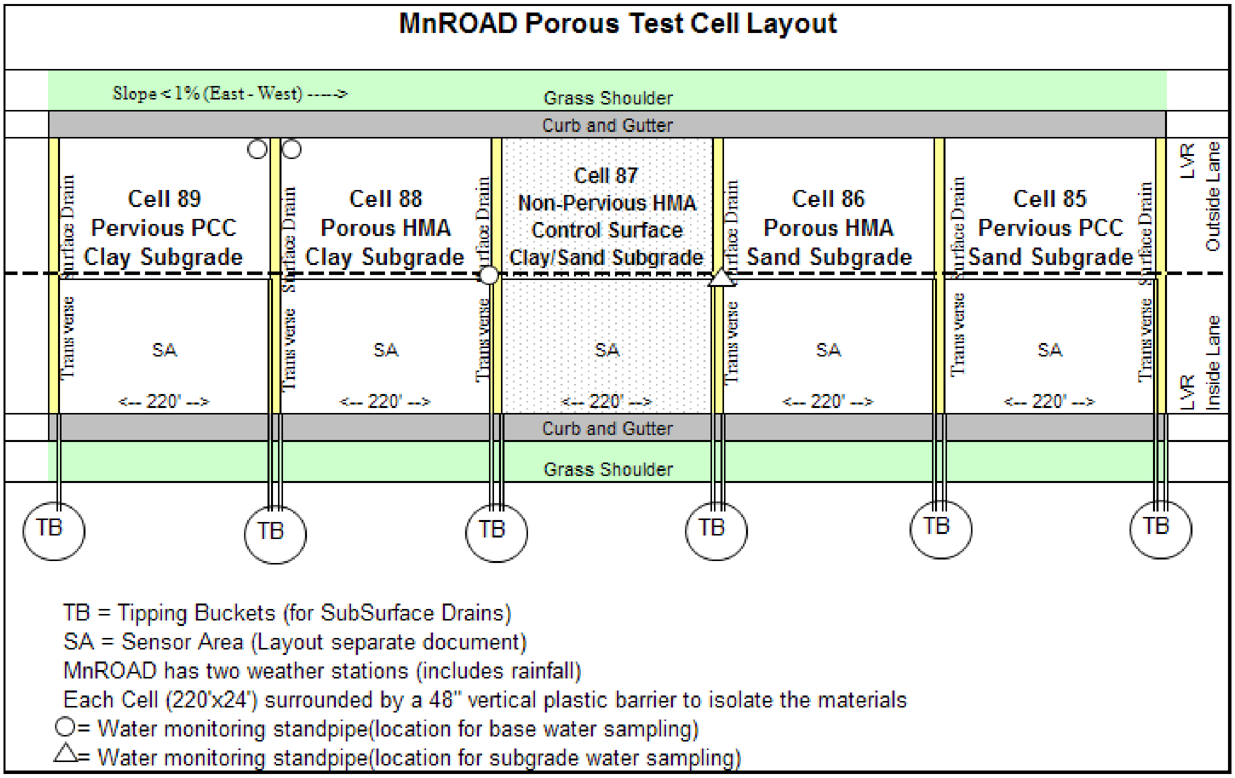


Figure 6.1. Cells and tipping bucket locations

6.3 WATER QUALITY

6.3.1 Standards

Minnesota waters are separated into beneficial use categories and different water quality standards for each of these categories exist. The beneficial uses of waters are taken from Minnesota Rules Chapter 7050.140. For purposes results will be compared to the Class 2 waters. These are the lakes and streams used for fishing and swimming. Water quality standards for these waters are shown in Table 6.3.

Table 6.3. Water quality standards

Minnesota Water Quality Standards for Class 2 Waters	
Turbidity (Naphthalene turbidity Unit (NTU)	10-25
Suspended Vol. Solids (mg/L)	NA
Suspended Solids (mg/L)	rivers 10-65
Solids, Total Volatile (mg/L)	NA
Solids, Total (mg/L)	NA
Nitrate+Nitrite Nitrogen, Total (mg/L as N)	NA
Kjeldahl Nitrogen, Total (mg/L)	NA
Phosphorus Total, LL (mg/L as P)	12-30
Chloride, Total (mg/L)	860
*Chromium LL (ug/L)	984
*Copper (ug/L)	9.2
Iron HL, Tot (ug/L)	NA
Lead (ug/L)	34
Mercury (ug/L)	6.9
*Nickel LL (ug/L)	789
*Zinc HL (ug/L)	65
Temp (^{o}C above for stream)	5
Temp (^{o} C above for lake)	3
PH	8.5

6.3.2 Sampling Methods

Water quality samples were taken from ground water wells; Well 1 and Well 2, tipping buckets; TB86, TB87, TB88, and Sample Ports; SP86, SP88. Four water samples were taken from each sampling tube; 1 liter for general, 250 ml for nutrients, 250 ml for metals, and 125 ml for mercury. MnDOT water quality and testing unit personnel measured water temperature, turbidity, dissolved oxygen, pH, and specific conductance. Samples were also sent to the Minnesota Department of Health for additional tests. The Department of Health tests include: turbidity, conductivity, suspended volatile solids, suspended solids, total volatile solids, total solids, chloride, nitrogen, phosphorous, cadmium, chromium, copper, iron, lead, mercury, nickel, and zinc content.

6.3.3 Groundwater Test Results

Baseline groundwater samples were taken on three different dates during 2008. This data was compared to runoff of the test sections to measure the effectiveness of the porous surface system and underlying soils. The groundwater testing results are attached in Appendix R. Results show that background concentration levels fall within the acceptable range of water quality standards. Runoff from the pavement is typically lower in concentrations of the tested parameters than the ground water.

Test samples taken for Cell 86 (SP86), which were in the groundwater below the pavement sections, shows that the turbidity, copper and lead are higher than the background levels in Well 1 and Well 2. It is uncertain why these are higher without an in depth analysis and further research. Surprisingly the concentrations of chlorides increased with each sample. These were below water quality standard for chlorides but did generate some concerns as to why the increase. Table 6.4 lists the salt applications to the facility during the research period. Further testing showed that the chloride levels dropped in 2011, and MnDOT did not salt MnROAD facility in 2011. Chloride concentrations under cell 86 were increasing due to salting the low-volume loop road and the salt concentrations increased due to the test sections were lined which limited groundwater flow under the cells. Test data is attached in Appendix T.

Table 6.4. Salt application at MnROAD

Salt application at MN/ROAD facility			
Jan 13-2009	2000 lbs.	800 lbs./mile	mainline
Jan 15 2009	3000 lbs.	600 lbs. /mile	Mainline, parking lot, driveway, low-volume road(LVR)
Jan 21 2009	Salt brine 23%salt by weight in water	380 gal per mile	mainline
Dec 30 2009	4000 lbs.	800 lbs. per mile	Mainline and LVR
Nov 23 2010		400 lbs. per mile	LVR
Nov 30, 2010		600 lbs. per mile	LVR
2011- present	none		

6.3.4 Surface Water Testing

Water quality samples were taken from the tipping buckets from cell 86, 87, and 88. These are labeled TB86, TB87, and TB88 in Figure 6.1. Results show that surface runoff has no measurable impacts to ground water or water quality standards for 2a waters. Test data is shown in Appendix T.

6.3.5 Filtration Testing

Originally the samples were going to be taken from lysimeters but due to construction issues these could not be installed. Instead sampling tubes were installed at the end sections of each cell. Water quality samples were taken at cell 86 and 88 but only two samples were taken in cell 88 due to unknown factors. Since samples were not collected directly below the pavement filtration comparisons could not be made. Results from Fassman and Blackbourn [43] research states that porous pavements do decrease copper and zinc concentrations.

6.3.6 Temperature Monitoring

Temperature trees are located in Cell 86 (porous over sand), Cell 23 (standard pavement), and Cell 88 (porous over clay). The trees range in depth from 0.5 inches to 72 inches. Electronic conductance measurements were taken at 15 minute intervals and these measurements were translated to temperatures. These are temperatures of the ground and not the storm water as it flows through the soil, but it can be assumed that as the water passes through these layers of soil that the water would approach these temperatures. The dates used for the temperature data were the event dates that captured a 1.0 inch plus storm. Comparing the air temperatures to the pavement sections shows that the porous sections are consistently higher than conventional pavements in colder months. The underlying depths of the porous pavement in warmer months are cooler than the above air temperatures. The air voids in the porous sections must act as a thermal layer providing warmer temps in cooler climate conditions and help provide cooler temps in warmer climate conditions. Appendix T shows results for each of the test sections.

7 SUMMARY AND CONCLUSIONS

- This section summarizes the results of the research project and lessons learned. The primary objective of LRRB investigation 878 was to determine pavement performance and maintenance considerations of a full-depth porous asphalt roadway in a cold climate. A secondary objective involved understanding the environmental effects of this type of pavement installation. To provide for these research objectives, MnROAD LVR test cells 86 and 88 and control cell 87 were constructed in 2008-2009, have received approximately 40,000 applied ESALs, and have been tested and monitored for three full years as of December 2011.
- The porous asphalt test sections are performing well, in spite of what is considered to be significant loading for this type of pavement. The only significant pavement distresses observed to-date are rutting in the loaded lane, and shallow surface raveling. Other pavement distress on the porous test cells is minimal. The cells are performing very well in characteristics of ride quality, permeability, stiffness modulus, strain response, safety, and quietness. More challenges were experienced during the environmental (water) testing for the project. Some of the sampling devices could not be installed as planned; others did not perform as anticipated. However, comparative water quality sampling was performed, and subsurface temperature data was analyzed. Snow accumulation and melting rates were monitored by time-lapse camera. The environmental testing protocols and devices needed were unusual for MnROAD and the lessons learned from this project will inform future MnROAD projects.

7.1 PAVEMENT PERFORMANCE SUMMARY AND CONCLUSIONS

- The asphalt mixture design approach was to develop a high strength porous mix, to ensure the pavement would last for the entire study period under the intense loading on the LVR. Therefore, Class A (crushed granite) aggregate was specified in the mixture and no recycled materials were allowed. The Lottman (TSR) and asphalt pavement analyzer (APA) tests were conducted and based on the results; a PG70-28 binder was selected. This is a higher temperature, polymer modified binder not often used with porous asphalt.
- The applied loads and/or clogging do not appear to be causing a significant increase in pavement density. Some decrease in surface permeability is evident. However, the lowest measured flow rate through the porous pavement is still over 0.5 inches per second; more than adequate for any expected rainfall event. No overflow from the porous cells was observed during the study period.
- Pavement deterioration in the form of raveling (first observed soon after construction) has progressed steadily, but affects less than the top 1 inch of the pavement. Initial raveling appeared to be related to mixture temperature segregation; possibly aggravated by the long wait time to begin rolling the relatively thick pavement in low ambient temperatures. The rate of raveling appeared to decline after the first high temperature summer weather, suggesting some self-healing of the mix took place.
- No cracking (fatigue or thermal) or other significant distresses have been observed on the PA cells, and the standard asphalt pavement “control” cell 87 has not developed any significant distresses.
- The average measured rutting on the porous asphalt sections is significant; approximately

0.60 inches. On the standard asphalt of cell 87 rutting is less than 0.16 inch. Rutting measurements are affected by an approximately 1 inch mid-lane settlement and unexplained seasonal variability in transverse profile elevation across the entire loaded lane.

- An unusual, composite (2-layer) base was utilized (4 inches of railroad ballast over 10 inches of CA-15 aggregate) which was designed as a solution to stability issues with the specified CA-15 aggregate. The composite base was lightly rolled prior to paving - an atypical practice in full-depth porous construction. However, the base appears to be performing well in terms of permeability and storage, indicating that the minor compaction of the base had no detrimental effect. There is not enough data about the composite base to form conclusions about its effect on rutting.
- Longitudinal roughness (IRI) on the porous cells was relatively high for newly constructed pavement (140 in/mi), and has increased only slightly. The higher Initial surface roughness is due to the special construction requirements on the 226 foot long test cells.
- The average back-calculated resilient modulus of cell 87 standard asphalt (PG 58-28 binder) is significantly higher than the porous asphalt (PG 70-28 binder). The porous asphalt develops increased stiffness later in the fall and loses stiffness earlier in the spring. The clay subgrade reduces base stiffness in cell 88, possibly by inhibiting drainage.
- The measured pavement strains in cell 88 (porous over clay) were higher than those in cell 86 (porous over sand). The porous HMA cells undergo more pavement strain than a comparable dense graded HMA. In some instances the porous pavement undergoes twice the strain of dense graded HMA under similar loading and temperature conditions. There is still not enough distress (no cracking) to form conclusions about either the effect of lower PA/base stiffness or the higher internal strains.
- As expected, the porous/pervious sections are quiet pavements with a maximum OBSI-measured sound intensity of approximately 101.2 dBA. Sound intensity decreases during warmer periods, possibly due to softening of the asphalt or higher moisture in the pavement voids. Sound absorption testing shows that the porous pavement has 5 times the sound absorption ability of standard HMA. The circular texture meter showed cells 86 and 88 have a slightly increasing surface texture in the loaded lane, which may be related to raveling.
- The skid resistance test demonstrated very good skid resistance with both the smooth and the ribbed tire tests, with an average FN of approximately 50. The smooth tire test results highlight the contribution of water absorption to skid resistance, as the PA pavement has about 50% better skid resistance than dense grade asphalt.
- Although the restricted traffic and minimal vegetation adjacent to the LVR do not introduce significant clogging agents to the porous pavement, mechanized vacuuming was performed - once in 2009 & 2010, and multiple times in 2011. The benefit of the vacuuming was difficult to quantify; there were issues related to reinstalling the permeameters in exactly the same location and the relatively high surface permeability made precise measurements difficult. However, vacuuming does appear to be having some beneficial effect on the permeability of the porous cells, and the accelerated rate of vacuuming in 2011 showed positive results. No other pavement maintenance or any repairs have been performed or needed on the porous cells since construction.

- Snow removal operations are the same as all other cells on the LVR, and some advantages in the rate of snow accumulation and melting have been observed (and monitored by time-lapse camera) on the porous cells. Snow and ice appears to melt faster (and moisture disappears after melting) on the PA cells than standard pavements – particularly when sunshine reaches the pavement. This has been observed even in very low ambient temperatures and frozen subsurface conditions. Better snow and ice melt (and less refreezing) on the porous pavement should decrease the need for expensive and undesirable salt applications in cold climates.
- Thermocouple data shows that the internal temperature of the porous pavement increases faster and more often than standard asphalt in late winter; the higher sun angle during that period could be contributing to higher internal temperatures (and the observed snow melt advantages). Subsurface heat transfer throughout the layers appears better in the PA cells; however the reason for that remains unknown without additional research.

7.2 ENVIRONMENTAL SUMMARY AND CONCLUSIONS

7.2.1 Filtration

- Sampling ports were installed at cells 88 and 86 to be used for substitute data collection but due to these ports were not capturing a given area of runoff nor had any water to analyze the filtering capabilities, filtration data could not be provided. Samples taken at the groundwater wells were taken at different times as the ports on cell 87 and 86 which made it difficult to make qualitative comparisons. Average values are provided which indicates that the porous asphalt reduces copper and zinc concentrations. Research from others confirms that porous pavement sections do provide reductions in zinc and copper.

7.2.2 Water Quality

- Water quality samples taken from sample ports in cell 86 and cell 88 were consistent between samples for all the parameters tested and most were within water quality standards for class 2 waters. Copper was higher in concentrations but was consistent with the groundwater concentrations in the area. Concentrations of chlorides were of concern as they were increasing between each of the samples taken; further testing showed that the concentrations dropped in 2011. Increasing concentrations were directly related to salting the road and having the test cells lined limiting groundwater flow thru the sections.
- Surface runoff samples taken from cells 86 and 87 were below water quality standards for class 2 waters.

7.2.3 Thermal Cooling

- Data from the thermocouple trees for the porous sections provided opportunities to analyze any cooling effects the sections may have as storm water passes through the porous pavement structure. During the summer months temperatures of the underlying soils are cooler than the surface soils for both non porous and porous sections. However the porous sections provided cooler temperatures comparatively for each depth in the thermocouple tree. As stormwater travels thru the porous section profile and into underlying soils it is cooled. Therefore porous pavement does provide a benefit to cool storm water prior to discharge to resource waters.

7.2.4 Lessons Learned

- After the lysimeters were not installed as planned, different methods for capturing water as it filters thought the pavement and ballast layers could have been discussed during the planning stages, and more than one option made available during construction, so that samples could be taken for water quality.
- Water quality samples of groundwater wells should have been taken at the same time as the sampling ports on cell 86 to get comparative results.
- Develop a process to make sure that equipment was working on a weekly or monthly basis.
- Provide for automated sampling at strategic locations in the site.

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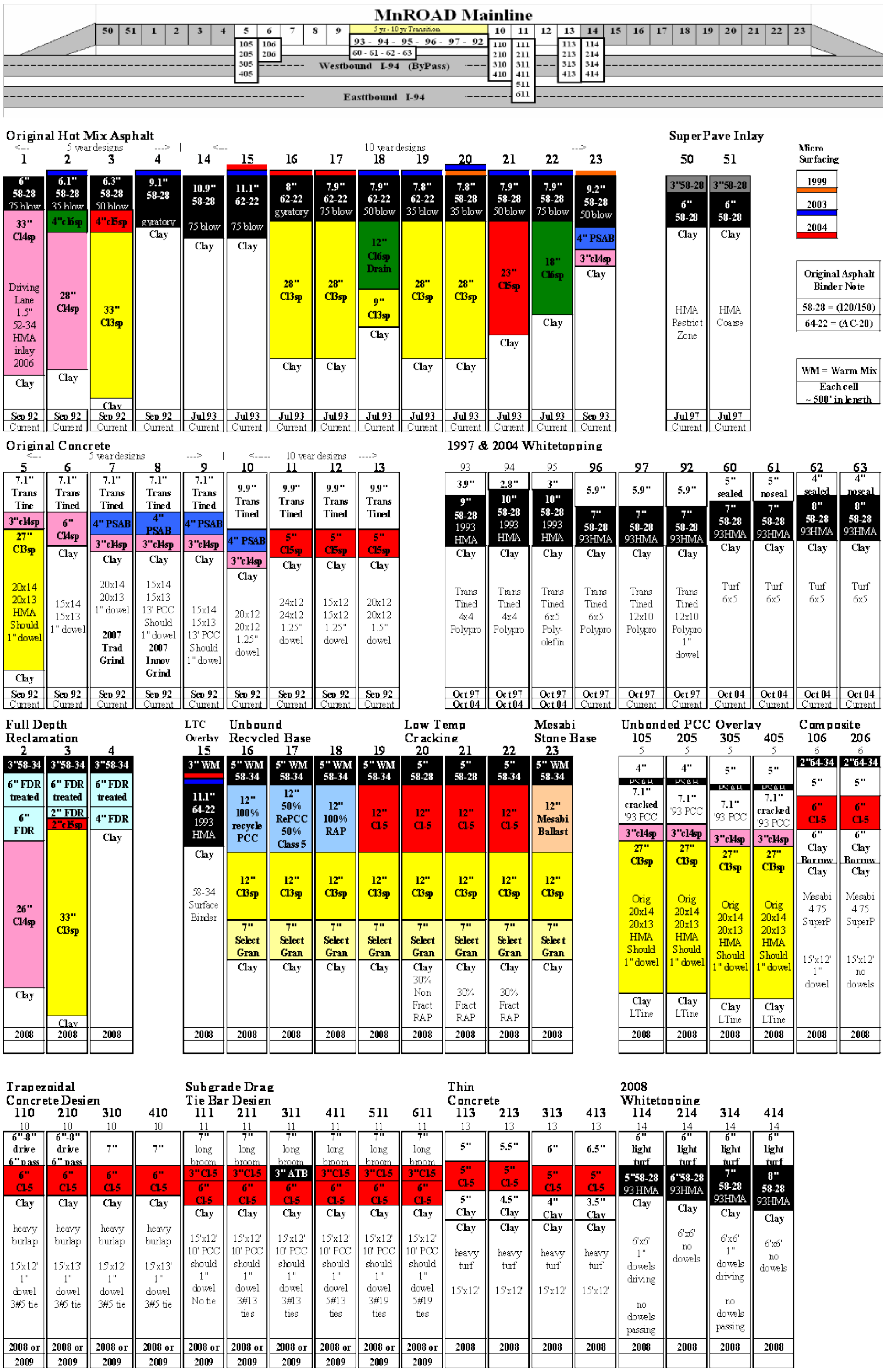
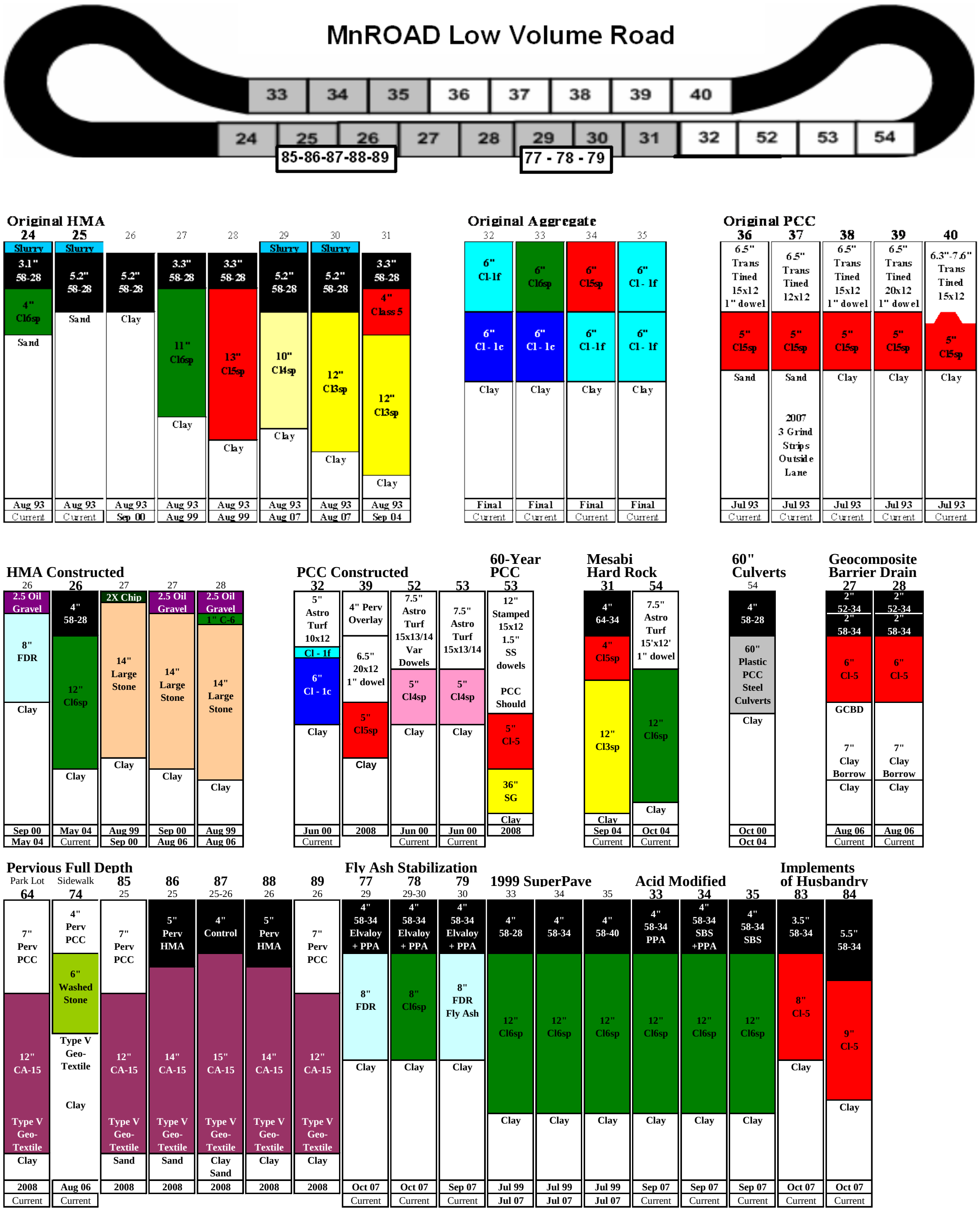
APPENDIX A: POST-PHASE II MNROAD MAINLINE AND LVR TEST SECTIONS

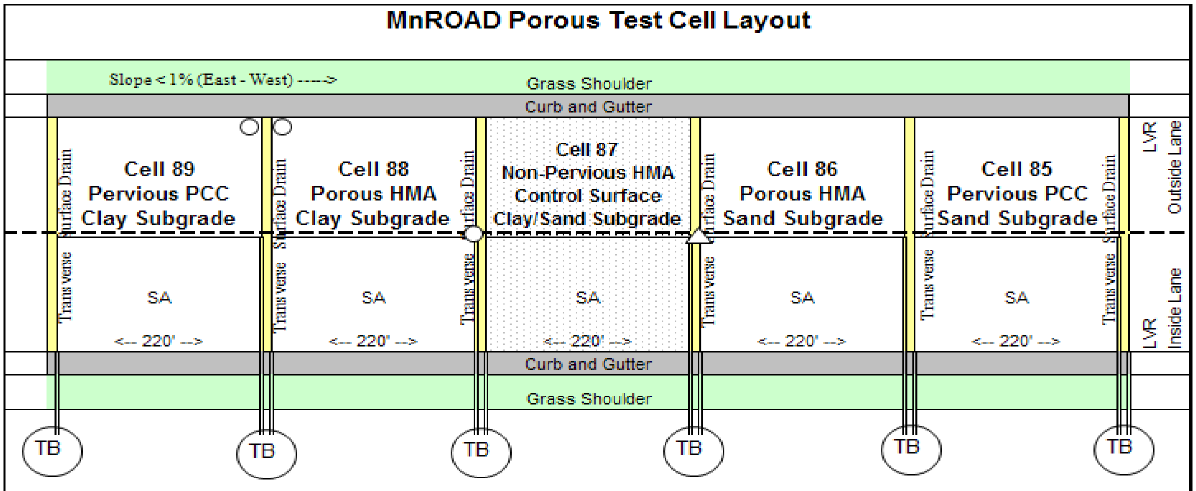


MnROAD "Mainline" Test Cell Layout.

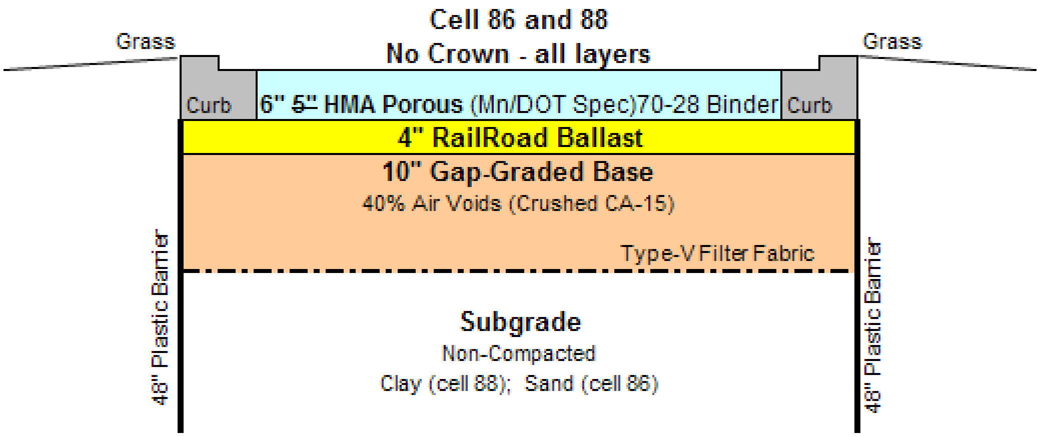


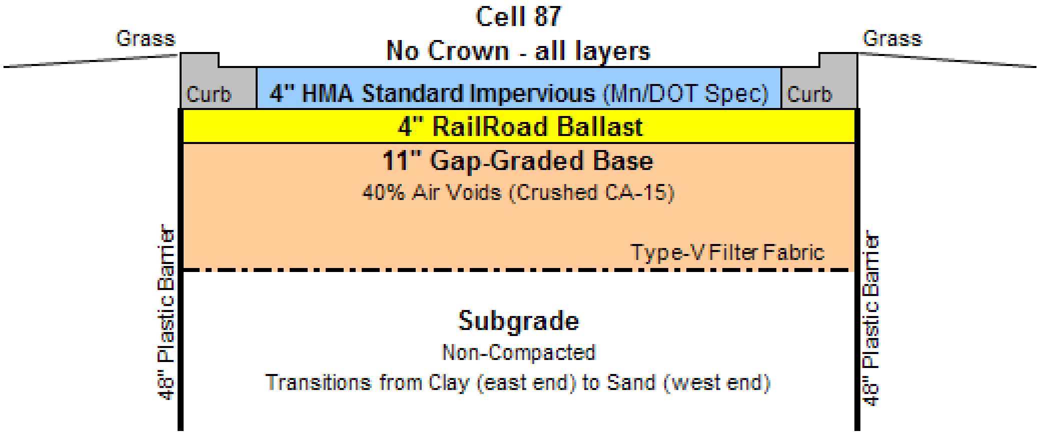
MnROAD “Low-Volume Road” (LVR) Test Cell Layout

APPENDIX B: AS-BUILT LAYOUTS CROSS SECTIONS FOR CELLS 86-88



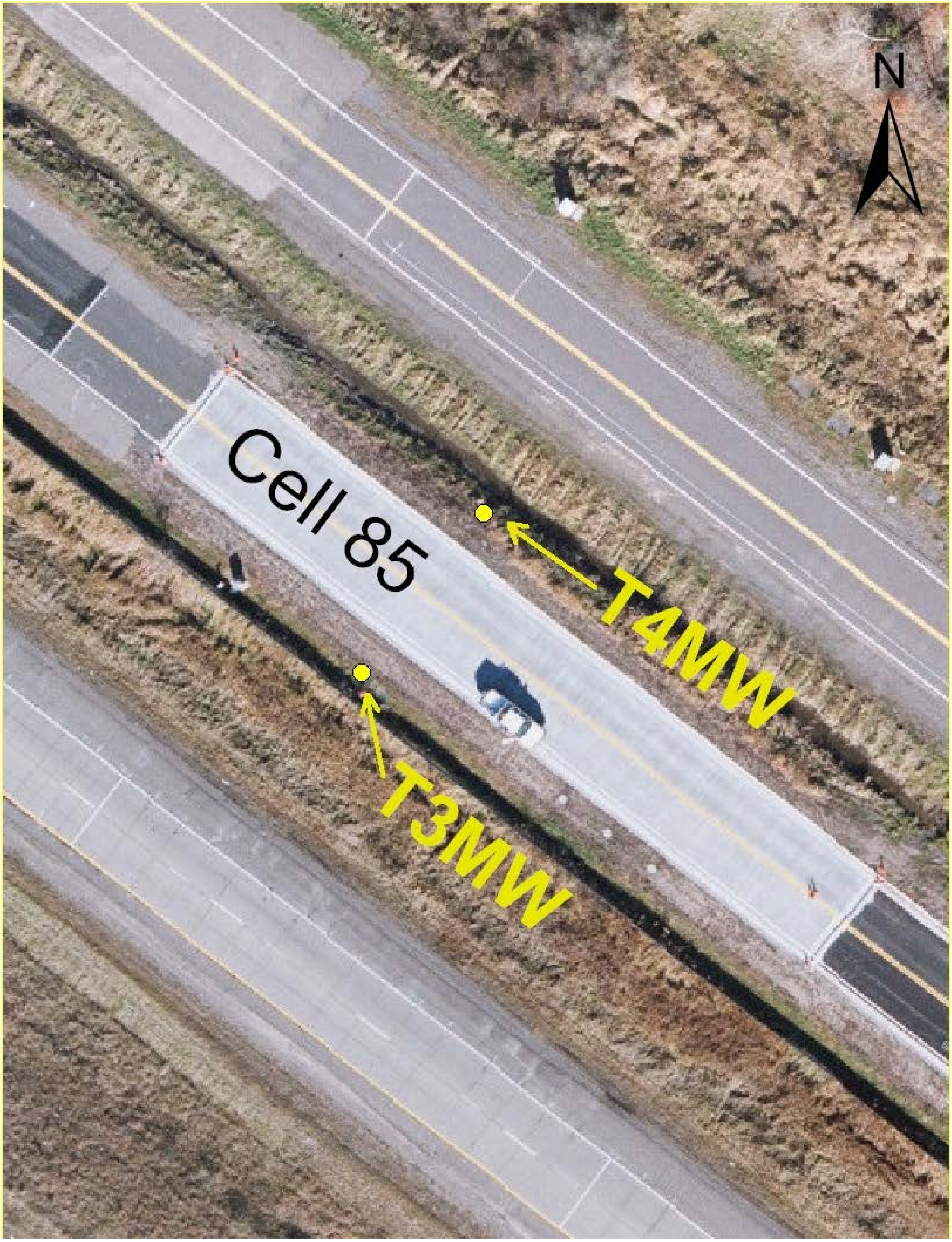
TB = Tipping Buckets (for SubSurface Drains)
SA = Sensor Area (Layout separate document)
MnROAD has two weather stations (includes rainfall)
Each Cell (220'x24') surrounded by a 48" vertical plastic barrier to isolate the materials
○= Water monitoring standpipe(location for base water sampling)
△= Water monitoring standpipe(location for subgrade water sampling)






N
Cell 85
Cell 86
Cell 87
Cell 88
Cell 89
Mainline Test Section
WB
I 94
EB

APPENDIX C: PIEZOMETER WELLS AND SAMPLING PORTS USED FOR PROJECT

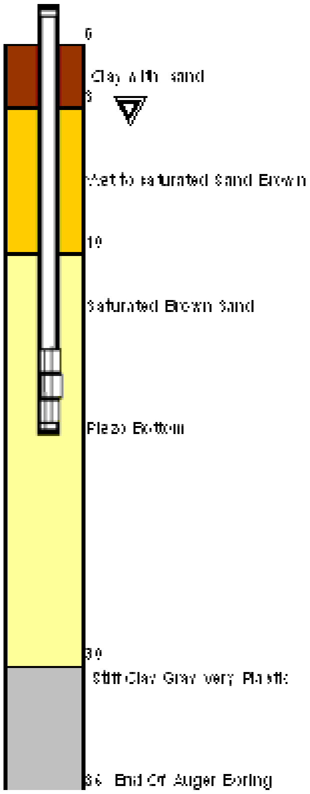

N
Cell 85
T4MW
T3MW

Cell 86 Sample Port

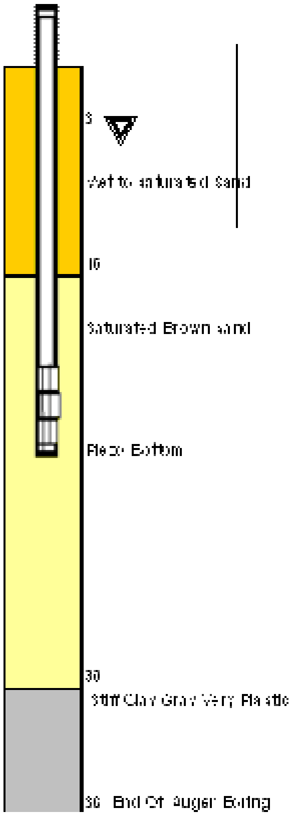
Cell 88 Tipping Bucket Sample Port

APPENDIX D: PIEZOMETER WELL BORINGS; WELLS # 1-4

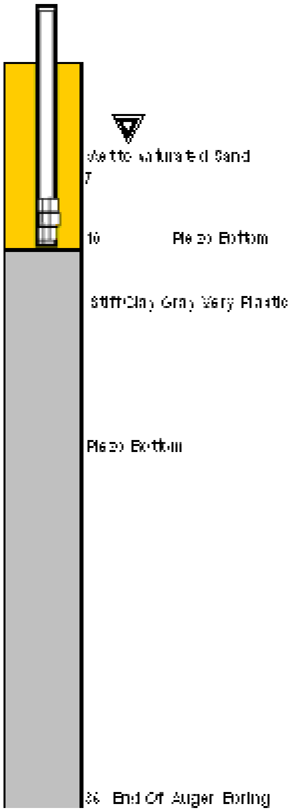
Pervious Well 1



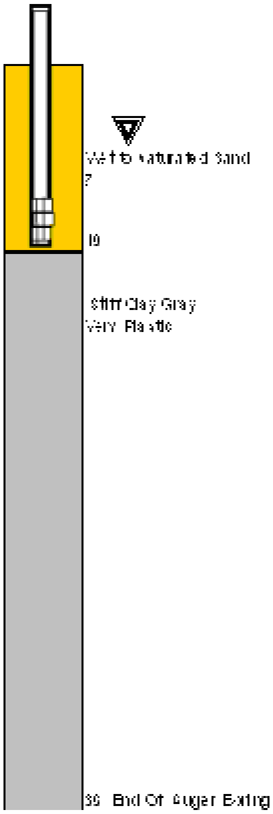
Pervious Well 2



Pervious Well 3

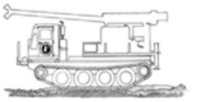


Pervious Well 4



APPENDIX E: CONE PENETROMETER (CPT) LOGS

Minnesota Department of Transportation
Geotechnical Section
Cone Penetration Test Index Sheet 1.0 (CPT 1.0)



USER NOTES, ABBREVIATIONS AND DEFINITIONS

This Index sheet accompanies Cone Penetration Test Data. Please refer to the Boring Log Descriptive Terminology Sheet for information relevant to conventional boring logs.

This Cone Penetration Test (CPT) Sounding follows ASTM D 5778 and was made by ordinary and conventional methods and with care deemed adequate for the Department's design purposes. Since this sounding was not taken to gather information relating to the construction of the project, the data noted in the field and recorded may not necessarily be the same as that which a contractor would desire. While the Department believes that the information as to the conditions and materials reported is accurate, it does not warrant that the information is necessarily complete. This information has been edited or abridged and may not reveal all the information which might be useful or of interest to the contractor. Consequently, the Department will make available at its offices, the field logs relating to this sounding.

Since subsurface conditions outside each CPT Sounding are unknown, and soil, rock and water conditions cannot be relied upon to be consistent or uniform, no warrant is made that conditions adjacent to this sounding will necessarily be the same as or similar to those shown on this log. Furthermore, the Department will not be responsible for any interpretations, assumptions, projections or interpolations made by contractors, or other users of this log.

Water pressure measurements and subsequent interpreted water levels shown on this log should be used with discretion since they represent dynamic conditions. Dynamic Pore water pressure measurements may deviate substantially from hydrostatic conditions, especially in cohesive soils. In cohesive soils, water pressures often take extended periods of time to reach equilibrium and thus reflect their true field level. Water levels can be expected to vary both seasonally and yearly. The absence of notations on this log regarding water does not necessarily mean that this boring was dry or that the contractor will not encounter subsurface water during the course of construction.

CPT Terminology

CPT ....Cone Penetration Test
CPTU...........Cone Penetration Test with Pore Pressure measurements
SCPTU ....Cone Penetration Test with Pore Pressure and Seismic measurements
Piezocone...Common name for CPTU test

(Note: This test is not related to the Dynamic Cone Penetrometer DCP)

q_T TIP RESISTANCE

The resistance at the cone corrected for water pressure. Data is from cone with 60 degree apex angle and a 10 cm^2 end area.

f_s SLEEVE FRICTION RESISTANCE

The resistance along the sleeve of the penetrometer.

FR Friction Ratio

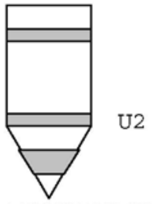
Ratio of sleeve friction over corrected tip resistance.
FR = fs/qt

V_s Shear Wave Velocity

A measure of the speed at which a siesmic wave travels through soil/rock.

PORE WATER MEASUREMENTS

Pore water measurements reported on CPT Log are representative of water pressures measured at the U2 location, just behind the cone tip, prior to the sleeve, as shown in the figure below. These measurements are considered to be dynamic water pressures due to the local disturbance caused by the cone tip. Dynamic water pressure decay and Static water pressure measurements are reported on a Pore Water Pressure Dissipation Graph.



SBT SOIL BEHAVIOR TYPE

Soil Classification methods for the Cone Penetration Test are based on correlation charts developed from observations of CPT data and conventional borings. Please note that these classification charts are meant to provide a guide to Soil Behavior Type and should not be used to infer a soil classification based on grain size distribution.

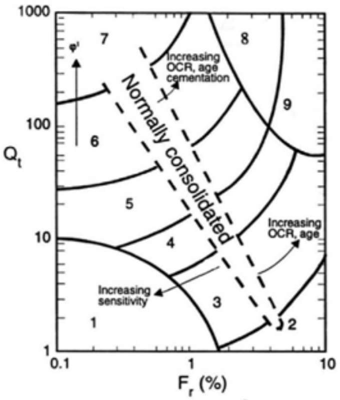
The numbers corresponding to different regions on the charts represent the following soil behavior types:

1. Sensitive, Fine Grained
2. Organic Soils - Peats
3. Clays - Clay to Silty Clay
4. Silt Mixtures - Clayey Silt to Silty Clay
5. Sand Mixtures - Silty Sand to Sandy Silt
6. Sands - Clean Sand to Silty Sand
7. Gravelly Sand to Sand
8. Very Stiff Sand to Clayey Sand
9. Very Stiff, Fine Grained

Note that engineering judgment, and comparison with conventional borings is especially important in the proper interpretation of CPT data in certain geo-materials.

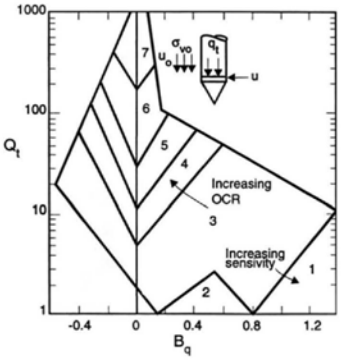
The following charts are used to provide a Soil Behavior Type for the CPT Data.

Robertson CPT 1990
Soil Behavior type based on friction ratio



$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \qquad F_r = \frac{f_s}{q_t - \sigma_{vo}} \times 100\%$$

Robertson CPTU 1990
Soil Behavior type based on pore pressure



$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \qquad B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}}$$

where ...

Q_T..........................normalized cone resistance
B_q..........................pore pressure ratio
F_r ....Normalized friction ratio
σ_{vo} ....overburden pressure
σ'_{vo} ....effective over burden pressure
u_2 ....measured pore pressure
u_0 ....equilibrium pore pressure

G:\GEOTECH\PUBLIC\FORMS\CPTINDEX.DOC January 30, 2002

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

CONE PENETRATION TEST RESULTS

UNIQUE NUMBER 69249

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Sounding No.	Ground Elevation
8680-157		I94	c01e	961.8 (OTM)

Location ft. LT

Wright Co. Coordinate: X=542794 Y=205298 (ft.)

Latitude (North)=45°15'58.06" Longitude (West)=93°43'01.70"

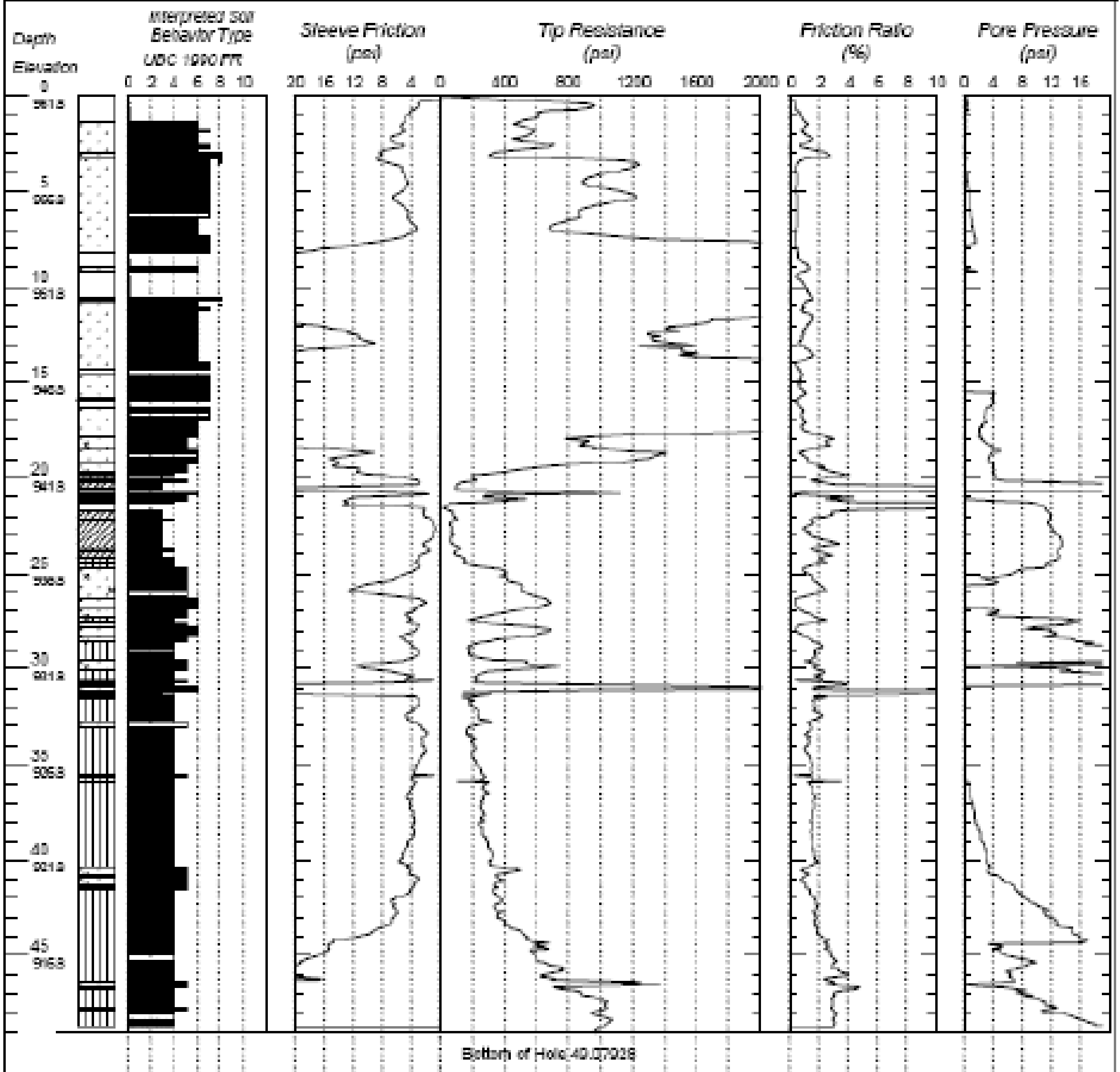
CPT Machine 203094 CPT Truck

CPT Operator R. Lueck

Hole Type CPT-STD

SHEET 1 of 1

Date Completed 11/13/07



Bottom of Hole 49.07928

Index Sheet Code 3.0

E13N0701C.DAT

Soil Class: Rock Class: Edit: Date: 3/16/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

CONE PENETRATION TEST RESULTS

UNIQUE NUMBER 69250

U.S. Customary Units

State Project **8680-157**	*Bridge No. or Job Desc.*	*Trunk Highway/Location* **I94**	*Sounding No.* **c02e**	*Ground Elevation* **961.6** *(DTM)*

Location , , ft. LT

Wright Co. Coordinate: X=542975 Y=205151 (ft.)

Latitude (North)=45°15'36.72" *Longitude (West)*=93°42'39.18"

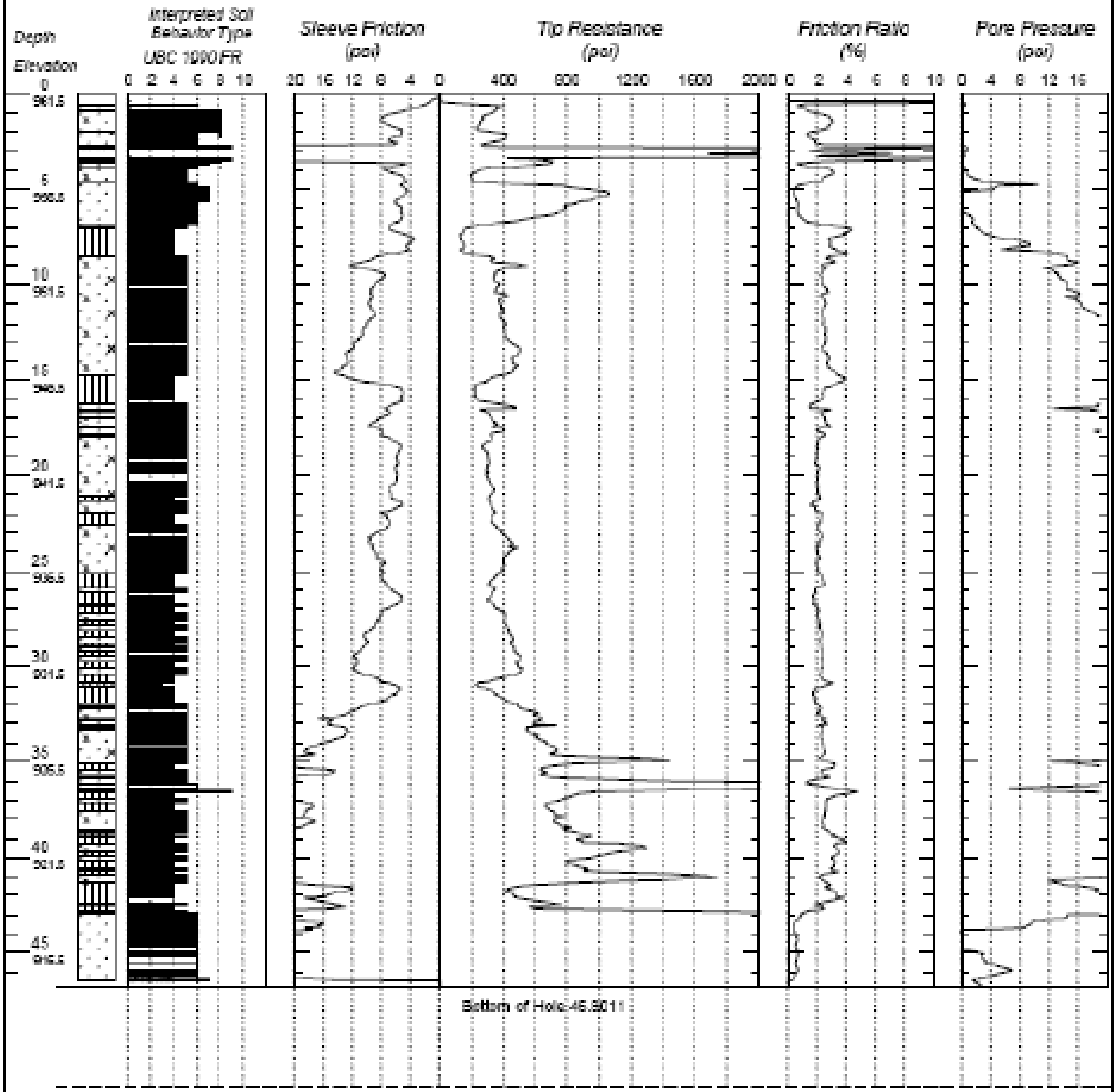
CPT Machine 203094 CPT Truck

CPT Operator **R. Lueck**

Hole Type CPT-STD

SHEET 1 of 1

Date Completed 11/13/07



Index Sheet Code 3.0 E13N0702C.DAT *Soil Class. Rock Class. Edit. Date: 3/16/05*

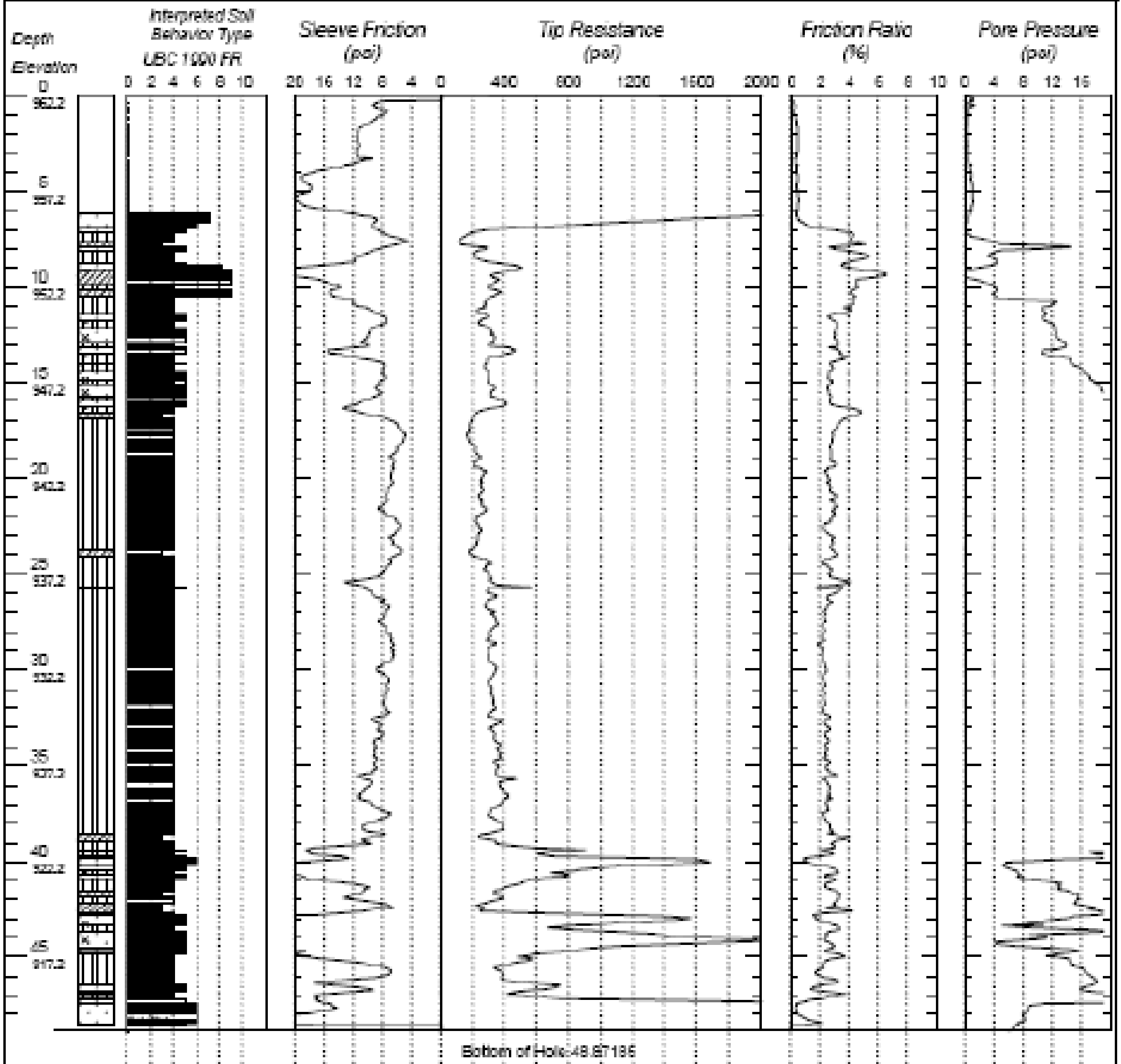
MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

CONE PENETRATION TEST RESULTS

UNIQUE NUMBER 69251

U.S. Customary Units

State Project **8680-157**	*Bridge No. or Job Desc.*	*Trunk Highway/Location* **I94**	*Sounding No.* **c03e**	*Ground Elevation* **962.2** *(DTM)*
Location **, , ft. LT** Wright Co. Coordinate: X=542942 Y=205120 (ft.) *Latitude (North)=45°15'36.48"* *Longitude (West)=93°42'59.64"*		*CPT Machine* 203I94 CPT Truck *CPT Operator* **R. Lueck** *Hole Type* CPT-STD		*SHEET 1 of 1* *Date Completed* **11/13/07**



Index Sheet Code 3.0 E13N0704C.DAT *Soil Class: Rock Class: Edit: Date: 3/18/08*

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

CONE PENETRATION TEST RESULTS

UNIQUE NUMBER 69252

U.S. Customary Units

State Project 8680-157	Bridge No. or Job Desc.	Trunk Highway/Location I94	Sounding No. c04e	Ground Elevation 962.1 (DTM)

Location , , ft. LT

Wright Co. Coordinate: X=542835 Y=206204 (ft.)

Latitude (North)=45°15'57.25" Longitude (West)=93°43'01.13"

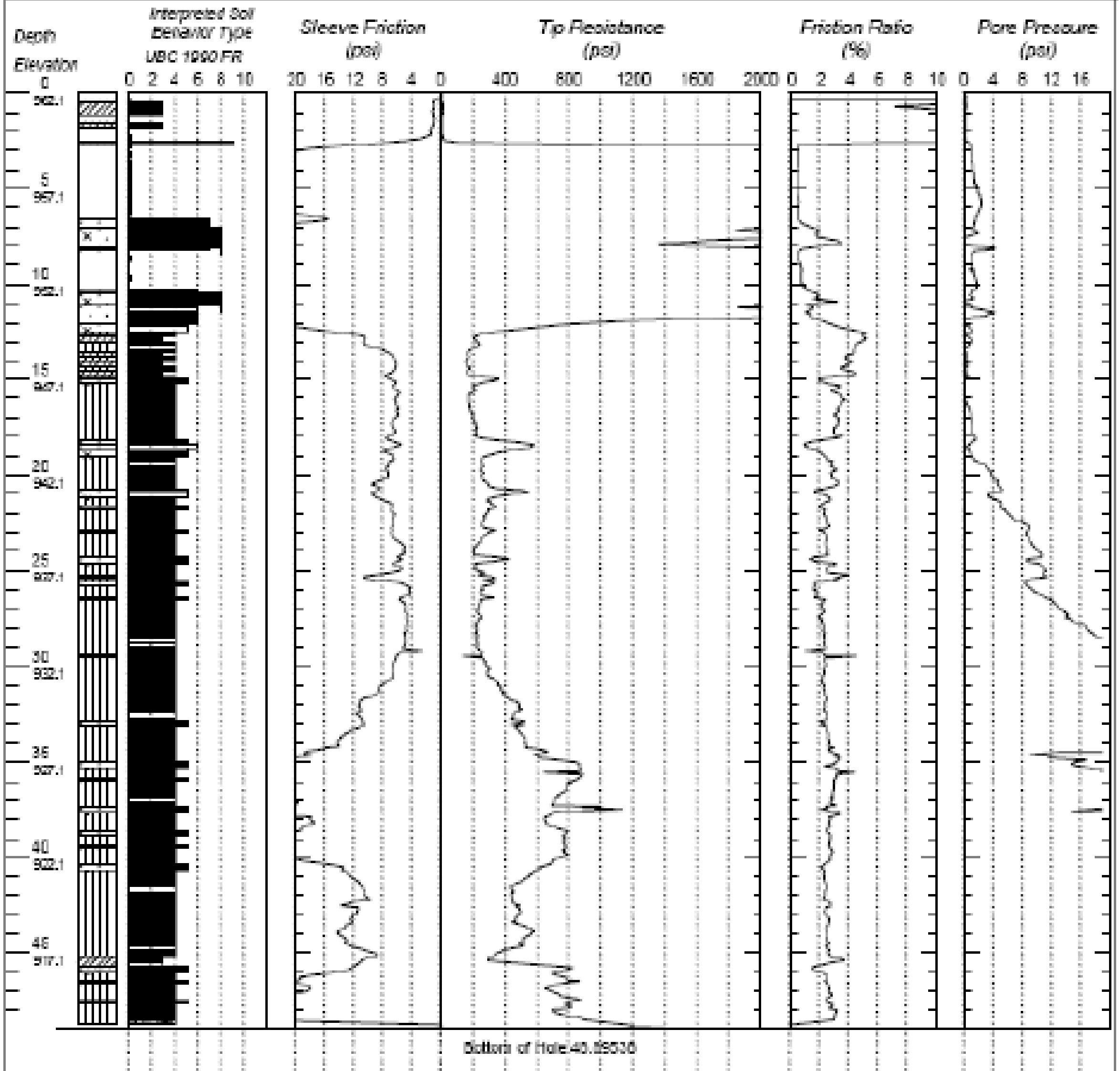
CPT Machine 203094 CPT Truck

CPT Operator R. Lueck

Hole Type CPT-8TD

SHEET 1 of 1

Date Completed 11/13/07



Bottom of Hole 48.89530

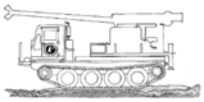
Index Sheet Code 3.0

E13N0705C.DAT

Soil Class: Rock Class: Edit: Date: 3/18/08

APPENDIX F: FOUNDATION BORING LOGS

Minnesota Department of Transportation
Geotechnical Section
Boring Log Descriptive Terminology (English Units)



USER NOTES, ABBREVIATIONS AND DEFINITIONS - Additional information available in Geotechnical Manual.

This boring was made by ordinary and conventional methods and with care deemed adequate for the Department's design purposes. Since this boring was not taken to gather information relating to the construction of the project, the data noted in the field and recorded may not necessarily be the same as that which a contractor would desire. While the Department believes that the information as to the conditions and materials reported is accurate, it does not warrant that the information is necessarily complete. This information has been edited or abridged and may not reveal all the information which might be useful or of interest to the contractor. Consequently, the Department will make available at its offices, the field logs relating to this boring.

Since subsurface conditions outside each borehole are unknown, and soil, rock and water conditions cannot be relied upon to be consistent or uniform, no warrant is made that conditions adjacent to this boring will necessarily be the same as or similar to those shown on this log. Furthermore, the Department will not be responsible for any interpretations, assumptions, projections or interpolations made by contractors, or other users of this log.

Water levels recorded on this log should be used with discretion since the use of drilling fluids in borings may seriously distort the true field conditions. Also, water levels in cohesive soils often take extended periods of time to reach equilibrium and thus reflect their true field level. Water levels can be expected to vary both seasonally and yearly. The absence of notations on this log regarding water does not necessarily mean that this boring was dry or that the contractor will not encounter subsurface water during the course of construction.

WR	Weight of Rod
Mud	Drilling Fluids in Sample
CS	Continuous Sample

SOIL/CORE TESTS

SPT N_{60} ..... ASTM D1586 Modified Blows per foot with 140 lb. hammer and a standard energy of 210 ft-lbs. This energy represents 60% of the potential energy of the system and is the average energy provided by a Rope & Cathead system.

MC	Moisture Content
COH	Cohesion
•	Sample Density
LL	Liquid Limit
PI	Plasticity Index
F	Phi Angle
REC	Percent Core Recovered
RQD	Rock Quality Description

(Percent of total core interval consisting of unbroken pieces 4 inches or longer)

ACL .... Average Core Length (Average length of core that is greater than 4 inches long)

Core Breaks . Number of natural core breaks per 2-foot interval.

DISCONTINUITY SPACING

Fractures	Distance	Bedding
Very Close	<2 inches	Very Thin
Close	2-12 inches	Thin
Mod. Close	12-36 inches	Medium
Wide	>36 inches	Thick

RELATIVE DENSITY

Compactness - Granular Soils	BPF
very loose	0-4
loose	5-10
medium dense	11-24
dense	25-50
very dense	>50

Consistency - Cohesive Soils	BPF
very soft	0-1
soft	2-4
firm	5-8
stiff	9-15
very stiff	16-30
hard	31-60
very hard	> 60

COLOR

blk	Black	**wht**	White
grn	Green	**brn**	Brown
orng	Orange	**yel**	Yellow
dk	Dark	**lt**	Light
IOS	Iron Oxide Stained		

GRAIN SIZE /PLASTICITY

VF	Very Fine	**pl**	Plastic
F	Fine	**slpl**	Slightly Plastic
Cr	Coarse		

SOIL/ROCK TERMS

C	Clay	**Lmst**	Limestone
L	Loam	**Sst**	Sandstone
S	Sand	**Dolo**	Dolostone
Si	Silt	**wx**	weathered
G	Gravel (No. 10 Sieve to 3 inches)		
Bldr	Boulder (over 3 inches)		
T	till (unsorted, nonstratified glacial deposits)		

WATER MEASUREMENT

AB	After Bailing
AC	After Completion
AF	After Flushing
w/C	with Casing
w/M	with Mud
WSD	While Sampling/Drilling
w/AUG	with Hollow Stem Auger

MISCELLANEOUS

NA	Not Applicable
w/	with
w/o	with out
sat	saturated

DRILLING OPERATIONS

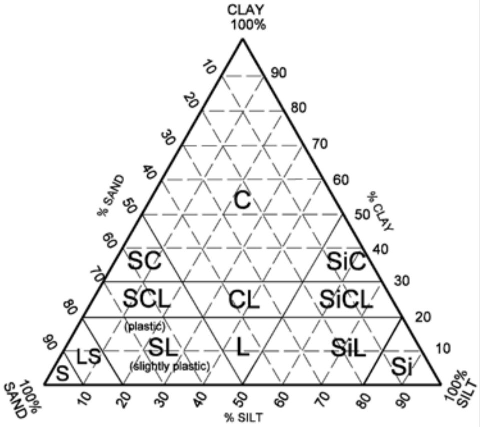
AUG	Augered
CD	Core Drilled
DBD	Disturbed by Drilling
DBJ	Disturbed by Jetting
PD	Plug Drilled
ST	Split Tube (SPT test)
TW	Thinwall (Shelby Tube)
WS	Wash Sample
NSR	No Sample Retrieved
WH	Weight of Hammer

Index Sheet No. 3.0 July 1997

DRILLING SYMBOLS

◫	**Vane Shear Test**
WS	**Washed Sample** Collected during plug drilling
≀	**Augered**
PD	**Plug Drilled** (Rotary drilled with fluid)
☒	**Split Tube Sample** (SPT N_{60} with 2 in. split tube with liners)
▩	**Thin Wall Sample** (3 inch Thin Wall Tube)
▮	**Core Drilled** (NV Core Barrel, unless otherwise noted)
CS	**Continuous Soil Sample**
A/P	**Augered and Plug Drilled**
Jet	**Jetted**
A/J	**Augered and Jetted**

Mn/DOT TRIANGULAR TEXTURAL CLASSIFICATION SYSTEM



MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 70089

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
9680-157		Interstate Highway I94	T1MW	960.1 (survey)

Location , , ft. LT
Wright Co. Coordinate: X=542570 Y=205391 (ft.)
Latitude (North)=45°15'39.10" Longitude (West)=93°43'04.83"

Drill Machine 205120 CME(LC55) Track
Hammer CME Automatic Calibrated
SHEET 1 of 1
Drilling Completed 2/13/08

Depth Elev.	Classification	SPT N60 REC (%)	MC (%) RQD (%)	COH (psf) ACL (ft)	γ (pcf) Core Breaks	Other Tests Or Remarks Formation or Member
	slightly plastic Sandy Loam with a few pebbles, dark gray-brown and moist		16			
4.0 956.1	plastic Loam, grays and moist	8	23			
5.0 954.1	Loamy Sand with some Gravel and a few pockets of plastic Sandy Loam, brown to gray-brown, moist to wet	48	10			
		12	16			
		9	16			
		6	15			
		18	20			
22.0 938.1	Loamy Sand and Gravel, brown and saturated	43	16			
25.5 934.6						

Bottom of Hole - 25.5'
Water measured at 9.6' while sampling and/or drilling with augers

Index Sheet Code 3.0

Soil Class:DSB Rock Class: Edit: Date: 3/18/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 70089

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
8680-157		Interstate Highway I94	T1MW	960.1 (survey)

Location , , ft. LT
Wright Co. Coordinate: X=642670 Y=206391 (ft.)
Latitude (North)=45°15'59.10" Longitude (West)=93°43'04.93"

Drill Machine 205120 CME(LC55) Track
Hammer CME Automatic Calibrated
SHEET 1 of 1
Drilling Completed 2/13/08

DEPTH	Depth Elev.	Classification	SPT N_{60} REC (%)	MC (%) RQD (%)	COH (psf) ACL (ft)	γ (pcf) Core Breaks	Other Tests Or Remarks Formation or Member
		slightly plastic Sandy Loam with a few pebbles, dark gray-brown and moist		15			
5	4.0 956.1	plastic Loam, grays and moist	8	23			
	6.0 954.1	Loamy Sand with some Gravel and a few pockets of plastic Sandy Loam, brown to gray-brown, moist to wet	48	10			
10			12	16			
			9	16			
15			6	15			
20			18	20			
25	22.0 938.1	Loamy Sand and Gravel, brown and saturated	43	16			
	25.5 934.6						

Bottom of Hole - 25.5'
Water measured at 9.6' while sampling and/or drilling with augers

Index Sheet Code 3.0

Soil Class:D35 Rock Class: Edit: Date: 3/18/08
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

PIEZOMETER LOG & WATER LEVEL READINGS

UNIQUE NUMBER 70089 **MDH Number 577314**

Boring Log Addendum

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.
8680-157		I94	T1MW

Location

Wright Co. Coordinate: X=542570 Y=205391

Latitude (North)=45°15'59.10" Longitude (West)=93°43'04.83"

Drill Machine 205120 CME(LC55) Track

Ground Elevation 960.1 ()

Supervisor J. Hasselquist

Operator D. Zerwas

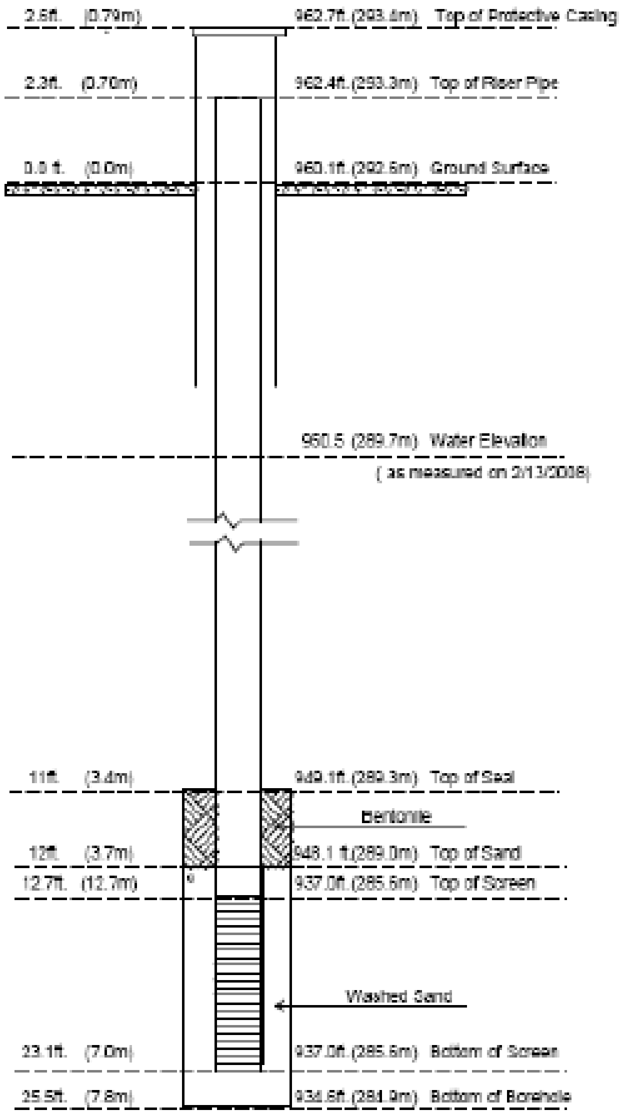
Install Date 2/13/2008

Sealed by

Seal Date

Seal Licensee

[illegible]



Interior Casing / Riser Pipe Details	
Type of Riser Pipe	2" PVC
Diameter of Riser Pipe	2 inch
Top of Riser Pipe	2.3 feet
Total Length of Riser Pipe	15
Screen Details	
Type of Screen	PVC
Diameter of Screen	2 inch
Screen Slot Size	0.01 slot
Depth to Top of Screen	12.7 feet
Screen Length	10.4 feet
Depth to Bottom of Screen	23.1 feet
Protective Casing Details	
Type of Casing	Steel
Diameter of Casing	6 inch
Height of Top of Casing	2.6 feet
Total Casing Length	7 feet
Lock Type & Number	2108
Diameter of Borehole	8 inch
Annular Space and Seal Details	
Type of Surface Seal	Bentonite/Cement
Type of Annular Seal	Native material
Type of Screen Seal	Bentonite
Type of Sand Pack	Washed Sand
Source of Sand	Mother Earth
Amount of Sand (pounds)	150
Type of Bottom Seal	Native material

Soil Class:DSB Rock Class: Edit: Date: 3/18/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 70090

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
8680-157		**Interstate Highway I94**	**T2MW**	**960.7** (survey)

Location , , **ft. LT**
Wright Co. Coordinate: X=540803 Y=205440 (ft.)
Latitude (North)=45°15'59.58" Longitude (West)=93°43'04.37"

Drill Machine **205120 CME(LC55) Track**
SHEET 1 of 1
Hammer **CME Automatic Calibrated**
Drilling Completed 2/13/08

DEPTH	Depth / Elev.	Classification	SPT N60 / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Other Tests Or Remarks / Formation or Member
	4.0 956.7	Loamy Sand with some Fine Gravel, dark brown and moist		8			
5		Sand with a little Gravel and a layer of Clay Loam, brown with gray, moist to wet	7	19			
▼	8.5 952.2		9	16			
10	12.0 948.7	Loamy Sand and Gravel, brown and saturated	5	15			
15		Loamy Sand with a little Gravel and a seam of plastic Sandy Loam, gray-brown and saturated	15	15			
20			22	14			
25	25.5 935.2		W/R	14			

Bottom of Hole - 25.5'
Water measured at 7.6' while sampling and/or drilling

Index Sheet Code 3.0
Soil Class:DSB Rock Class: Edit: Date: 3/18/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

PIEZOMETER LOG & WATER LEVEL READINGS

UNIQUE NUMBER 70090 **MDH Number 577321**

Boring Log Addendum

State Project 8680-157	*Bridge No. or Job Desc.*	*Trunk Highway/Location* I94	*Boring No.* T2MW

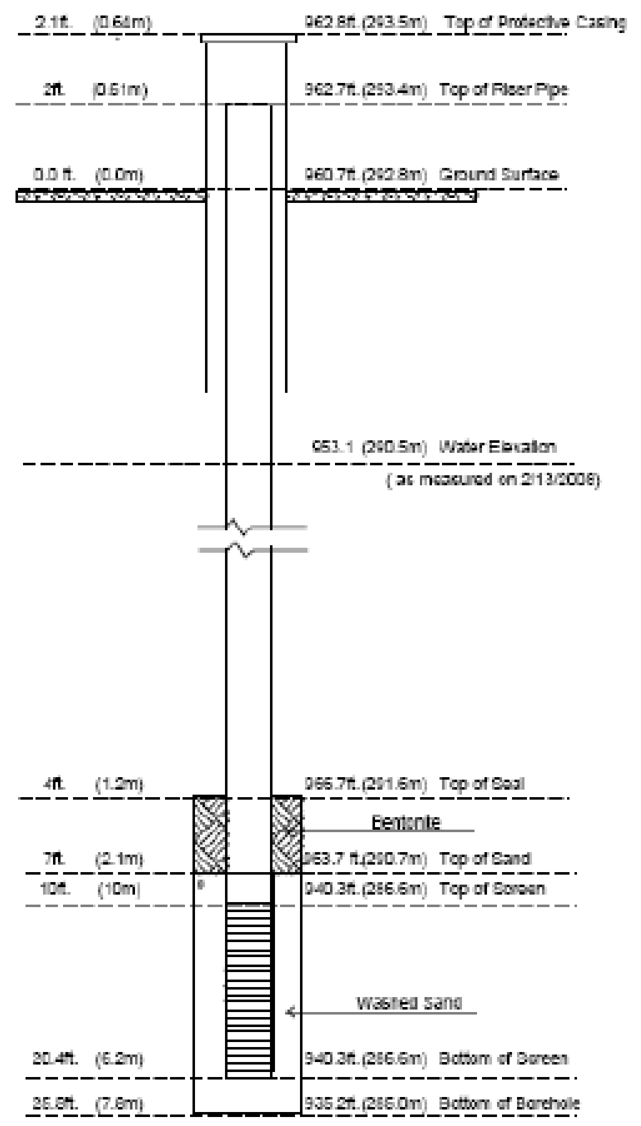
Location

Wright Co. Coordinate: X=542603 Y=205440

Latitude (North)=45°15'50.58" Longitude (West)=93°43'04.37"

Drill Machine	205120 CME(LC55) Track	*Ground Elevation*	960.7
Supervisor	J. Hasselquist		
Operator	D. Zerwas	*Install Date*	2/13/2008
Sealed by		*Seal Date*	
Seal Licensee			

If sealing details are blank, well has not been sealed as of time of printing (bottom right)



Interior Casing / Riser Pipe Details	
Type of Riser Pipe	2" PVC
Diameter of Riser Pipe	2 inch
Top of Riser Pipe	2 feet
Total Length of Riser Pipe	12
Screen Details	
Type of Screen	PVC
Diameter of Screen	2 inch
Screen Slot Size	0.01 slot
Depth to Top of Screen	10 feet
Screen Length	10.4 feet
Depth to Bottom of Screen	20.4 feet
Protective Casing Details	
Type of Casing	Steel
Diameter of Casing	6 inch
Height of Top of Casing	2.1 feet
Total Casing Length	7 feet
Lock Type & Number	2100
Diameter of Borehole	8 inch
Annular Space and Seal Details	
Type of Surface Seal	Bentonite/Cement
Type of Annular Seal	Bentonite
Type of Screen Seal	Bentonite
Type of Sand Pack	Washed Sand
Source of Sand	Mother Earth
Amount of Sand (pounds)	150
Type of Bottom Seal	Native material

Soil Class:DSB Rock Class: Edit: Date: 3/18/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 70091

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
8680-157		Interstate Highway I94	T3MW	960.9 (survey)

Location , , ft. LT
Wright Co. Coordinate: X=542934 Y=205116 (ft.)
Latitude (North)=45°15'56.37" Longitude (West)=93°42'59.75"

Drill Machine 205120 CME(LC55) Track
SHEET 1 of 1
Hammer CME Automatic Calibrated
Drilling completed 2/14/08

Depth / Elev.	Classification	SPT N_{60} / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (psf) / Core Breaks	Other Tests Or Remarks / Formation or Member
4.0 956.9	organic plastic Loam, black and moist		20			
7.0 953.9	slightly plastic Fine Sandy Loam, marbled light brown and light gray, moist	16	20			
12.0 948.9	slightly plastic Sandy Loam with a few pebbles, light gray-brown and moist	16	19			
22.0 938.9	Sandy Clay Loam with a few pebbles, gray-brown to gray, moist	13 15	18 17			
27.0 933.9	plastic Sandy Loam with some pebbles, gray and damp	27	15			
30.5 930.4	Sandy Clay Loam with a few pebbles, gray and moist	21	17			

Bottom of Hole - 30.5'
Water measured at 11.5' with auger

Index Sheet Code 3.0

Soil Class: Rock Class: Edit: Date: 3/18/08
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

PIEZOMETER LOG & WATER LEVEL READINGS

UNIQUE NUMBER 70091 **MDH Number 577322**

Boring Log Addendum

State Project 8680-157	*Bridge No. or Job Desc.*	*Trunk Highway/Location* I94	*Boring No.* T3MW

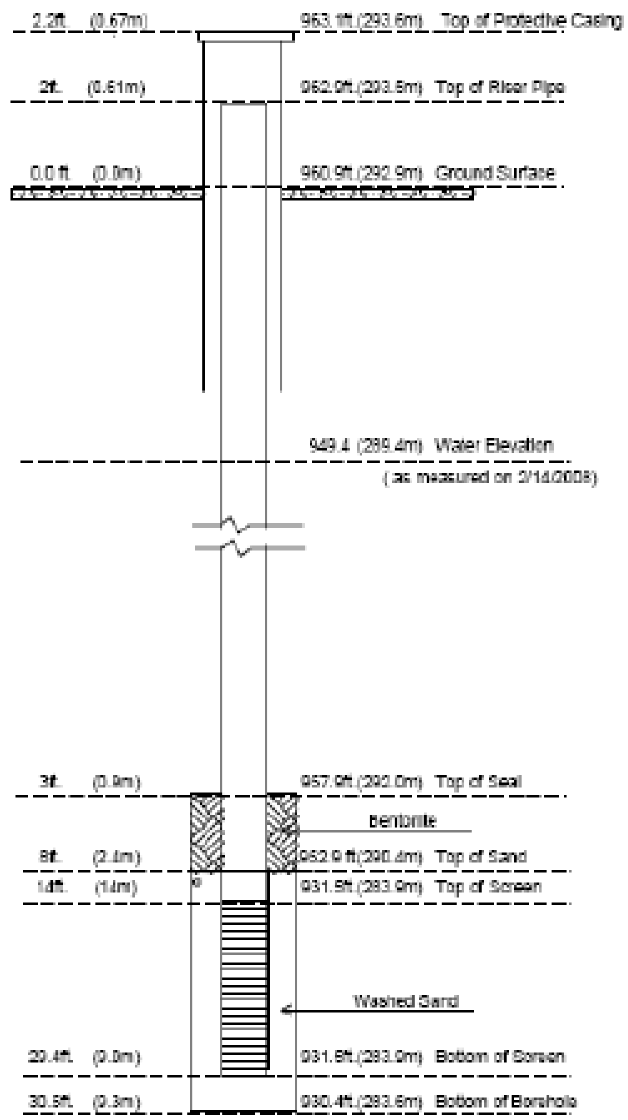
Location

Wright Co. Coordinate: X=542934 Y=205116

Latitude (North)=45°15'56.37" *Longitude (West)=93°42'59.75"*

Drill Machine	205120 CME(LC55) Track	*Ground Elevation*	960.9
Supervisor	J. Hasselquist		
Operator	D. Zerwas	*Install Date*	2/14/2008
Sealed by		*Seal Date*	
Seal Licensee			

If sealing details are blank, well has not been sealed as of time of printing (bottom right).



Interior Casing / Riser Pipe Details	
Type of Riser Pipe	2" PVC
Diameter of Riser Pipe	2 inch
Top of Riser Pipe	2 feet
Total Length of Riser Pipe	16
Screen Details	
Type of Screen	PVC
Diameter of Screen	2 inch
Screen Slot Size	0.01 slot
Depth to Top of Screen	14 feet
Screen Length	15.4 feet
Depth to Bottom of Screen	29.4 feet
Protective Casing Details	
Type of Casing	Steel
Diameter of Casing	6 inch
Height of Top of Casing	2.2 feet
Total Casing Length	7 feet
Lock Type & Number	2108
Diameter of Borehole	8 inch
Annular Space and Seal Details	
Type of Surface Seal	Bentonite/Cement
Type of Annular Seal	Bentonite
Type of Screen Seal	Bentonite
Type of Sand Pack	Washed Sand
Source of Sand	Mother Earth
Amount of Sand (pounds)	500
Type of Bottom Seal	Native material

Soil Class: Rock Class: Edit: Date: 3/18/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 70092

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
8680-157		Interstate Highway I94	T4MW	961.6 (survey)

Location , , ft. LT
Wright Co. Coordinate: X=542908 Y=205158 (ft.)
Latitude (North)=45°15'36.79" Longitude (West)=93°42'39.27"

Drill Machine 205120 CME(LC55) Track
SHEET 1 of 1
Hammer CME Automatic Calibrated
Drilling Completed 2/14/08

Depth Elev.	Classification	SPT N60	MC (%)	COH (psf)	γ (pcf)	Other Tests Or Remarks
4.5 957.1	plastic Sandy Loam, gray, moist to wet		18 26			
7.0 954.6	Sand with a little Gravel, brown and saturated	16	14			
12.0 949.6	plastic Sandy Loam with a few pebbles, brown and moist	17	19			
22.0 939.6	Sandy Clay Loam with some pebbles, gray and moist	15 19	17 16			
30.5 931.1	plastic Sandy Loam with a few pebbles, gray and damp	26 26	16 16			

Bottom of Hole - 30.5'
Water measured at 8.5' while sampling and/or drilling

Index Sheet Code 3.0

Soil Class: Rock Class: Edit: Date: 3/18/08

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

PIEZOMETER LOG & WATER LEVEL READINGS

UNIQUE NUMBER 70092 MDH Number 577323

Boring Log Addendum

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*
8680-157		I94	T4MW

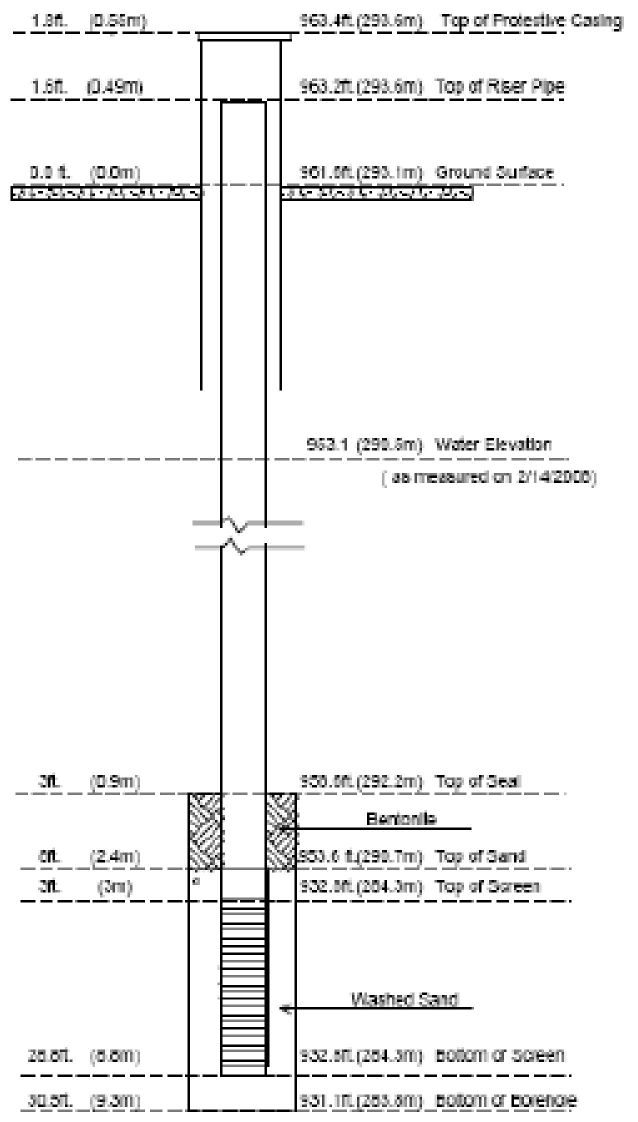
Location

Wright Co. Coordinate: X=542958 Y=205158

Latitude (North)=45°15'56.79' *Longitude (West)=93°42'59.27"*

Drill Machine	205120 CME(LC55) Track	*Ground Elevation*	961.6 ()
Supervisor	J. Hasselquist		
Operator	D. Zerwas	*Install Date*	2/14/2008
Sealed by		*Seal Date*	
Seal Licensee			

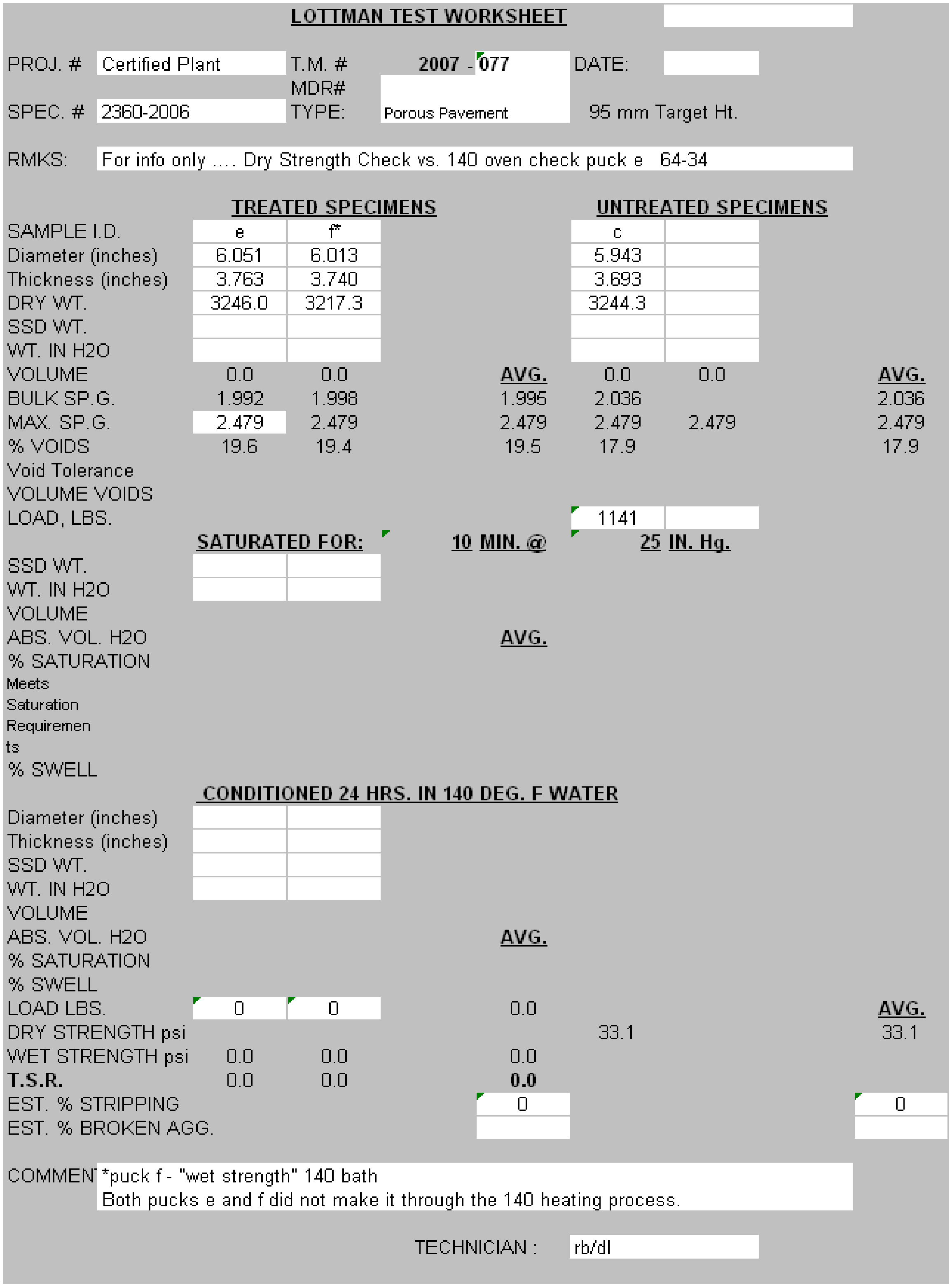
If sealing details are blank, well has not been sealed as of time of printing (bottom right).



Interior Casing / Riser Pipe Details	
Type of Riser Pipe	2" PVC
Diameter of Riser Pipe	2 inch
Top of Riser Pipe	1.6 feet
Total Length of Riser Pipe	10
Screen Details	
Type of Screen	PVC
Diameter of Screen	2 inch
Screen Slot Size	0.01 slot
Depth to Top of Screen	3 feet
Screen Length	20.4 feet
Depth to Bottom of Screen	28.8 feet
Protective Casing Details	
Type of Casing	Steel
Diameter of Casing	6 inch
Height of Top of Casing	1.8 feet
Total Casing Length	7 feet
Lock Type & Number	2108
Diameter of Borehole	8 inch
Annular Space and Seal Details	
Type of Surface Seal	Neat cement
Type of Annular Seal	Bentonite
Type of Screen Seal	Bentonite
Type of Sand Pack	Washed Sand
Source of Sand	Mother Earth
Amount of Sand (pounds)	500
Type of Bottom Seal	Native material

Soil Class: Rock Class: Edit: Date: 3/18/08

APPENDIX G: POROUS ASPHALT LOTTMAN TEST RESULTS



LOTTMAN TEST WORKSHEET

PROJ. # Certified Plant T.M. # **2007 - 077** DATE:
MDR#
SPEC. # 2360-2006 TYPE: Porous Pavement 95 mm Target Ht.

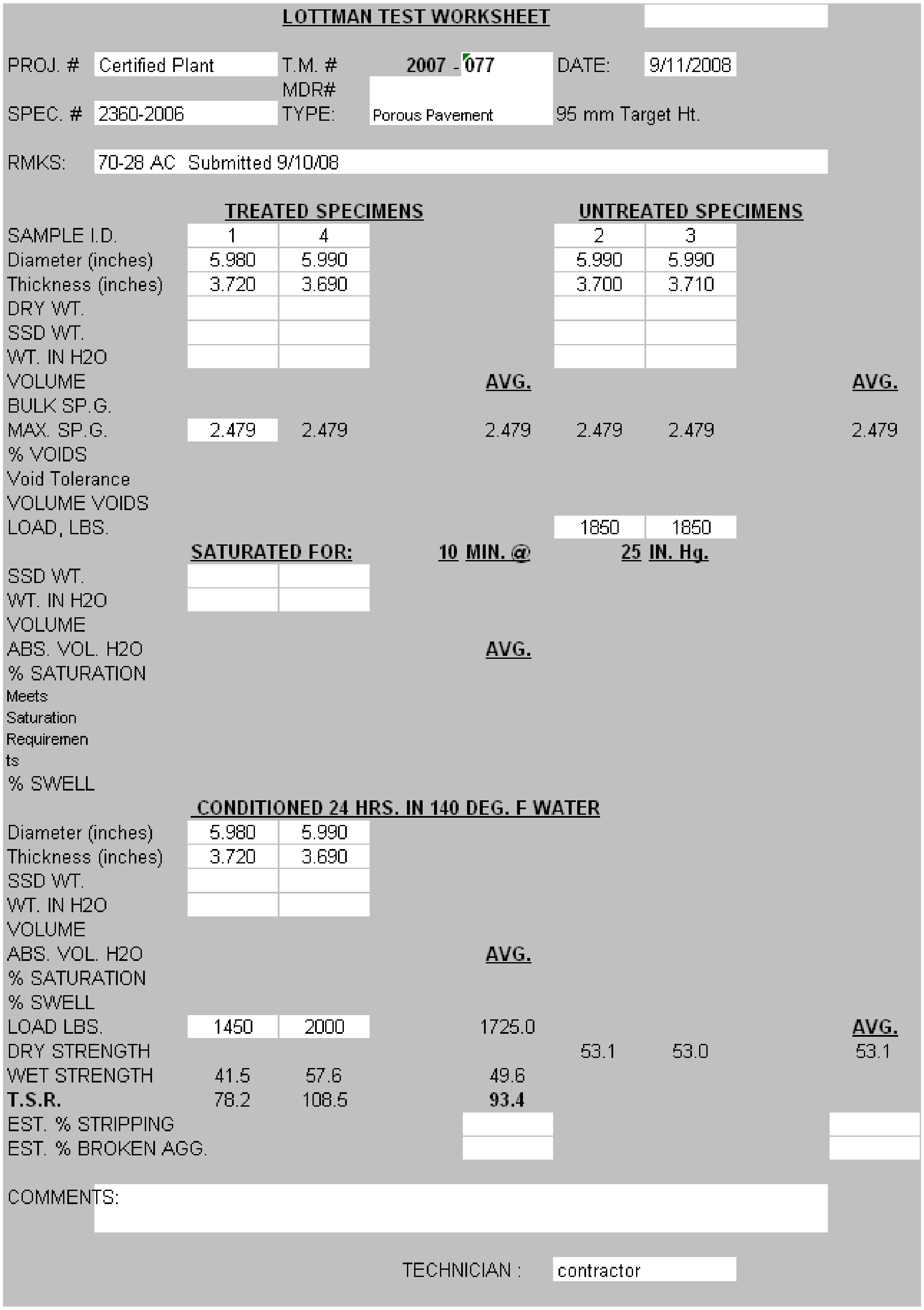
RMKS: For info only .... Dry Strength Check vs. 140 oven check puck e 64-34

	TREATED SPECIMENS			**UNTREATED SPECIMENS**		
SAMPLE I.D.	e	f*		c		
Diameter (inches)	6.051	6.013		5.943		
Thickness (inches)	3.763	3.740		3.693		
DRY WT.	3246.0	3217.3		3244.3		
SSD WT.						
WT. IN H2O						
VOLUME	0.0	0.0	**AVG.**	0.0	0.0	**AVG.**
BULK SP.G.	1.992	1.998	1.995	2.036		2.036
MAX. SP.G.	2.479	2.479	2.479	2.479	2.479	2.479
% VOIDS	19.6	19.4	19.5	17.9		17.9
Void Tolerance						
VOLUME VOIDS						
LOAD, LBS.				1141		
	SATURATED FOR:		**10 MIN. @**		**25 IN. Hg.**	
SSD WT.						
WT. IN H2O						
VOLUME						
ABS. VOL. H2O			**AVG.**			
% SATURATION						
Meets Saturation Requirements						
% SWELL						
	CONDITIONED 24 HRS. IN 140 DEG. F WATER					
Diameter (inches)						
Thickness (inches)						
SSD WT.						
WT. IN H2O						
VOLUME						
ABS. VOL. H2O			**AVG.**			
% SATURATION						
% SWELL						
LOAD LBS.	0	0	0.0			**AVG.**
DRY STRENGTH psi				33.1		33.1
WET STRENGTH psi	0.0	0.0	0.0			
T.S.R.	0.0	0.0	**0.0**			
EST. % STRIPPING			0			0
EST. % BROKEN AGG.						

COMMENT *puck f - "wet strength" 140 bath
Both pucks e and f did not make it through the 140 heating process.

TECHNICIAN : rb/dl

Lottman Test Worksheet for 64–34 AC (Failing Results)



LOTTMAN TEST WORKSHEET

PROJ. # Certified Plant T.M. # 2007 - 077 DATE: 9/11/2008

MDR#

SPEC. # 2360-2006 TYPE: Porous Pavement 95 mm Target Ht.

RMKS: 70-28 AC Submitted 9/10/08

	TREATED SPECIMENS			UNTREATED SPECIMENS		
SAMPLE I.D.	1	4		2	3	
Diameter (inches)	5.980	5.990		5.990	5.990	
Thickness (inches)	3.720	3.690		3.700	3.710	
DRY WT.						
SSD WT.						
WT. IN H2O						
VOLUME			AVG.			AVG.
BULK SP.G.						
MAX. SP.G.	2.479	2.479	2.479	2.479	2.479	2.479
% VOIDS						
Void Tolerance						
VOLUME VOIDS						
LOAD, LBS.				1850	1850	
	SATURATED FOR:		10 MIN. @	25 IN. Hg.		
SSD WT.						
WT. IN H2O						
VOLUME						
ABS. VOL. H2O			AVG.			
% SATURATION						
Meets Saturation Requirements						
% SWELL						
	CONDITIONED 24 HRS. IN 140 DEG. F WATER					
Diameter (inches)	5.980	5.990				
Thickness (inches)	3.720	3.690				
SSD WT.						
WT. IN H2O						
VOLUME						
ABS. VOL. H2O			AVG.			
% SATURATION						
% SWELL						
LOAD LBS.	1450	2000	1725.0			AVG.
DRY STRENGTH				53.1	53.0	53.1
WET STRENGTH	41.5	57.6	49.6			
T.S.R.	78.2	108.5	**93.4**			
EST. % STRIPPING						
EST. % BROKEN AGG.						

COMMENTS:

TECHNICIAN : contractor

Lottman Test Worksheet for 70–28 AC (Passing Results)

APPENDIX H: MIX DESIGN RECOMMENDATION FOR POROUS ASPHALT

BITUMINOUS PLANT MIX DESIGN REPORT

Mn/DOT - Office Of Materials and Road Research
1400 Gervais Avenue Maplewood, MN 55109
Phone: (651) 366-5459 FAX: (651) 366-5580

THIS MIX DESIGN REPORT IS NOT VALID UNTIL PLANT NO. INDICATED BELOW IS CERTIFIED.

#0- 2008-195

TO BE FILLED IN BY CONTRACTOR	
ENGINEER	**FOR**
PROJECT NUMBER 8680-157 (Mn/RD)	
CONTRACTOR SIGN.	

Date:	8/5/08
SPEC	**2360**
SPEC YEAR	**2005**
MIX TYPE	**POROUS**
AC GRADE	70-28

THIS MIXTURE HAS BEEN REVIEWED FOR VOLUMETRIC PROPERTIES ONLY, IT DOES NOT ASSURE THAT FIELD PLACEMENT AND COMPACTION REQUIREMENTS WILL BE MET.

PLANT NO. 900000 - 2008 JOB MIX FORMULA

Begin With Test Number

P O	R -	0 0 1

Sieve Size (mm) (in.)	**Composite Formula**	**JMF LIMITS**		
37.5 (1 ½)			-	
25.0 (1)			-	
19.0 (3/4)	100	100	-	100
12.5 (1/2)	87	85	-	91
9.5 (3/8)	62	58	-	66
4.75 (#4)	15	12	-	18
2.36 (#8)	6	5	-	9
0.075 (#200)	2	2	-	4
Spec. Voids	18.0	17.0	-	19.0
%AC	5.5 (TOTAL)	5.5	-	5.9

For Information Only Virgin Formula

P P	
E A	
R S	
C S	
E I	
N N	
T G	
%AC (NEW)	

TM# 0- 2008-077 **Indicates a Gyratory density of** 127.7 **lbs/ft^3 at** 50 **Design Gyrations.**

Use of anti-strip agent required NO

Proportions		Source of Material	Sp.G
45	%	AGGREGATE A 3/4" MINUS	2.736
45	%	AGGREGATE A 1/2"	2.715
10	%	AGGREGATE A 1/2" UNWASHED	2.702
0.3	%	FIBER STABILIZER	
	%		
	%		
	%		

Mix Aggregate Specific Gravity at the Listed Percentages = 2.723
Voids in the Coarse Aggregate - Dry Rodded Condition (VCA_{DRC}) = 42.5

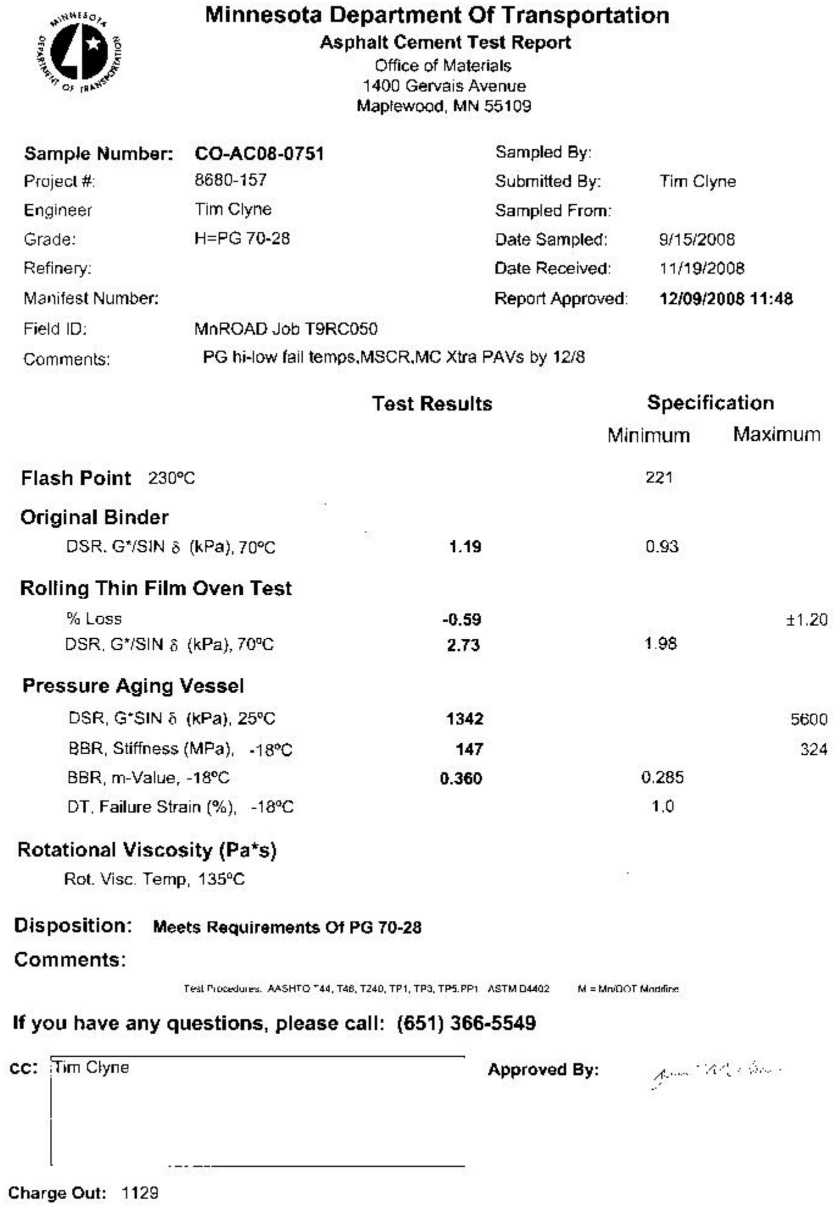
Remarks: + #4 AGGREGATE SPECIFIC GRAVITY AT THE LISTED PERCENTAGES = 2.725. MIXING TEMPERATURE = 309-322°F ; COMPACTION TEMPERATURE = 271-280°F

Mix Design Reviewed by:

cc:
Mn/DOT INSPECTION
Contractor

APPENDIX I: PA ACCEPTANCE SAMPLING AND TESTING INFORMATION

PG70-28 Asphalt Cement Test Report



Minnesota Department Of Transportation
Asphalt Cement Test Report
Office of Materials
1400 Gervais Avenue
Maplewood, MN 55109

Sample Number:	**CO-AC08-0751**	Sampled By:	
Project #:	8680-157	Submitted By:	Tim Clyne
Engineer	Tim Clyne	Sampled From:	
Grade:	H=PG 70-28	Date Sampled:	9/15/2008
Refinery:		Date Received:	11/19/2008
Manifest Number:		Report Approved:	**12/09/2008 11:48**
Field ID:	MnROAD Job T9RC050		
Comments:	PG hi-low fail temps,MSCR,MC Xtra PAVs by 12/8		

	Test Results	Specification	
		Minimum	Maximum
Flash Point 230°C		221	
Original Binder			
DSR, G*/SIN δ (kPa), 70°C	**1.19**	0.93	
Rolling Thin Film Oven Test			
% Loss	**-0.59**		±1.20
DSR, G*/SIN δ (kPa), 70°C	**2.73**	1.98	
Pressure Aging Vessel			
DSR, G*SIN δ (kPa), 25°C	**1342**		5600
BBR, Stiffness (MPa), -18°C	**147**		324
BBR, m-Value, -18°C	**0.360**	0.285	
DT, Failure Strain (%), -18°C		1.0	
Rotational Viscosity (Pa*s)			
Rot. Visc. Temp, 135°C			

Disposition: **Meets Requirements Of PG 70-28**

Comments:

Test Procedures: AASHTO T44, T48, T240, TP1, TP3, TP5,PP1 ASTM D4402 M = Mn/DOT Modified

If you have any questions, please call: (651) 366-5549

cc: Tim Clyne

Approved By:

Charge Out: 1129

PG70-28 Extracted Asphalt Cement Test Report

09BC 025 Gap = 1mm Plate diameter = 25mm Cell 86 - Porous HMA 70-28
binder extracted from mixture

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	34	241.86	20.83	1.01E-03	65.05	22.88	20750	8753	0.1592	18810	18.81	1000	20750	-9.67E-04	0.10052	0.10041	20.83
1.586	34	397.38	28.88	1.00E-03	65.06	31.9	28920	12190	0.2523	26230	26.23	1000	18240	1.79E-04	0.09999	0.099844	28.88
2.512	34	497.28	40.25	9.99E-04	65.07	44.55	40400	17030	0.3997	36630	36.63	1000	16080	5.10E-03	0.099855	0.09965	40.25
3.98	34	562.47	56.11	9.97E-04	65.08	62.25	56460	23790	0.6335	51200	51.2	1000	14180	0.012467	0.099677	0.099391	56.11
6.309	34	605.22	78.32	9.99E-04	65.14	86.74	78700	33090	1.004	71400	71.4	1000	12470	4.20E-03	0.099927	0.099528	78.33
10	34	635.38	109.2	9.99E-04	65.13	121.2	1.10E+05	46250	1.592	99770	99.77	1000	10990	2.28E-03	0.099923	0.099364	109.3
15.84	34	657.53	152.3	9.99E-04	65.07	169.5	1.54E+05	64790	2.522	1.39E+05	139.4	1000	9701	-1.38E-04	0.099889	0.099104	152.3
25.12	34	671.44	212	9.99E-04	64.92	237	2.15E+05	91010	3.998	1.94E+05	194.4	1000	8546	-0.029533	0.099918	0.098812	212.1
39.81	34	682.56	294.7	1.00E-03	64.68	331.6	3.00E+05	1.28E+05	6.336	2.71E+05	271	1000	7529	3.33E-04	0.099995	0.098429	295
63.09	34	690.19	407.4	9.98E-04	64.35	464	4.18E+05	1.81E+05	10.04	3.77E+05	377.1	1000	6630	-0.032567	0.099831	0.097612	408.3
100	34	695.94	560.4	1.00E-03	63.71	647.6	5.81E+05	2.57E+05	15.92	5.21E+05	520.5	1000	5804	-0.024067	0.10015	0.096972	563

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	40	242	9.297	1.00E-03	65.6	10.18	9273	3831	0.1592	8445	8.445	1000	9274	-1.73E-03	0.10031	0.10026	9.297
1.586	40	397.45	12.95	1.00E-03	65.55	14.22	12950	5369	0.2523	11790	11.79	1000	8167	8.13E-03	0.10004	0.09998	12.95
2.512	40	497.34	18.06	1.00E-03	65.48	19.87	18080	7503	0.3997	16450	16.45	1000	7199	8.40E-03	0.10001	0.099921	18.07
3.98	40	562.08	25.24	1.00E-03	65.55	27.76	25270	10460	0.6335	23000	23	1000	6348	0.010133	0.10003	0.099899	25.24
6.309	40	604.91	35.28	9.99E-04	65.66	38.83	35380	14580	1.004	32240	32.24	1000	5608	-8.30E-03	0.099911	0.099736	35.29
10	40	634.64	49.48	9.98E-04	65.72	54.53	49710	20440	1.592	45310	45.31	1000	4970	2.60E-03	0.099825	0.09958	49.5
15.84	40	656.64	69.15	9.99E-04	65.88	76.19	69540	28420	2.522	63470	63.47	1000	4389	1.00E-04	0.099867	0.099525	69.21
25.12	40	670.69	96.82	9.99E-04	65.9	106.9	97550	39840	3.998	89050	89.05	1000	3883	-0.020667	0.099875	0.099394	96.96
39.81	40	682.17	135.6	1.00E-03	65.97	149.9	1.37E+05	55740	6.336	1.25E+05	125	1000	3438	3.93E-03	0.099998	0.099322	135.9
63.09	40	689.86	189.4	1.00E-03	65.92	210.4	1.92E+05	78380	10.04	1.75E+05	175.4	1000	3044	-0.026967	0.10003	0.099074	190.3
100	40	696.06	265.6	1.01E-03	65.72	296.3	2.70E+05	1.11E+05	15.92	2.46E+05	246.2	1000	2700	0.028733	0.10053	0.099168	267.8

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	46	241.51	11.28	2.50E-03	66.63	4.916	4513	1790	0.1592	4142	4.142	1000	4513	2.93E-03	0.25	0.24995	11.28
1.586	46	397	15.89	2.50E-03	66.4	6.929	6349	2542	0.2523	5818	5.818	1000	4005	1.03E-03	0.25031	0.25023	15.89
2.512	46	497.42	22.32	2.51E-03	66.26	9.722	8900	3583	0.3997	8147	8.147	1000	3543	4.07E-03	0.25092	0.25081	22.32
3.98	46	562.27	31.25	2.51E-03	66.19	13.63	12470	5034	0.6335	11410	11.41	1000	3133	0.029967	0.25081	0.25066	31.26
6.309	46	605.38	43.79	2.51E-03	66.24	19.12	17500	7053	1.004	16020	16.02	1000	2774	-0.011241	0.25051	0.2503	43.81
10	46	635.67	61.47	2.51E-03	66.31	26.81	24550	9863	1.592	22480	22.48	1000	2455	1.90E-03	0.25089	0.25059	61.52
15.84	46	657.75	86.1	2.51E-03	66.46	37.55	34430	13750	2.522	31560	31.56	1000	2173	0.011267	0.25088	0.25046	86.23
25.12	46	671.58	120.7	2.51E-03	66.61	52.74	48410	19210	3.998	44430	44.43	1000	1927	7.81E-03	0.25067	0.25009	121.1
39.81	46	682.72	169.4	2.51E-03	66.77	74.1	68090	26860	6.336	62570	62.57	1000	1710	-3.33E-04	0.25079	0.24997	170.2
63.09	46	690.44	237.4	2.51E-03	66.91	104.3	95950	37630	10.04	88260	88.26	1000	1521	-0.047897	0.25073	0.24958	239.5
100	46	696.67	331.1	2.50E-03	67.01	147	1.35E+05	52860	15.92	1.25E+05	124.6	1000	1353	0.0199	0.25011	0.2485	336.2

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	52	241.89	10.21	4.97E-03	68.2	2.213	2055	763.1	0.1592	1908	1.908	1000	2055	3.43E-03	0.49721	0.49716	10.22
1.586	52	397.5	14.53	4.99E-03	67.78	3.149	2915	1102	0.2523	2698	2.698	1000	1838	1.03E-03	0.49863	0.49857	14.53
2.512	52	497.23	20.58	4.99E-03	67.42	4.466	4123	1583	0.3997	3807	3.807	1000	1642	0.051	0.49935	0.49925	20.59
3.98	52	562.08	29.07	5.00E-03	67.17	6.31	5815	2257	0.6335	5360	5.36	1000	1461	0.061633	0.50026	0.50012	29.08
6.309	52	604.86	40.97	5.00E-03	67.03	8.913	8207	3203	1.004	7556	7.556	1000	1301	-7.83E-03	0.4999	0.49971	41.01
10	52	635.08	57.73	5.01E-03	66.99	12.55	11550	4515	1.592	10630	10.63	1000	1155	2.67E-04	0.50108	0.50081	57.84
15.84	52	657.11	81.16	5.01E-03	67.02	17.65	16250	6345	2.522	14960	14.96	1000	1026	-0.0108	0.50129	0.50091	81.41
25.12	52	671.02	114.1	5.02E-03	67.11	24.83	22880	8898	3.998	21080	21.08	1000	910.7	-0.16342	0.50197	0.50143	114.7
39.81	52	682.14	160	5.01E-03	67.26	34.99	32270	12470	6.336	29760	29.76	1000	810.6	-1.93E-03	0.50137	0.50062	161.5
63.09	52	689.77	224.3	5.02E-03	67.42	49.33	45550	17490	10.04	42060	42.06	1000	721.9	-0.14057	0.50199	0.50094	228.2
100	52	696.03	312.4	5.01E-03	67.59	69.7	64430	24560	15.92	59570	59.57	1000	644.2	0.11321	0.50075	0.49926	321.7

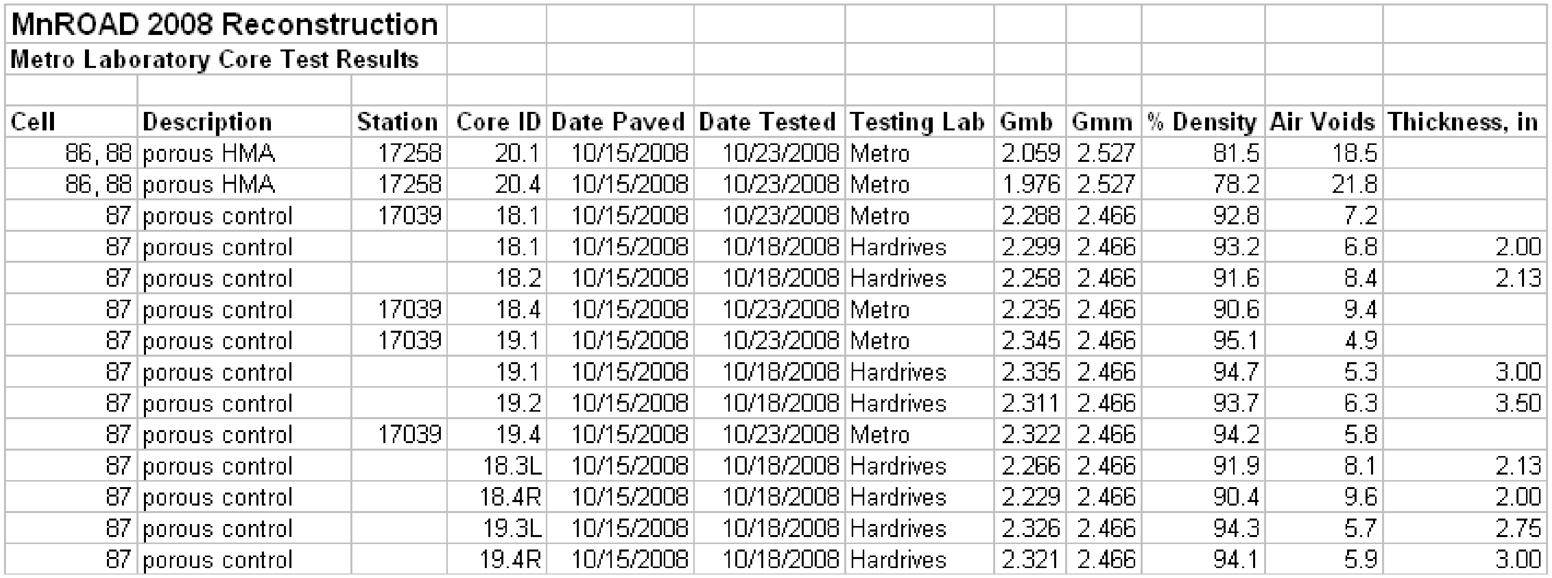
ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	58	242.11	8.2	7.95E-03	70.24	1.096	1032	348.7	0.1592	970.9	0.9709	1000	1032	-1.44E-03	0.79501	0.79498	8.201
1.586	58	397.56	11.81	8.03E-03	69.6	1.571	1472	513.2	0.2523	1380	1.38	1000	928.4	0.031367	0.80292	0.80287	11.82
2.512	58	497.36	16.77	8.01E-03	69.04	2.244	2096	749.7	0.3997	1957	1.957	1000	834.4	0.085167	0.80057	0.8005	16.78
3.98	58	562.23	23.7	7.95E-03	68.57	3.206	2984	1090	0.6335	2778	2.778	1000	749.6	0.10423	0.79505	0.79495	23.72
6.309	58	604.91	33.56	7.93E-03	68.22	4.568	4242	1574	1.004	3939	3.939	1000	672.4	-0.17415	0.79281	0.79266	33.63
10	58	649.59	48.05	7.98E-03	67.98	6.514	6039	2264	1.592	5598	5.598	1000	603.8	-3.62E-03	0.79846	0.79824	48.2
15.84	58	671.7	67.51	7.95E-03	67.85	9.23	8549	3224	2.522	7918	7.918	1000	539.5	-0.026	0.79454	0.79424	67.9
25.12	58	685.52	95.36	7.96E-03	67.81	13.07	12100	4572	3.998	11210	11.21	1000	481.8	0.0246	0.79639	0.79595	96.33
39.81	58	696.67	134.1	7.98E-03	67.86	18.48	17110	6449	6.336	15850	15.85	1000	429.9	-6.70E-03	0.79816	0.79755	136.5
63.09	58	704.28	187.7	7.99E-03	67.99	26.13	24230	9081	10.04	22460	22.46	1000	384	-0.19697	0.79907	0.7982	193.4
100	58	710.47	261.4	8.00E-03	68.18	36.99	34340	12760	15.92	31880	31.88	1000	343.3	-0.086931	0.79994	0.79871	274.3

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	64	241.95	7.933	0.014913	72.84	0.5569	532.1	157	0.1592	508.4	0.5084	1000	532.1	6.33E-03	1.4913	1.4912	7.935
1.586	64	397.41	11.49	0.015097	71.95	0.8011	761.7	236	0.2523	724.2	0.7242	1000	480.4	0.071323	1.5097	1.5096	11.5
2.512	64	546.28	16.53	0.014963	71.15	1.169	1106	357.3	0.3997	1047	1.047	1000	440.3	0.027267	1.4963	1.4963	16.55
3.98	64	611.11	23.88	0.015098	70.45	1.681	1584	530.2	0.6335	1493	1.493	1000	398.1	-3.64E-03	1.5098	1.5097	23.92
6.309	64	654.27	34.06	0.015087	69.88	2.412	2265	779.1	1.004	2126	2.126	1000	358.9	-0.27048	1.5087	1.5085	34.16
10	64	684	48.3	0.015033	69.41	3.452	3232	1136	1.592	3025	3.025	1000	323.1	5.43E-03	1.5033	1.5031	48.58
15.84	64	706.02	68.17	0.015013	69.05	4.912	4587	1640	2.522	4284	4.284	1000	289.5	-0.0192	1.5013	1.501	68.86
25.12	64	719.61	95.76	0.014981	68.79	6.979	6507	2354	3.998	6066	6.066	1000	259	-0.091133	1.4981	1.4977	97.45
39.81	64	731.06	133.8	0.014968	68.65	9.895	9216	3356	6.336	8583	8.583	1000	231.5	-7.03E-03	1.4968	1.4962	137.9
63.09	64	738.67	185.9	0.014955	68.58	14.02	13060	4768	10.04	12150	12.15	1000	206.9	-0.29353	1.4955	1.4946	195.1
100	64	745.05	258.3	0.014948	68.57	19.89	18520	6765	15.92	17240	17.24	1000	185.1	-0.0217	1.4948	1.4936	276.6

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	70	241.86	8.237	0.030261	75.96	0.2807	272.3	66.04	0.1592	264.2	0.2642	1000	272.3	6.87E-03	3.0261	3.0261	8.241
1.586	70	397.45	12.02	0.03016	74.82	0.4134	398.9	104.5	0.2523	385	0.385	1000	251.6	0.086933	3.016	3.016	12.03
2.512	70	497.28	17.47	0.030001	73.77	0.6074	583.2	163	0.3997	560	0.56	1000	232.2	0.30293	3.0001	3	17.5
3.98	70	562.02	25.28	0.030047	72.81	0.8831	843.7	249.4	0.6335	806	0.806	1000	212	0.073161	3.0047	3.0046	25.35
6.309	70	604.81	36.37	0.029895	71.98	1.286	1223	378.3	1.004	1163	1.163	1000	193.8	0.29037	2.9895	2.9894	36.56
10	70	634.64	52.41	0.030026	71.26	1.86	1762	566	1.592	1668	1.668	1000	176.1	-6.47E-03	3.0026	3.0024	52.89
15.84	70	656.64	74.42	0.029959	70.66	2.676	2525	836.4	2.522	2382	2.382	1000	159.3	0.24283	2.9959	2.9956	75.64
25.12	70	670.5	105.2	0.030009	70.15	3.831	3604	1223	3.998	3390	3.39	1000	143.5	0.68193	3.0009	3.0004	108.1
39.81	70	681.53	147.6	0.03006	69.77	5.476	5139	1777	6.336	4822	4.822	1000	129.1	-5.47E-03	3.006	3.0054	154.4
63.09	70	689.33	206.7	0.030067	69.49	7.824	7327	2568	10.04	6863	6.863	1000	116.1	-0.098903	3.0067	3.0058	220.2
100	70	695.47	297.4	0.030055	69.31	11.17	10450	3692	15.92	9779	9.779	1000	104.5	-0.50407	3.0055	3.0042	314

ang. frequency	temperature	time	osc. stress	strain	delta	|G*|/sin(delta)	|G*|	G'	frequency	G"	G*|.sin(delta	gap	|n*|	torque	% strain	% strain (sample)	osc. stress (sample)
rad/s	°C	s	Pa		degrees	kPa	Pa	Pa	Hz	Pa	kPa	micro m	Pa.s	micro N.m			Pa
1	76	241.84	8.404	0.060221	79.6	0.142	139.7	25.2	0.1592	137.4	0.1374	1000	139.7	0.10987	6.0221	6.0221	8.41
1.586	76	397.42	12.52	0.059999	78.28	0.2134	209	42.44	0.2523	204.6	0.2046	1000	131.8	0.26473	5.9999	5.9998	12.54
2.512	76	497.25	18.58	0.060077	77	0.3181	310	69.75	0.3997	302	0.302	1000	123.4	0.5698	6.0077	6.0077	18.62
3.98	76	561.97	27.31	0.060002	75.77	0.4716	457.1	112.4	0.6335	443.1	0.4431	1000	114.8	-0.4575	6.0002	6.0001	27.43
6.309	76	604.77	39.93	0.059877	74.67	0.6968	672	177.7	1.004	648.1	0.6481	1000	106.5	-0.56383	5.9877	5.9876	40.24
10	76	634.45	57.99	0.060112	73.67	1.019	978.2	275	1.592	938.7	0.9387	1000	97.8	-0.012367	6.0112	6.011	58.8
15.84	76	656.63	83.25	0.059975	72.79	1.488	1422	420.5	2.522	1358	1.358	1000	89.71	-0.064867	5.9975	5.9972	85.25
25.12	76	670.45	118.4	0.059876	72.03	2.16	2055	634	3.998	1955	1.955	1000	81.8	-1.0235	5.9876	5.9871	123
39.81	76	681.56	168.3	0.060049	71.36	3.119	2955	944.4	6.336	2800	2.8	1000	74.24	-0.022714	6.0049	6.0042	177.4
63.09	76	689.17	244.4	0.060107	70.82	4.491	4242	1394	10.04	4007	4.007	1000	67.23	-0.43103	6.0107	6.0097	254.9
100	76	695.55	395.1	0.060075	70.41	6.461	6087	2041	15.92	5735	5.735	1000	60.86	-0.6239	6.0075	6.006	365.6

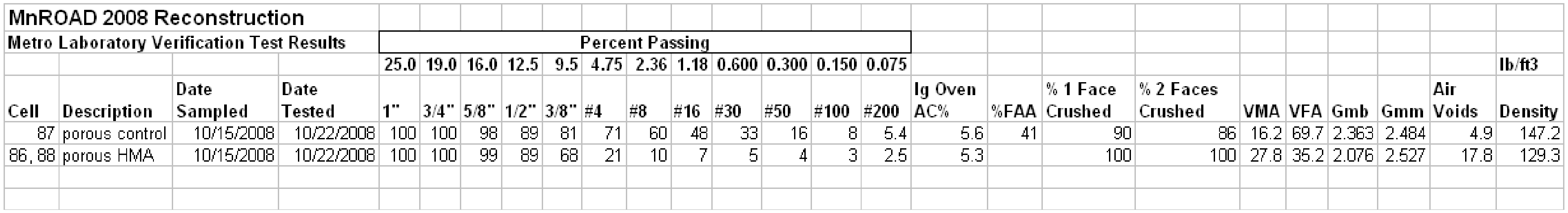
Core Test reports



MnROAD 2008 Reconstruction

Metro Laboratory Core Test Results

Cell	Description	Station	Core ID	Date Paved	Date Tested	Testing Lab	Gmb	Gmm	% Density	Air Voids	Thickness, in
86, 88	porous HMA	17258	20.1	10/15/2008	10/23/2008	Metro	2.059	2.527	81.5	18.5	
86, 88	porous HMA	17258	20.4	10/15/2008	10/23/2008	Metro	1.976	2.527	78.2	21.8	
87	porous control	17039	18.1	10/15/2008	10/23/2008	Metro	2.288	2.466	92.8	7.2	
87	porous control		18.1	10/15/2008	10/18/2008	Hardrives	2.299	2.466	93.2	6.8	2.00
87	porous control		18.2	10/15/2008	10/18/2008	Hardrives	2.258	2.466	91.6	8.4	2.13
87	porous control	17039	18.4	10/15/2008	10/23/2008	Metro	2.235	2.466	90.6	9.4	
87	porous control	17039	19.1	10/15/2008	10/23/2008	Metro	2.345	2.466	95.1	4.9	
87	porous control		19.1	10/15/2008	10/18/2008	Hardrives	2.335	2.466	94.7	5.3	3.00
87	porous control		19.2	10/15/2008	10/18/2008	Hardrives	2.311	2.466	93.7	6.3	3.50
87	porous control	17039	19.4	10/15/2008	10/23/2008	Metro	2.322	2.466	94.2	5.8	
87	porous control		18.3L	10/15/2008	10/18/2008	Hardrives	2.266	2.466	91.9	8.1	2.13
87	porous control		18.4R	10/15/2008	10/18/2008	Hardrives	2.229	2.466	90.4	9.6	2.00
87	porous control		19.3L	10/15/2008	10/18/2008	Hardrives	2.326	2.466	94.3	5.7	2.75
87	porous control		19.4R	10/15/2008	10/18/2008	Hardrives	2.321	2.466	94.1	5.9	3.00



MnROAD 2008 Reconstruction

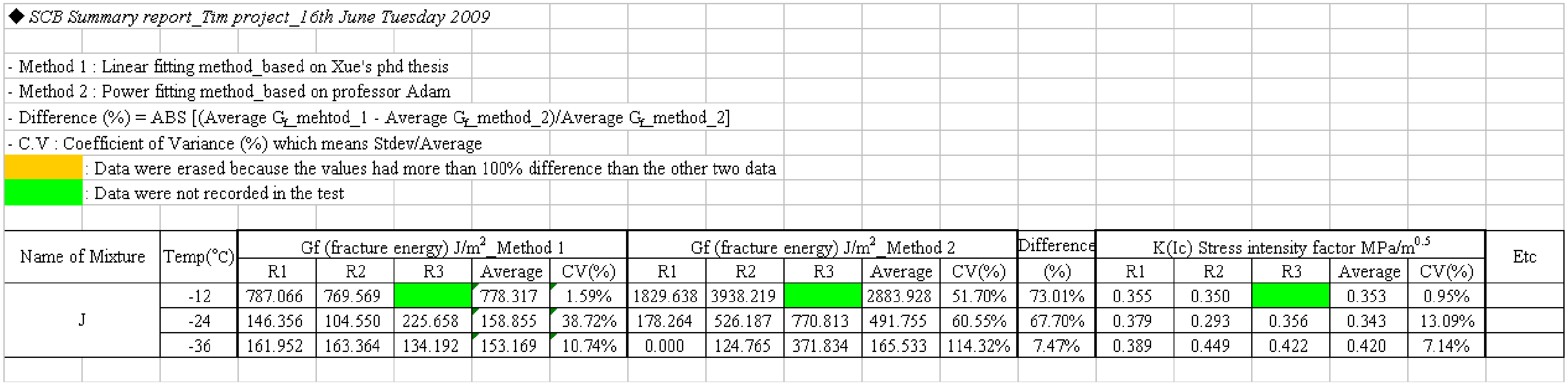
Metro Laboratory Verification Test Results

				Percent Passing																			
				25.0	19.0	16.0	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075								lb/ft3
Cell	Description	Date Sampled	Date Tested	1"	3/4"	5/8"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	Ig Oven AC%	%FAA	% 1 Face Crushed	% 2 Faces Crushed	VMA	VFA	Gmb	Gmm	Air Voids	Density
87	porous control	10/15/2008	10/22/2008	100	100	98	89	81	71	60	48	33	16	8	5.4	5.6	41	90	86	16.2	69.7	2.363	2.484	4.9	147.2
86, 88	porous HMA	10/15/2008	10/22/2008	100	100	99	89	68	21	10	7	5	4	3	2.5	5.3		100	100	27.8	35.2	2.076	2.527	17.8	129.3

Porous HMA and control HMA sent to TxDOT for Overlay & Hamburg testing

DESCRIPTION	MNROAD_ID	TxDOT ID	Gr	RECORDED #PASSES TO FAILURE (20000 Pass Max)	RUT DEPTH @ FAILURE (mm., 12.5mm max)	RECORDED #PASSES TO FAILURE (1000 Cycle Max)	DESIGN MODULUS (ksi) FROM VMETER	DENSITY (%)	NOTES/COMMENTS
SPWEB440H Sp 1, porous HMA, PG 70-28; sent to TxDOT for Overlay & Hamburg testing	8608BM011/86 08BM014	F09540189	2.516	20000	8.6	1000	527	76.7%	* - TxDOT does not have Hamburg or Overlay specifications for Open Graded Friction Courses. These tests are usually molded to 93% density. However, based on recommendations of MnRoad personnel all Hamburg & Overlay specimens were molded to 50 gyrations
SPWEB340B, porous HMA control, PG 58-28; sent to TxDOT for Overlay & Hamburg testing	8708BM011/87 08BM020	F09540190	2.457	2961	12.5	667	615	92.1%	

SCB Summary Testing Report



◆ *SCB Summary report_Tim project_16th June Tuesday 2009*

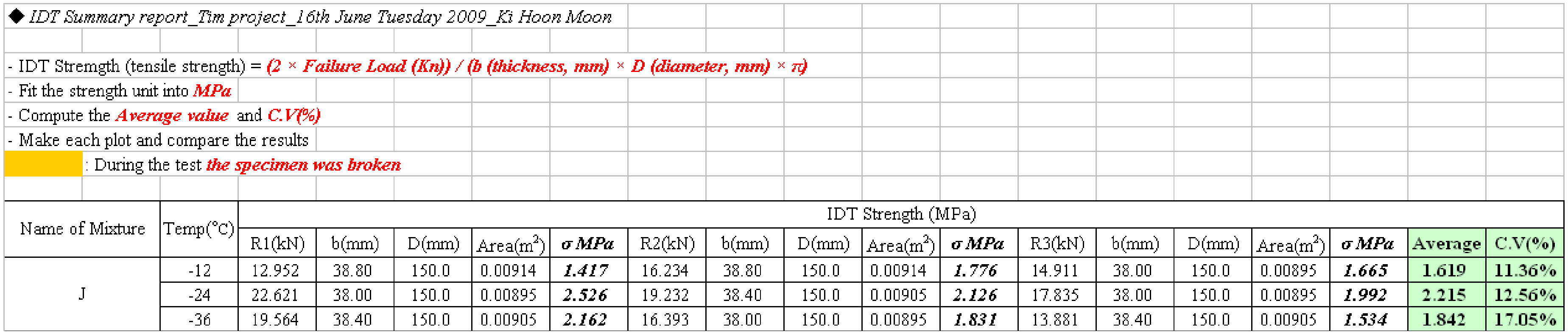
- Method 1 : Linear fitting method_based on Xue's phd thesis
- Method 2 : Power fitting method_based on professor Adam
- Difference (%) = ABS [(Average G_f_mehtod_1 - Average G_f_method_2)/Average G_f_method_2]
- C.V : Coefficient of Variance (%) which means Stdev/Average

🟧 : Data were erased because the values had more than 100% difference than the other two data

🟩 : Data were not recorded in the test

Name of Mixture	Temp(°C)	Gf (fracture energy) J/m^2_Method 1					Gf (fracture energy) J/m^2_Method 2					Difference	K(Ic) Stress intensity factor MPa/m$^{0.5}$					Etc
		R1	R2	R3	Average	CV(%)	R1	R2	R3	Average	CV(%)	(%)	R1	R2	R3	Average	CV(%)	
J	-12	787.066	769.569	🟩	778.317	1.59%	1829.638	3938.219	🟩	2883.928	51.70%	73.01%	0.355	0.350	🟩	0.353	0.95%	
	-24	146.356	104.550	225.658	158.855	38.72%	178.264	526.187	770.813	491.755	60.55%	67.70%	0.379	0.293	0.356	0.343	13.09%	
	-36	161.952	163.364	134.192	153.169	10.74%	0.000	124.765	371.834	165.533	114.32%	7.47%	0.389	0.449	0.422	0.420	7.14%	

IDT Summary Testing Report



◆ *IDT Summary report_Tim project_16th June Tuesday 2009_Ki Hoon Moon*

- IDT Stremgth (tensile strength) = ***(2 × Failure Load (Kn)) / (b (thickness, mm) × D (diameter, mm) × π)***
- Fit the strength unit into ***MPa***
- Compute the ***Average value*** and ***C.V(%)***
- Make each plot and compare the results

🟨 : During the test ***the specimen was broken***

Name of Mixture	Temp(°C)	IDT Strength (MPa)																
		R1(kN)	b(mm)	D(mm)	Area(m^2)	***σ MPa***	R2(kN)	b(mm)	D(mm)	Area(m^2)	***σ MPa***	R3(kN)	b(mm)	D(mm)	Area(m^2)	***σ MPa***	**Average**	**C.V(%)**
J	-12	12.952	38.80	150.0	0.00914	***1.417***	16.234	38.80	150.0	0.00914	***1.776***	14.911	38.00	150.0	0.00895	***1.665***	**1.619**	**11.36%**
	-24	22.621	38.00	150.0	0.00895	***2.526***	19.232	38.40	150.0	0.00905	***2.126***	17.835	38.00	150.0	0.00895	***1.992***	**2.215**	**12.56%**
	-36	19.564	38.40	150.0	0.00905	***2.162***	16.393	38.00	150.0	0.00895	***1.831***	13.881	38.40	150.0	0.00905	***1.534***	**1.842**	**17.05%**

APPENDIX J: RESULTS OF FREEZE-THAW TESTING

MINNESOTA DEPARTMENT OF TRANSPORTATION FREEZE/THAW WORKSHEET FOR POROUS HMA 1-6

SAMPLE #		MU09-1-6
Cycle #:		**10**
Date:		4/10/2009
Cycle #:		**20**
Date:		4/20/2009
Cycle #:		**30**
Date:		4/24/2009
Cycle #:		**40**
Date:		4/28/2009
Cycle #:		**50**
Date:		5/4/2009
Cycle #:		**60**
Date:		5/8/2009
Cycle #:		**70**
Date:		5/12/2009
Cycle #:		**80**
Date:		5/18/2009
Cycle #:		**90**
Date:		5/26/2009
Cycle #:		**100**
Date:		6/1/2009
Cycle #:		**110**
Date:		6/5/2009
Cycle #:		**120**
Date:		6/9/2009
Cycle #:		**130**
Date:		6/15/2009
Cycle #:		**140**
Date:		6/19/2009
Cycle #:		**150**
Date:		6/23/2009
Cycle #:		**160**
Date:		6/29/2009
Cycle #:		**170**
Date:		7/6/2009
		Page 1 of 1

Remarks:

For information only.

No noticeable degradation after 170 ASTM C1262

freeze thaw cycles 3% saline solution.

APPENDIX K: POROUS ASPHALT THICKNESS DESIGN METHOD

Porous Asphalt Pavement Design using Soil Factors

Layer thicknesses;

Porous HMA (Spec 2360)	5	inches
CA-15 Base	14	inches

Sand Subgrade Soil factor = 50

Clay Subgrade Soil Factor = 120

GE Factors;

GE = GE factor x H — for each material above subgrade

5" (Porous Asphalt - Spec 2360) X 2.25 (GE Factor for Low volume) = 11.25

14" (CA-15 Base) X 1.0 (GE factor conservatively assumed to be 1.0) = 14.0

Sum of the computed GE values; GE = **25.25**

Use State Aid Manual Fig F-892.210

Clay Subgrade;	9 ton @ less than 150 HCADT	Meets Requirements?
	S.F = 120	
	Minimum Bit GE = 7.0	**YES (11.5)**
	Total GE = 20.5	**YES (25.25)**

The Computed G.E. value of 25.25 is more than the needed value of 20.5, which is minimum for a soil factor of 120.

Sand Subgrade	9 ton @ less than 150 HCADT	Meets Requirements?
	S.F. = 50	
	Minimum Bit GE = 7.0	**YES (11.5)**
	Total GE = 10.25	**YES (25.25)**

The Computed G.E. value of 25.25 is more than the needed value of 10.25, which is minimum for a soil factor of 50.

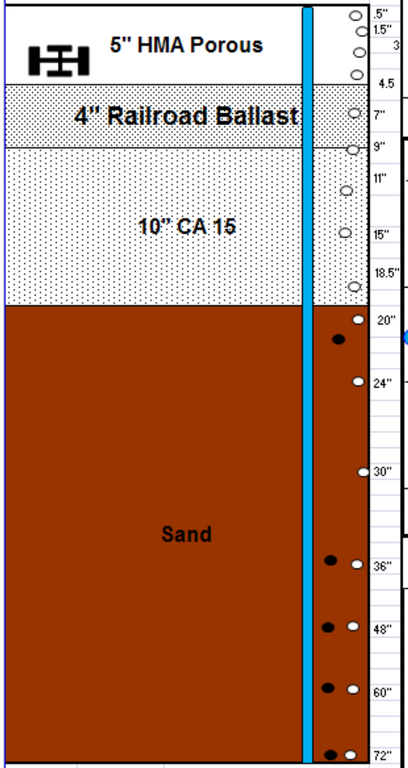
The 5" porous asphalt with 14' CA-15 base will meet 9 ton @ < 150 HCADT Specs over Clay and Sand Subgrade.

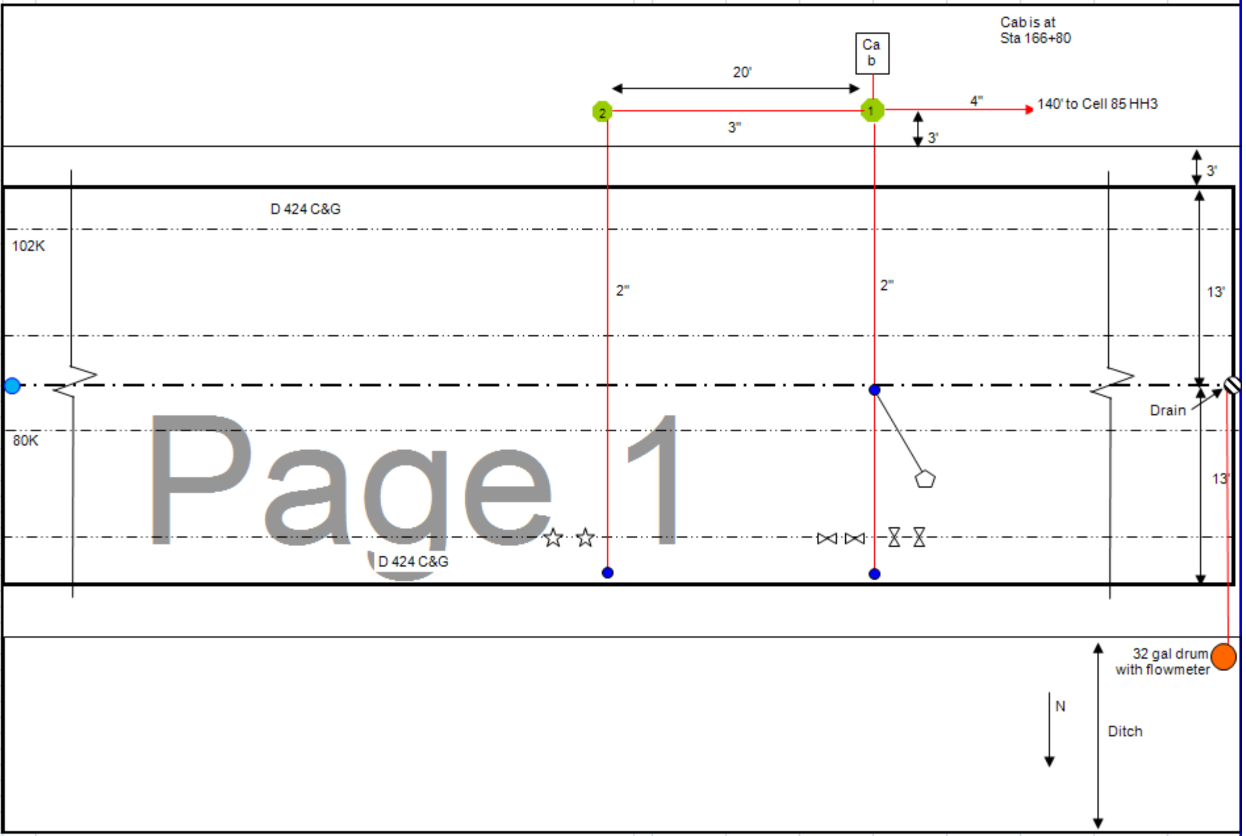
APPENDIX L: CELLS 86, 87, AND 88 INSTRUMENTATION LAYOUT

MnROAD Instumentation Summary, Porous HMA over Sand

Cell	86
Project	8680-157

Section View





Sensor Requirement

Code	Number	Sensor	Description
TC	16	ThermoCouple (Temperature)	Measures Temperature - Installed in a Thermal Couple Tree to a depth of 6' from the surface
EC	5	Decagon ECH$_2$O-TE (Moisture)	Measures volumetric moisture content, temperature, electric conductivity
TE	2	CTL Strain Gauge, TE	Embedded transverse (TE) strain gauge-measures transverse strain at the bottom of bound layers
LE	2	CTL Strain Gauge, LE	Embedded longitdinal (LE) strain gauge-measures longitdinal strain at the bottom of bound layers
PG	2	Geokon Pressure Cell, PG	Measures normal stress at base/subgrade interface

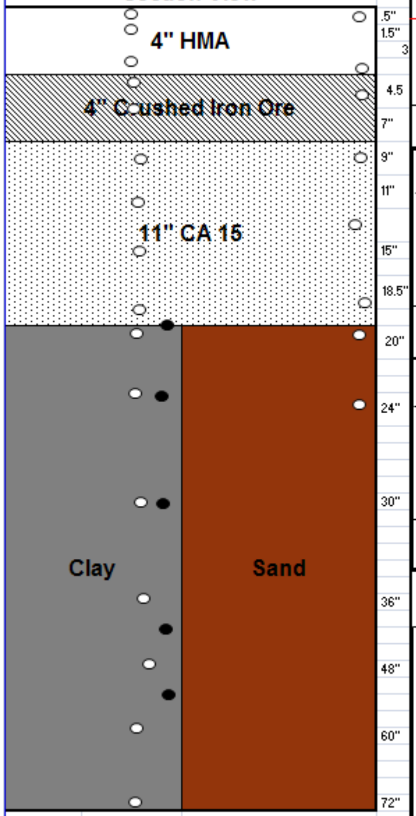
Legend

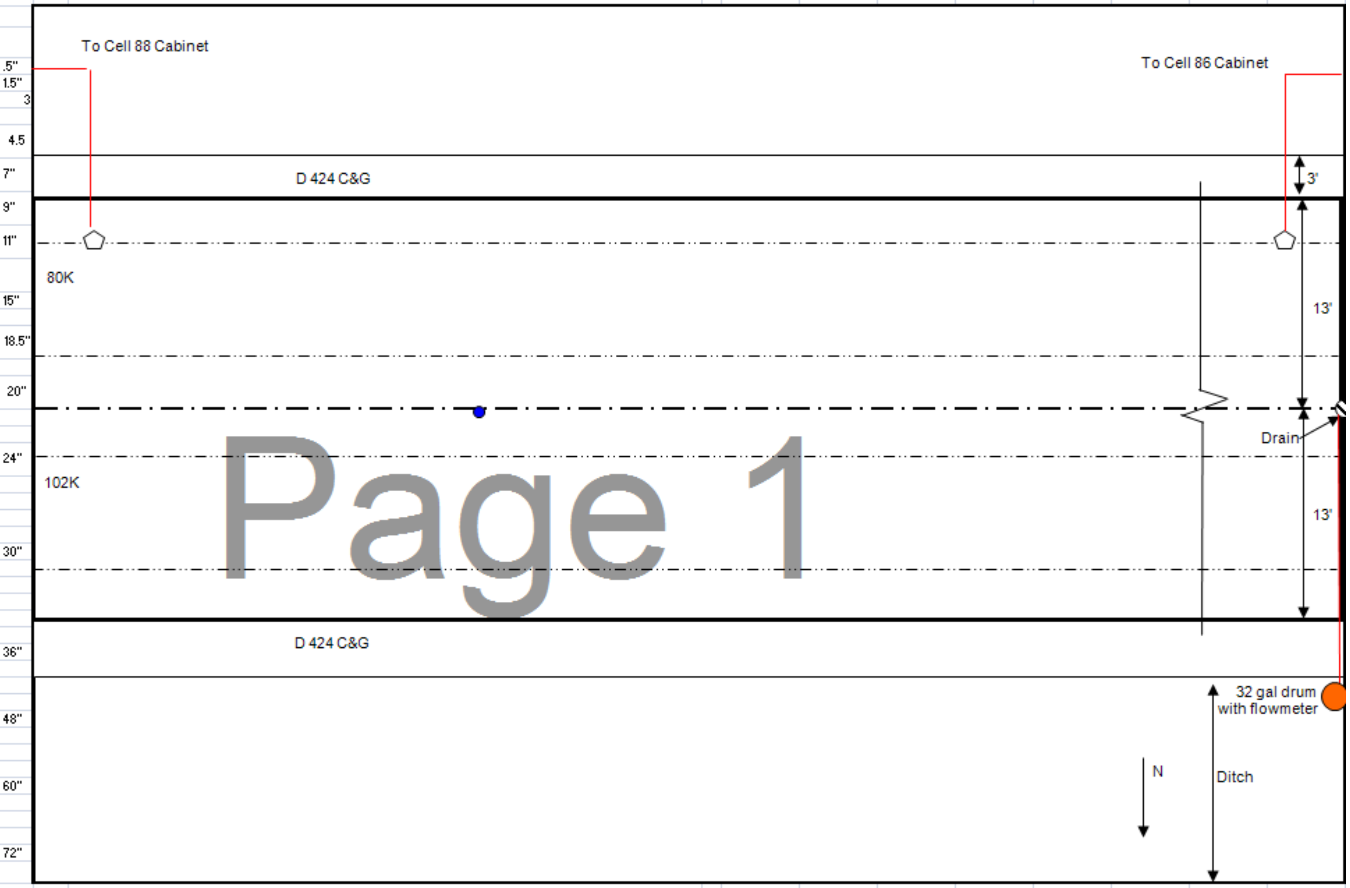
●	Risers	—··—··	Wheelpath (9.5' offset from CL)
– – –	Centerline	········	Chain Link Fence
⋈	LE Sensors	——	Conduit
⧗	TE Sensors	○	TC Sensors
☆	PG Sensor	●	EC Sensors
⬠	TC/ M Sensors		
●	Handhole	●	Groundwater sampling standpipe

MnROAD Instumentation Summary, Pervious/Porous Control Section

Cell	87
Project	8680-157

Section View





Sensor Requirement

Code	Number	Sensor	Description
TC	0	ThermoCouple (Temperature)	Measures Temperature - Installed in a Thermal Couple Tree to a depth of 8' from the surface
EC	0	EcH2O-TE (Moisture)	Measure volumetric moisture content, temperature, electric conductivity
TE	0	TE Sensor	Embedded transverse strain gauge-measures transverse strain at the bottom of bound layers
LE	0	LE Sensor	Embedded longitdinal strain gauge-measures longitdinal strain at the bottom of bound layers
PG	0	PG Sensor	Measures normal stress at base/subgrade interface

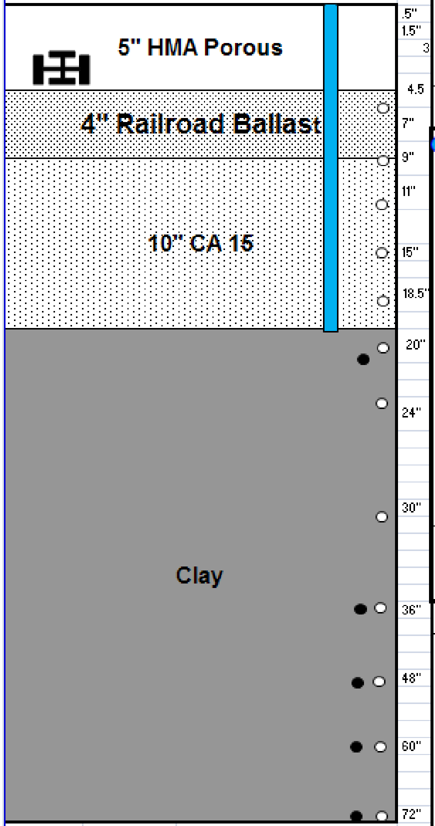
Legend

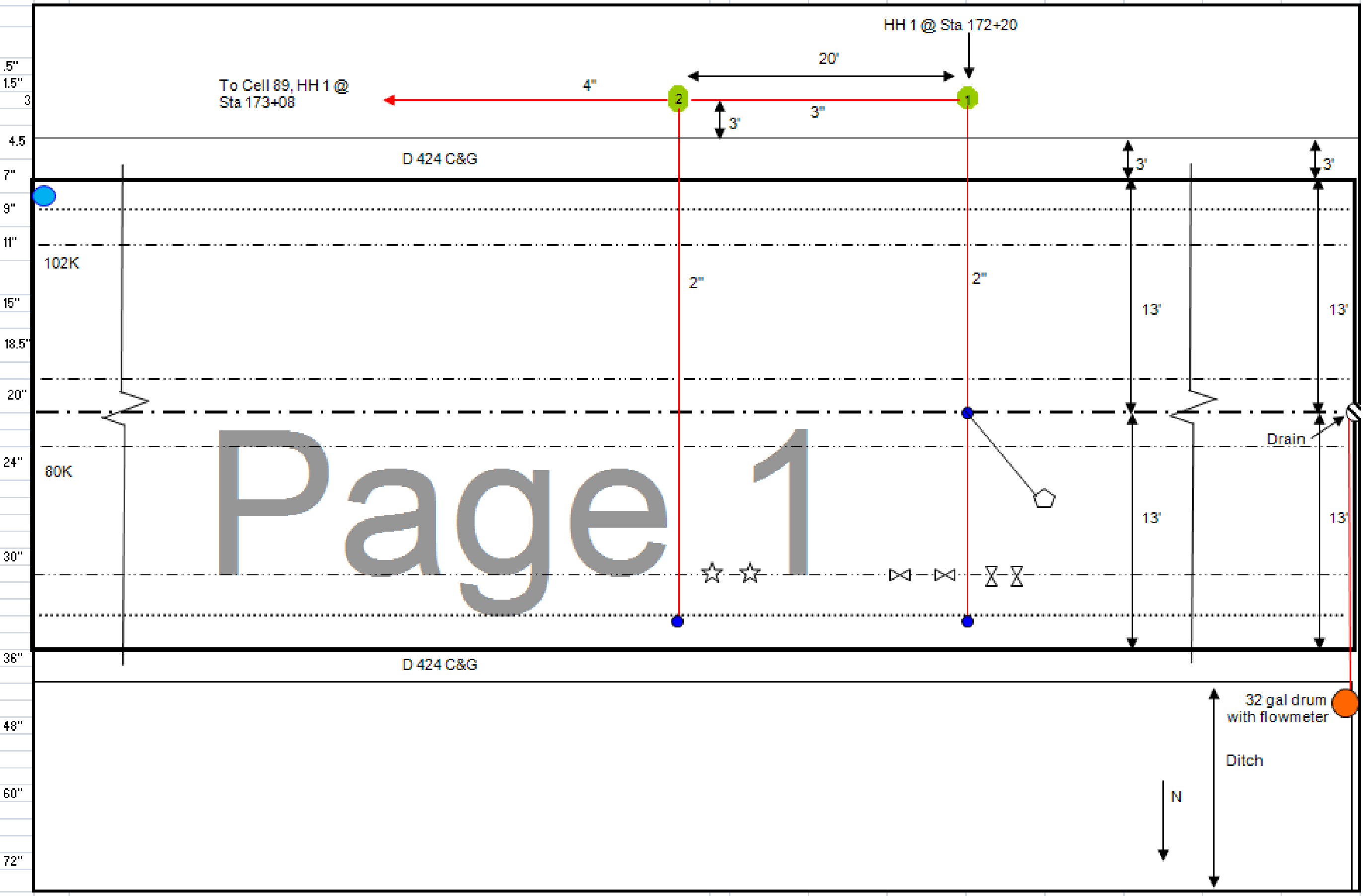
●	Risers	—·—·—	Wheelpath (9.5' offset from CL)
– – –	Centerline	········	Chain Link Fence
⋈	LE Sensors	—	Conduit
⧗	TE Sensors	○	TC Sensors
☆	PG Sensor	●	EC Sensors
⬠	TC/ M Sensor		
●	Handhole		

MnROAD Instumentation Summary, Porous HMA over Clay

Cell	88
Project	8680-157

Section View



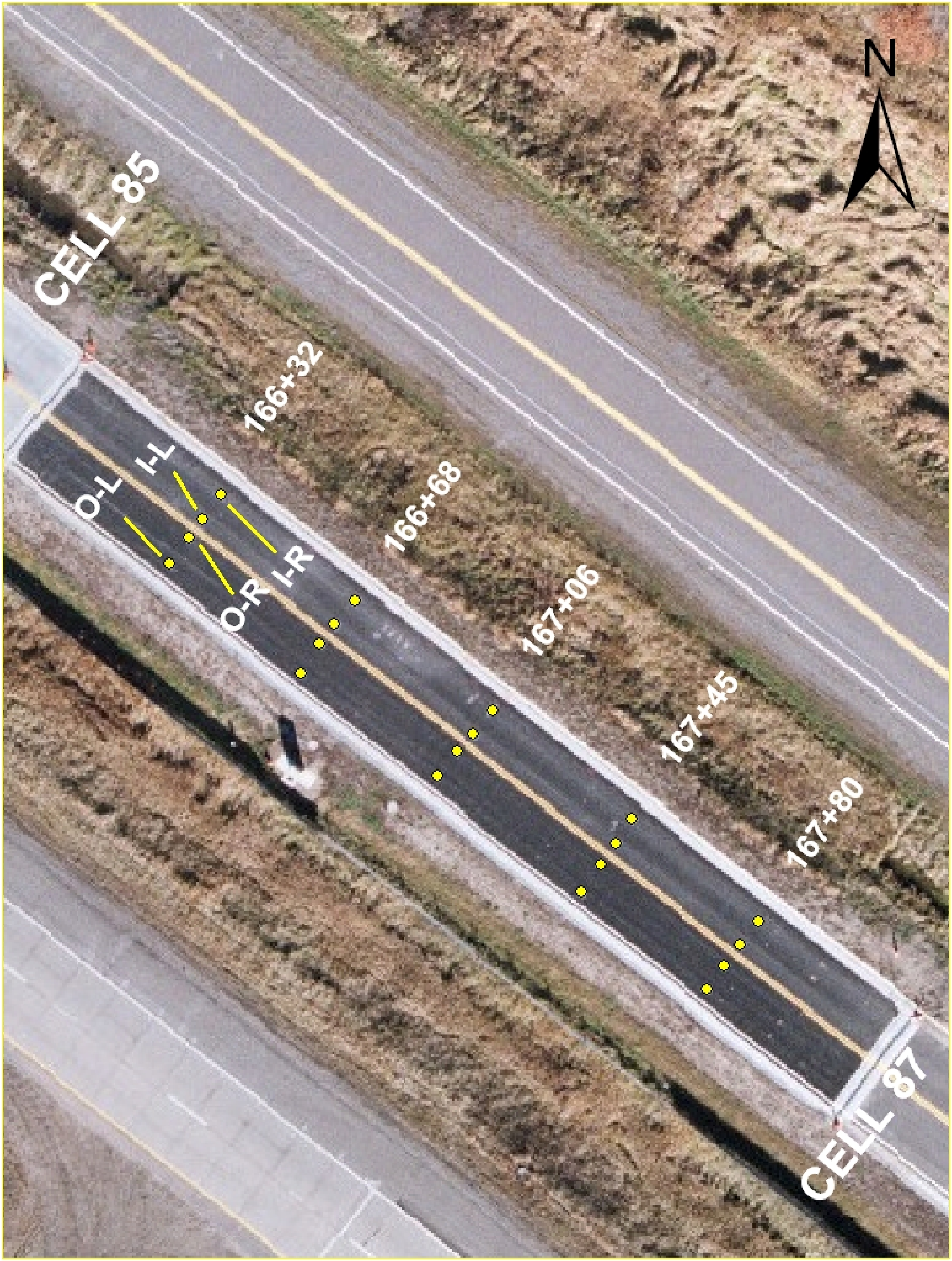


Sensor Requirement

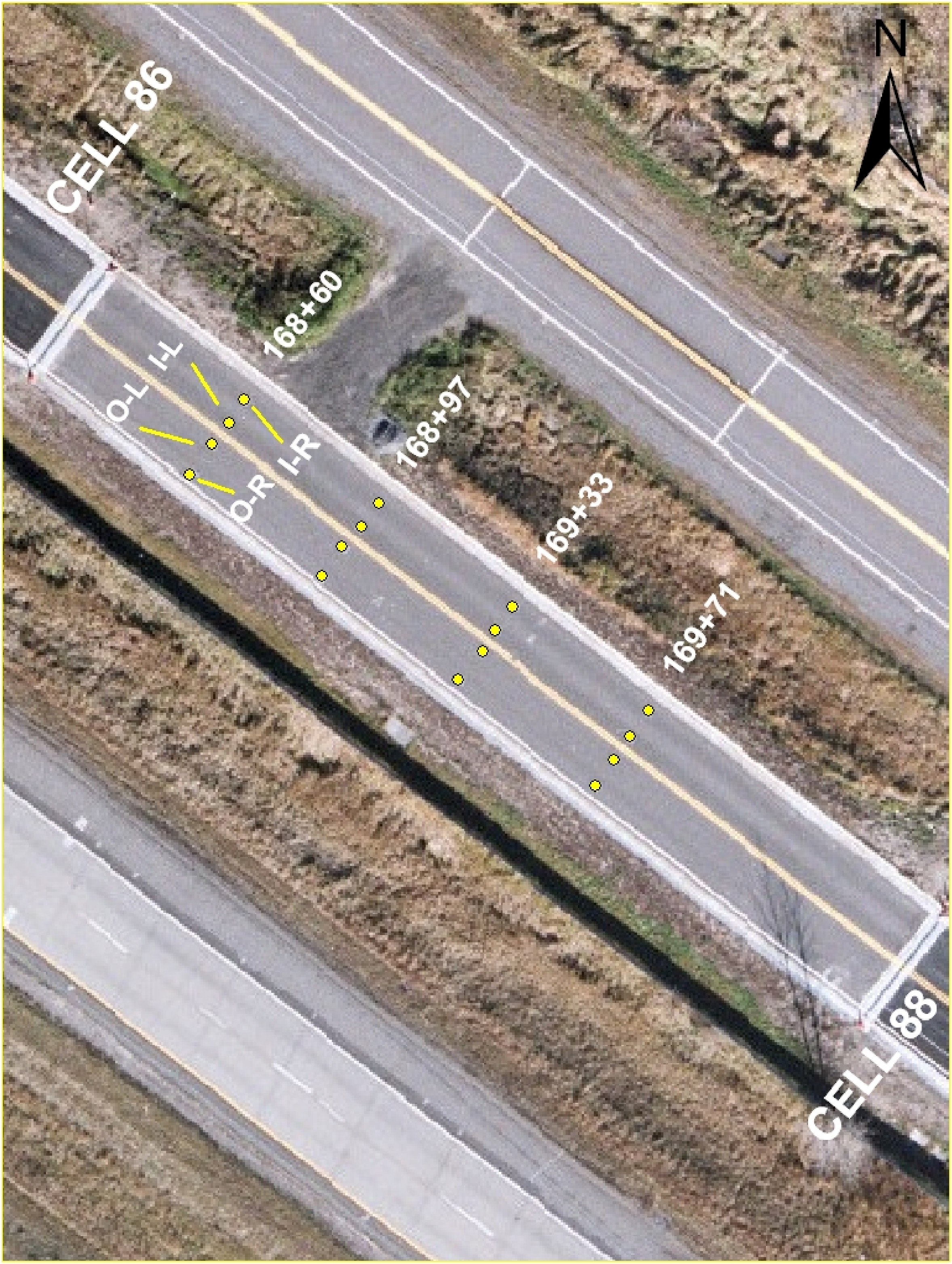
Code	Number	Sensor	Description
TC	16	ThermoCouple (Temperature)	Measures Temperature - Installed in a Thermal Couple Tree to a depth of 6' from the surface
EC	5	Dedcagon ECH$_2$O-TE (Moisture)	Measures volumetric moisture content, temperature, electric conductivity
TE	2	CTL Strain Gauge, TE	Embedded transverse (TE) strain gauge-measures transverse strain at the bottom of bound layers
LE	2	CTL Strain Gauge, LE	Embedded longitdinal (LE) strain gauge-measures longitdinal strain at the bottom of bound layers
PG	2	Geokon Pressure Cell, PG	Measures normal stress at base/subgrade interface

Legend			
●	Risers	—··—··	Wheelpath (9.5' offset from CL)
– – –	Centerline	▪▪▪▪▪▪▪▪	Chain Link Fence
⋈	LE	——	Conduit
⧗	TE	○	TC Sensors
☆	PG Sensor	●	EC Sensors
⬠	TC/ M Sensor		
●	Handhole	●	base water sampling tube

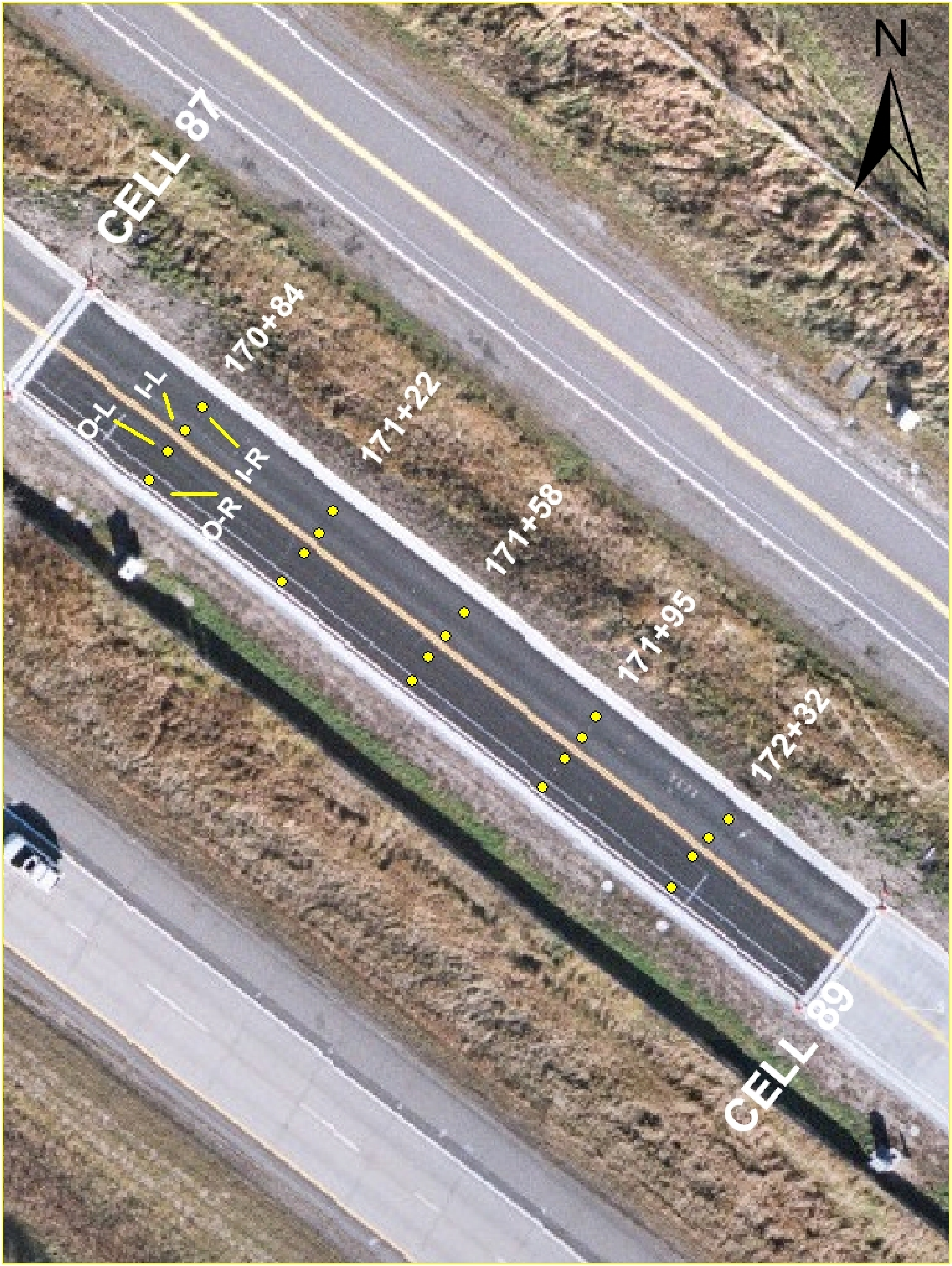
APPENDIX M: CELLS 86-88 PERMEABILITY TEST POINT LOCATIONS AND DATA



Cell 86



Cell 87



Cell 88

Detailed Porous Asphalt Permeability Testing Data: Cell 86

CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
86	11/13/2008	16557	9.5	Inside	1.94	8	0	690.8
86	11/13/2008	16557	6	Inside	4.82	8	0	278.1
86	11/13/2008	16557	6	Inside	4.7	8	0	285.2
86	11/13/2008	16557	-9.5	Outside	2.49	8	0	538.2
86	11/13/2008	16557	-9.5	Outside	2.12	8	0	632.2
86	1/23/2009	16684	-9.5	Inside	4.37	8	0	306.7
86	6/11/2009	16657	-9.5	Outside	8.78	36	11	477.0
86	6/11/2009	16657	-9.5	Outside	4.85	30	11	656.3
86	7/24/2009	16657	-9.5	Inside	12	50	11	544.5
86	7/24/2009	16684	9.5	Outside	3	26	11	837.7
86	7/24/2009	16684	-9.5	Inside	7	47	11	861.6
86	7/24/2009	16707	9.5	Outside	4	29	11	753.9
86	7/24/2009	16707	-9.5	Inside	4	32	11	879.5
86	7/24/2009	16657	9.5	Outside	6	34	11	642.2
86	10/7/2009	16780	-10	Inside	6	37	11	726.0
86	10/7/2009	16632	-10	Inside	9	37	11	484.0
86	10/7/2009	16632	10	Outside	4	37	11	1088.9
86	10/7/2009	16706	10	Outside	3	37	11	1451.9
86	10/7/2009	16780	10	Outside	6	37	11	726.0
86	10/7/2009	16632	-3	Inside	8	37	11	544.5
86	10/7/2009	16706	-10	Inside	4	37	11	1088.9
86	10/7/2009	16780	-3	Inside	3	37	11	1451.9
86	10/7/2009	16706	-3	Inside	4	37	11	1088.9
86	10/8/2009	16706	-6	Inside	1.81	37	11	2406.5
86	10/8/2009	16780	-6	Inside	1.32	37	11	3299.8
86	10/8/2009	16632	-6	Inside	7.31	37	11	595.9
86	4/5/2010	16706	-6	Inside	2.04	23	11	985.5
86	4/5/2010	16706	-10	Inside	2.06	20	11	731.9
86	4/5/2010	16632	-6	Inside	7.59	41	11	662.2
86	4/5/2010	16632	-10	Inside	6.31	32	11	557.5
86	4/5/2010	16780	10	Outside	3.69	27	11	726.4
86	4/5/2010	16780	-10	Inside	4.91	31	11	682.4
86	4/5/2010	16780	-6	Inside	4.88	31	11	686.6
86	9/14/2010	16632	-2.5	Inside	19.53	49	10	334.5
86	9/14/2010	16668	-2.5	Inside	11.53	52	10	610.3
86	9/14/2010	16706	-2.5	Inside	10.22	52	10	688.5
86	9/14/2010	16745	-2.5	Inside	12.97	52	10	542.5
86	9/14/2010	16780	-2.5	Inside	9.15	49	10	714.1
86	9/14/2010	16632	-9.5	Inside	23.07	54	10	319.5
86	9/14/2010	16668	-9.5	Inside	13.68	49	10	477.6
86	9/14/2010	16706	-9.5	Inside	13.75	51	10	499.5
86	9/14/2010	16745	-9.5	Inside	20.16	56	10	382.3
86	9/14/2010	16780	-9.5	Inside	17.53	51	10	391.8
86	9/14/2010	16632	2.5	Outside	11.87	52	10	592.8
86	9/14/2010	16668	2.5	Outside	11.32	53	10	636.4
86	9/14/2010	16706	2.5	Outside	3.34	25	10	752.4

CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
86	9/14/2010	16745	2.5	Outside	17.47	50	10	383.6
86	9/14/2010	16780	2.5	Outside	14.37	50	10	466.3
86	9/14/2010	16632	9.5	Outside	11.25	49	10	580.8
86	9/14/2010	16668	9.5	Outside	7.35	43	10	752.2
86	9/14/2010	16706	9.5	Outside	7.03	42	10	762.6
86	9/14/2010	16745	9.5	Outside	11.97	54	10	615.8
86	9/14/2010	16780	9.5	Outside	9.16	41	10	567.0
86	9/29/2010	16657	-6	Inside	8.56	42	10	626.3
86	9/29/2010	16632	-6	Inside	12.47	45	10	470.2
86	9/29/2010	16780	-6	Inside	9.6	42	10	558.4
86	9/29/2010	16706	-6	Inside	5.22	34	10	770.3
86	10/12/2010	16745	-2.5	Inside	11.6	48	10	548.8
86	10/12/2010	16632	9.5	Outside	9.4	44	10	606.0
86	10/12/2010	16745	-2.5	Inside	11.12	48	10	572.5
86	10/12/2010	16632	-6	Inside	11.63	45	10	504.2
86	10/12/2010	16745	2.5	Outside	14.78	50	10	453.4
86	10/12/2010	16632	-9.5	Inside	17.54	49	10	372.5
86	10/12/2010	16632	-6	Inside	10.84	45	10	540.9
86	4/21/2011	16632	-2.5	Inside	18.31	52	10	384.3
86	4/21/2011	16668	2.5	Outside	6.81	35	10	615.0
86	4/21/2011	16632	-9.5	Inside	23.22	50	10	288.6
86	4/21/2011	16657	9.5	Outside	8.97	40	10	560.3
86	4/21/2011	16632	9.5	Outside	7.34	38	10	639.1
86	4/21/2011	16780	-6	Inside	12.22	45	10	479.8
86	4/21/2011	16780	-2.5	Inside	9.85	42	10	544.3
86	4/21/2011	16780	-9.5	Inside	16.53	48	10	385.1
86	4/21/2011	16745	-2.5	Inside	10.56	41	10	491.8
86	4/21/2011	16745	-9.5	Inside	20.84	49	10	313.5
86	4/21/2011	16706	-6	Inside	7.03	40	10	714.9
86	4/21/2011	16780	9.5	Outside	8.93	37	10	506.5
86	4/21/2011	16780	2.5	Outside	11.72	44	10	486.0
86	4/21/2011	16745	9.5	Outside	10.06	41	10	516.2
86	4/21/2011	16745	2.5	Outside	15.12	42	10	354.6
86	4/21/2011	16706	9.5	Outside	7.15	39	10	679.5
86	4/21/2011	16706	2.5	Outside	4.56	32	10	808.3
86	4/21/2011	16684	9.5	Outside	23.78	47	10	260.7
86	4/21/2011	16668	9.5	Outside	5.03	33	10	766.0
86	4/21/2011	16632	-6	Inside	13.59	48	10	468.4
86	4/21/2011	16657	-9.5	Inside	29.85	52	10	235.7
86	4/21/2011	16657	-6	Inside	8.47	43	10	652.7
86	4/21/2011	16668	-9.5	Inside	10.47	42	10	512.0
86	4/21/2011	16668	-2.5	Inside	7.78	37	10	581.4
86	4/21/2011	16684	-9.5	Inside	11.13	42	10	481.7
86	4/21/2011	16706	-9.5	Inside	8.97	40	10	560.3
86	4/21/2011	16706	-2.5	Inside	5.22	31	10	674.0
86	4/21/2011	16632	2.5	Outside	8.63	41	10	601.8

CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
86	5/4/2011	16668	9.5	Outside	6.78	40	10	741.3
86	5/4/2011	16780	2.5	Outside	15.5	48	10	410.7
86	5/4/2011	16706	-9.5	Inside	14.22	49	10	459.5
86	10/11/2011	16780	9.5	Outside	16.5	46	10	365.5
86	10/11/2011	16745	2.5	Outside	12	43	10	460.7
86	10/11/2011	16745	9.5	Outside	21.75	51	10	315.8
86	10/11/2011	16706	2.5	Outside	6.97	37	10	649.0
86	10/11/2011	16706	9.5	Outside	5.56	34	10	723.2
86	10/11/2011	16668	2.5	Outside	6.38	37	10	709.0
86	10/11/2011	16668	9.5	Outside	8.09	32	10	455.6
86	10/11/2011	16632	2.5	Outside	9.12	43	10	606.2
86	10/11/2011	16632	9.5	Outside	7.47	37	10	605.5
86	10/11/2011	16780	-2.5	Inside	11.13	42	10	481.7
86	10/11/2011	16780	2.5	Outside	12.93	42	10	414.6
86	10/11/2011	16745	-2.5	Inside	12.9	42	10	415.6
86	10/11/2011	16745	-9.5	Inside	20.91	49	10	312.5
86	10/11/2011	16706	-2.5	Inside	9.06	41	10	573.2
86	10/11/2011	16706	-9.5	Inside	13.06	44	10	436.1
86	10/11/2011	16668	-2.5	Inside	7.15	34	10	562.3
86	10/11/2011	16668	-9.5	Inside	9.5	38	10	493.8
86	10/11/2011	16632	-2.5	Inside	16.07	44	10	354.5
86	10/11/2011	16632	-9.5	Inside	22.28	49	10	293.3
86	10/11/2011	16780	-9.5	Inside	23.88	50	10	280.6
86	11/3/2011	16668	2.5	Outside	6.56	34	10	612.9
86	11/3/2011	16706	9.5	Outside	5.47	31	10	643.2
86	11/3/2011	16706	2.5	Outside	9.5	48	10	670.1
86	11/3/2011	16745	9.5	Outside	22.1	55	10	341.1
86	11/3/2011	16745	2.5	Outside	14.32	50	10	468.0
86	11/3/2011	16780	9.5	Outside	17.87	52	10	393.7
86	11/3/2011	16780	2.5	Outside	16.04	52	10	438.7
86	11/3/2011	16632	-9.5	Inside	29.19	56	10	264.0
86	11/3/2011	16632	-2.5	Inside	20.38	53	10	353.5
86	11/3/2011	16668	-9.5	Inside	13.97	50	10	479.7
86	11/3/2011	16668	-2.5	Inside	10.87	46	10	554.8
86	11/3/2011	16706	-9.5	Inside	14.25	52	10	493.8
86	11/3/2011	16706	-2.5	Inside	9.81	45	10	597.7
86	11/3/2011	16745	-9.5	Inside	26.53	53	10	271.5
86	11/3/2011	16745	-2.5	Inside	16.31	54	10	452.0
86	11/3/2011	16780	-9.5	Inside	25.28	57	10	311.5
86	11/3/2011	16780	-2.5	Inside	10.53	46	10	572.8
86	11/3/2011	16632	9.5	Outside	12.84	51	10	534.9
86	11/3/2011	16632	2.5	Outside	13.66	54	10	539.6
86	11/3/2011	16668	9.5	Outside	13.07	54	10	564.0

Cell 88

CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
88	11/13/2008	17166.5	-9.5	Outside	3.49	8	0	384.0
88	11/13/2008	17166.5	-9.5	Outside	3.18	8	0	421.5
88	11/13/2008	17166.5	6	Inside	3.31	8	0	404.9
88	11/13/2008	17166.5	6	Inside	3.47	8	0	386.2
88	11/13/2008	17166.5	9.5	Inside	3.76	8	0	356.4
88	11/13/2008	17228.5	9.5	Inside	3.94	8	0	340.2
88	11/13/2008	17228.5	-9.5	Outside	3.54	8	0	378.6
88	11/13/2008	17228.5	-9.5	Outside	4.19	8	0	319.9
88	11/13/2008	17228.5	6	Inside	2.46	8	0	544.8
88	11/13/2008	17228.5	6	Inside	2.75	8	0	487.4
88	11/13/2008	17228.5	9.5	Inside	3.57	8	0	375.4
88	11/13/2008	17166.5	9.5	Inside	4.09	8	0	327.7
88	1/23/2009	17166.5	-9.5	Inside	5.19	8	0	258.2
88	7/24/2009	17166.5	-9.5	Inside	12	42	11	432.8
88	7/24/2009	17166.5	9.5	Outside	7	36	11	598.3
88	7/24/2009	17228.5	9.5	Outside	4	30	11	795.8
88	7/24/2009	17228.5	-9.5	Inside	13	46	11	451.0
88	10/7/2009	17232	-10	Inside	10	37	11	435.6
88	10/7/2009	17084	-10	Inside	6	37	11	726.0
88	10/7/2009	17158	-10	Inside	7	37	11	622.3
88	10/7/2009	17084	10	Outside	2	22	11	921.4
88	10/7/2009	17232	-3	Inside	10	37	11	435.6
88	10/7/2009	17158	-3	Inside	8	37	11	544.5
88	10/7/2009	17158	10	Outside	3	27	11	893.5
88	10/7/2009	17232	10	Outside	3	23	11	670.1
88	10/7/2009	17084	-3	Inside	7	37	11	622.3
88	10/8/2009	17232	-6	Inside	9.91	37	11	439.5
88	10/8/2009	17158	-6	Inside	7.6	37	11	573.1
88	10/8/2009	17232	-6	Inside	6.13	37	11	710.6
88	4/5/2010	17158	-10	Inside	6.09	32	11	577.7
88	4/5/2010	17158	10	Outside	2.18	25	11	1075.9
88	4/5/2010	17084	-6	Inside	4.75	30	11	670.1
88	4/5/2010	17232	-6	Inside	16.12	44	11	343.0
88	4/5/2010	17158	-6	Inside	4.84	30	11	657.7
88	4/5/2010	17232	10	Outside	5.22	37	11	834.4
88	4/5/2010	17084	-10	Inside	4.15	28	11	686.3
88	4/5/2010	17084	10	Outside	3.1	27	11	864.7
88	4/5/2010	17232	-10	Inside	12.84	43	11	417.5
88	9/14/2010	17158	-9.5	Inside	28.22	57	10	279.0
88	9/14/2010	17195	-9.5	Inside	23.91	57	10	329.3
88	9/14/2010	17232	-9.5	Inside	33.56	62	10	259.6
88	9/14/2010	17232	9.5	Outside	10.65	53	10	676.4
88	9/14/2010	17195	9.5	Outside	11.75	52	10	598.8
88	9/14/2010	17158	9.5	Outside	6.22	40	10	808.0
88	9/14/2010	17122	9.5	Outside	8.53	52	10	824.9
88	9/14/2010	17084	9.5	Outside	9.69	51	10	708.8

CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
88	9/14/2010	17084	2.5	Outside	11.63	50	10	576.2
88	9/14/2010	17122	2.5	Outside	10.37	50	10	646.2
88	9/14/2010	17122	-9.5	Inside	19.25	57	10	409.0
88	9/14/2010	17084	-9.5	Inside	15.09	54	10	488.5
88	9/14/2010	17232	-2.5	Inside	28.6	58	10	281.2
88	9/14/2010	17195	-2.5	Inside	25.12	56	10	306.8
88	9/14/2010	17158	-2.5	Inside	19.53	52	10	360.3
88	9/14/2010	17122	-2.5	Inside	17.69	53	10	407.2
88	9/14/2010	17084	-2.5	Inside	19.9	56	10	387.3
88	9/14/2010	17158	2.5	Outside	8.81	49	10	741.6
88	9/14/2010	17232	2.5	Outside	10.46	52	10	672.7
88	9/14/2010	17195	2.5	Outside	10.43	51	10	658.6
88	9/29/2010	17132	-6	Inside	18.22	52	10	386.2
88	9/29/2010	17158	-6	Inside	14.53	49	10	449.7
88	9/29/2010	17084	-6	Inside	12.25	44	10	465.0
88	10/12/2010	17084	-6	Inside	9.91	34	10	405.7
88	10/12/2010	17084	-9.5	Inside	13.75	44	10	414.3
88	10/12/2010	17084	-9.5	Inside	14.38	48	10	442.7
88	10/12/2010	17195	2.5	Outside	10	44	10	569.6
88	10/12/2010	17084	9.5	Outside	8.71	41	10	596.3
88	10/12/2010	17084	9.5	Outside	9.06	41	10	573.2
88	10/12/2010	17195	2.5	Outside	9.75	44	10	584.2
88	10/12/2010	17195	-2.5	Inside	23.22	53	10	310.2
88	4/21/2011	17084	-9.5	Inside	15.25	43	10	362.5
88	4/21/2011	17084	-2.5	Inside	14.89	43	10	371.3
88	4/21/2011	17084	-6	Inside	22.59	39	10	215.1
88	4/21/2011	17122	-9.5	Inside	15.03	47	10	412.4
88	4/21/2011	17122	-2.5	Inside	15.94	47	10	388.9
88	4/21/2011	17158	-9.5	Inside	15.43	46	10	390.9
88	4/21/2011	17158	-2.5	Inside	15.03	45	10	390.1
88	4/21/2011	17158	-6	Inside	15.06	44	10	378.2
88	4/21/2011	17166	-9.5	Inside	28.66	50	10	233.8
88	4/21/2011	17166	-2.5	Inside	16.75	47	10	370.1
88	4/21/2011	17166	-6	Inside	23.57	48	10	270.1
88	4/21/2011	17195	-9.5	Inside	18.29	46	10	329.7
88	4/21/2011	17195	-2.5	Inside	23.56	49	10	277.3
88	4/21/2011	17232	-9.5	Inside	23.44	49	10	278.7
88	4/21/2011	17232	-2.5	Inside	26	51	10	264.2
88	4/21/2011	17232	-6	Inside	23.21	48	10	274.3
88	4/21/2011	17084	2.5	Outside	10.09	40	10	498.1
88	4/21/2011	17084	9.5	Outside	5.91	37	10	765.4
88	4/21/2011	17122	2.5	Outside	7.92	38	10	592.3
88	4/21/2011	17122	9.5	Outside	5.44	34	10	739.1
88	4/21/2011	17158	2.5	Outside	6.12	34	10	657.0
88	4/21/2011	17158	9.5	Outside	5.84	37	10	774.5
88	4/21/2011	17166	2.5	Outside	6.5	42	10	824.8

CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
88	4/21/2011	17166	9.5	Outside	6.43	36	10	677.4
88	4/21/2011	17166	6	Outside	7.85	38	10	597.6
88	4/21/2011	17195	2.5	Outside	9.28	44	10	613.8
88	4/21/2011	17195	9.5	Outside	9.59	43	10	576.5
88	4/21/2011	17232	2.5	Outside	8.31	41	10	625.0
88	4/21/2011	17232	9.5	Outside	6.59	45	10	889.8
88	5/4/2011	17158	9.5	Outside	10.1	52	10	696.7
88	5/4/2011	17166	9.5	Outside	9.81	49	10	666.0
88	5/4/2011	17195	9.5	Outside	11.66	51	10	589.1
88	10/11/2011	17158	-2.5	Inside	25.37	48	10	250.9
88	10/11/2011	17158	-2.5	Inside	21.97	49	10	297.4
88	10/11/2011	17195	-2.5	Inside	24.91	51	10	275.7
88	10/11/2011	17195	-2.5	Inside	27.75	51	10	247.5
88	10/11/2011	17232	-2.5	Inside	33.78	52	10	208.3
88	10/11/2011	17232	-2.5	Inside	35.43	51	10	193.9
88	10/11/2011	17122	-2.5	Inside	16.94	45	10	346.1
88	10/11/2011	17122	-2.5	Inside	17.31	48	10	367.8
88	10/11/2011	17084	-2.5	Inside	16.72	47	10	370.7
88	10/11/2011	17084	-2.5	Inside	26.5	49	10	246.6
88	10/11/2011	17232	2.5	Outside	9.69	40	10	518.7
88	10/11/2011	17232	2.5	Outside	13.97	46	10	431.7
88	10/11/2011	17195	2.5	Outside	10.69	42	10	501.5
88	10/11/2011	17195	2.5	Outside	10.12	43	10	546.3
88	10/11/2011	17158	2.5	Outside	6.81	35	10	615.0
88	10/11/2011	17158	2.5	Outside	7.16	39	10	678.5
88	10/11/2011	17122	2.5	Outside	5.93	35	10	706.3
88	10/11/2011	17122	2.5	Outside	7.84	38	10	598.3
88	10/11/2011	17084	2.5	Outside	10.32	40	10	487.0
88	10/11/2011	17084	2.5	Outside	13.69	45	10	428.3
88	11/3/2011	17084	-9.5	Inside	17.88	54	10	412.3
88	11/3/2011	17084	9.5	Outside	13	47	10	476.8
88	11/3/2011	17084	2.5	Outside	10.94	45	10	536.0
88	11/3/2011	17084	-2.5	Inside	24.56	54	10	300.1
88	11/7/2011	17158	2.5	Outside	6.03	37	10	750.1
88	11/7/2011	17195	9.5	Outside	10.75	50	10	623.4
88	11/7/2011	17195	2.5	Outside	10.68	49	10	611.8
88	11/7/2011	17122	-9.5	Inside	18.94	49	10	345.0
88	11/7/2011	17232	-2.5	Inside	32.3	57	10	243.8
88	11/7/2011	17232	-9.5	Inside	28.9	52	10	243.5
88	11/7/2011	17195	-2.5	Inside	30.22	59	10	271.6
88	11/7/2011	17195	-9.5	Inside	22.06	52	10	319.0
88	11/7/2011	17158	-2.5	Inside	21.29	55	10	354.1
88	11/7/2011	17158	-9.5	Inside	26.57	56	10	290.0
88	11/7/2011	17122	-2.5	Inside	17.25	47	10	359.3
88	11/7/2011	17158	9.5	Outside	10.6	50	10	632.2
88	11/7/2011	17122	2.5	Outside	5.97	39	10	813.8

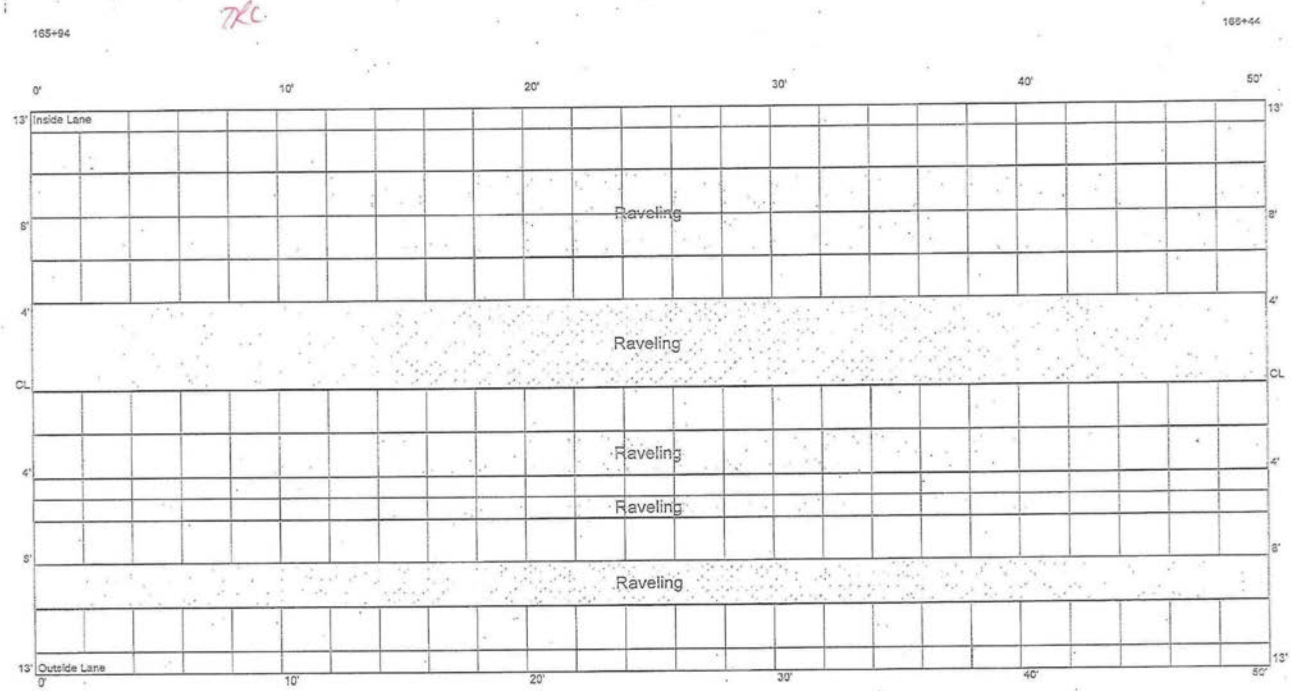
CELL	DAY	STATION	OFFSET_FT	LANE	FLOW_TIME_S	INITIAL_HEAD_CM	FINAL_HEAD_CM	Q = cm^3/s
88	11/7/2011	17122	9.5	Outside	8.37	49	10	780.6
88	11/7/2011	17232	9.5	Outside	12.97	50	10	516.7
88	11/7/2011	17232	2.5	Outside	9.69	50	10	691.6

APPENDIX N: CELLS 86 AND 88 VISUAL DISTRESS SURVEY, 2011

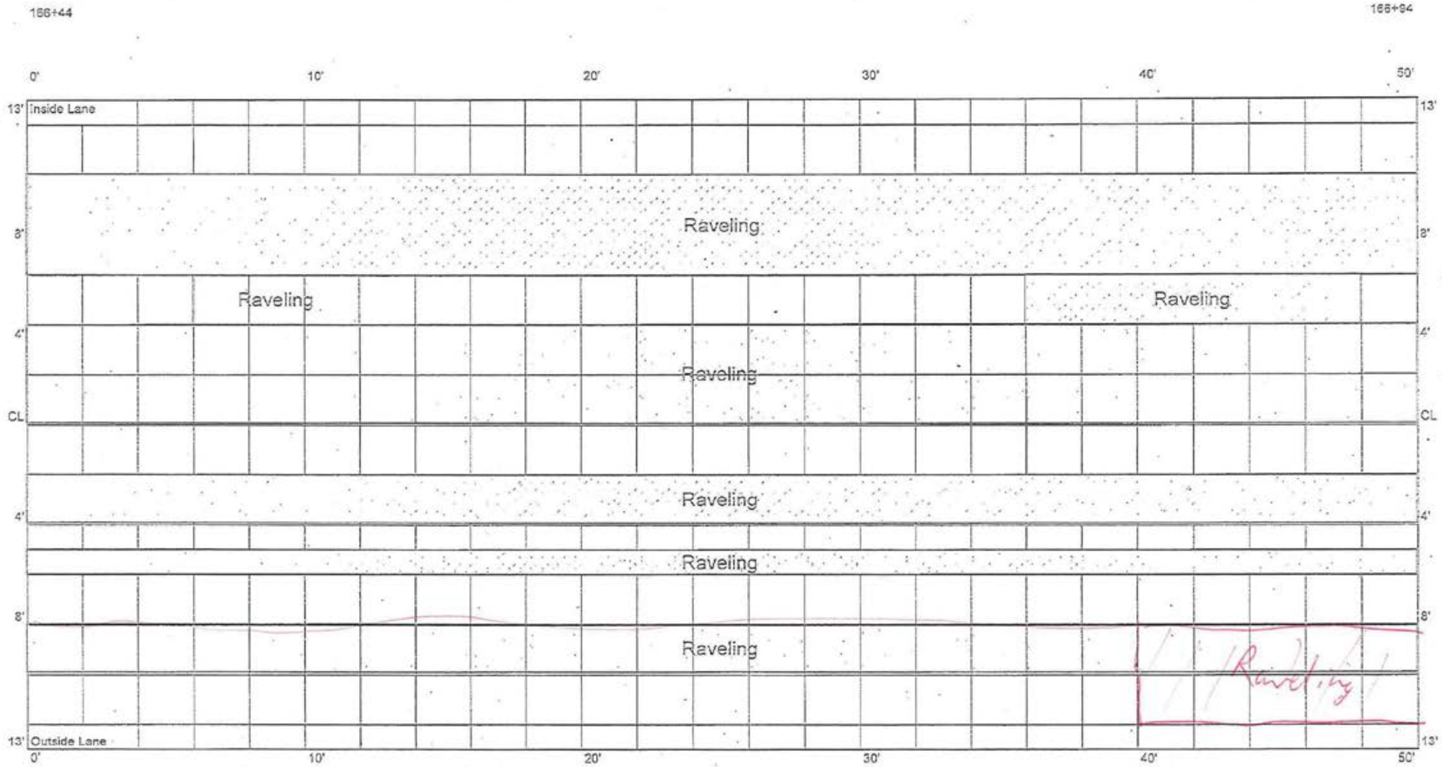
~~9/2[illegible]/2010 MKC~~ ~~4/25/2011 MKC~~

10/27/11
TKC

CELL 86
0 - 50 ft

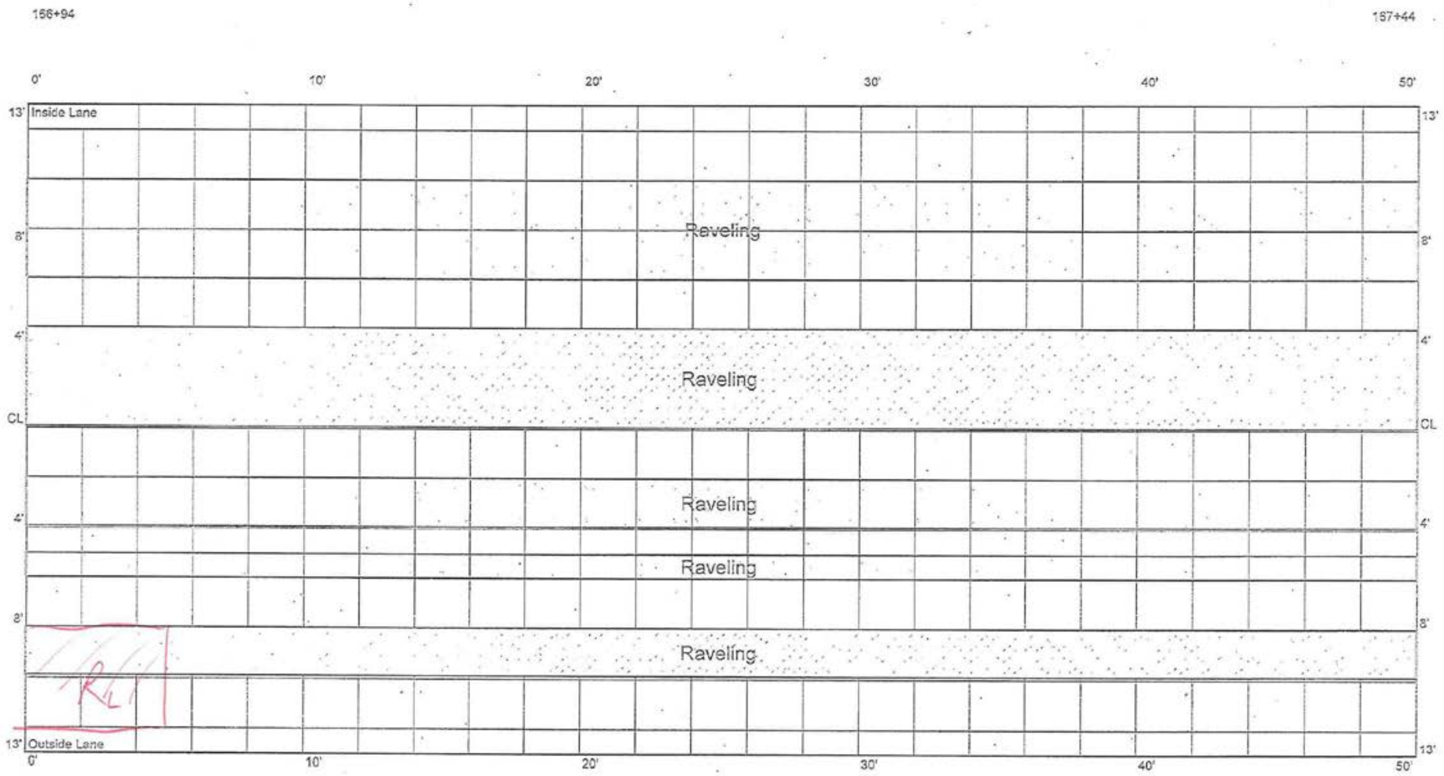


CELL 86
50 - 100 ft

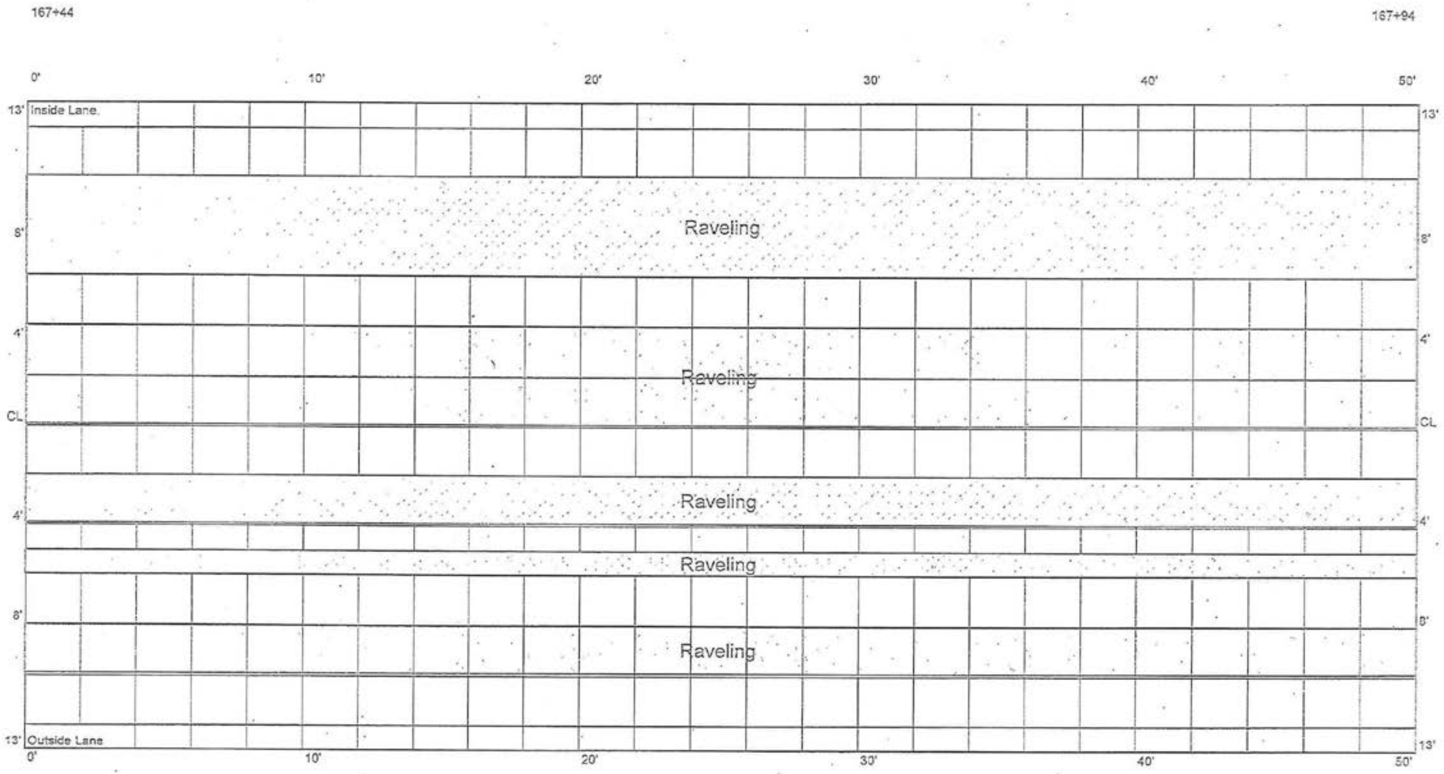


CELL 86

100 - 150 ft

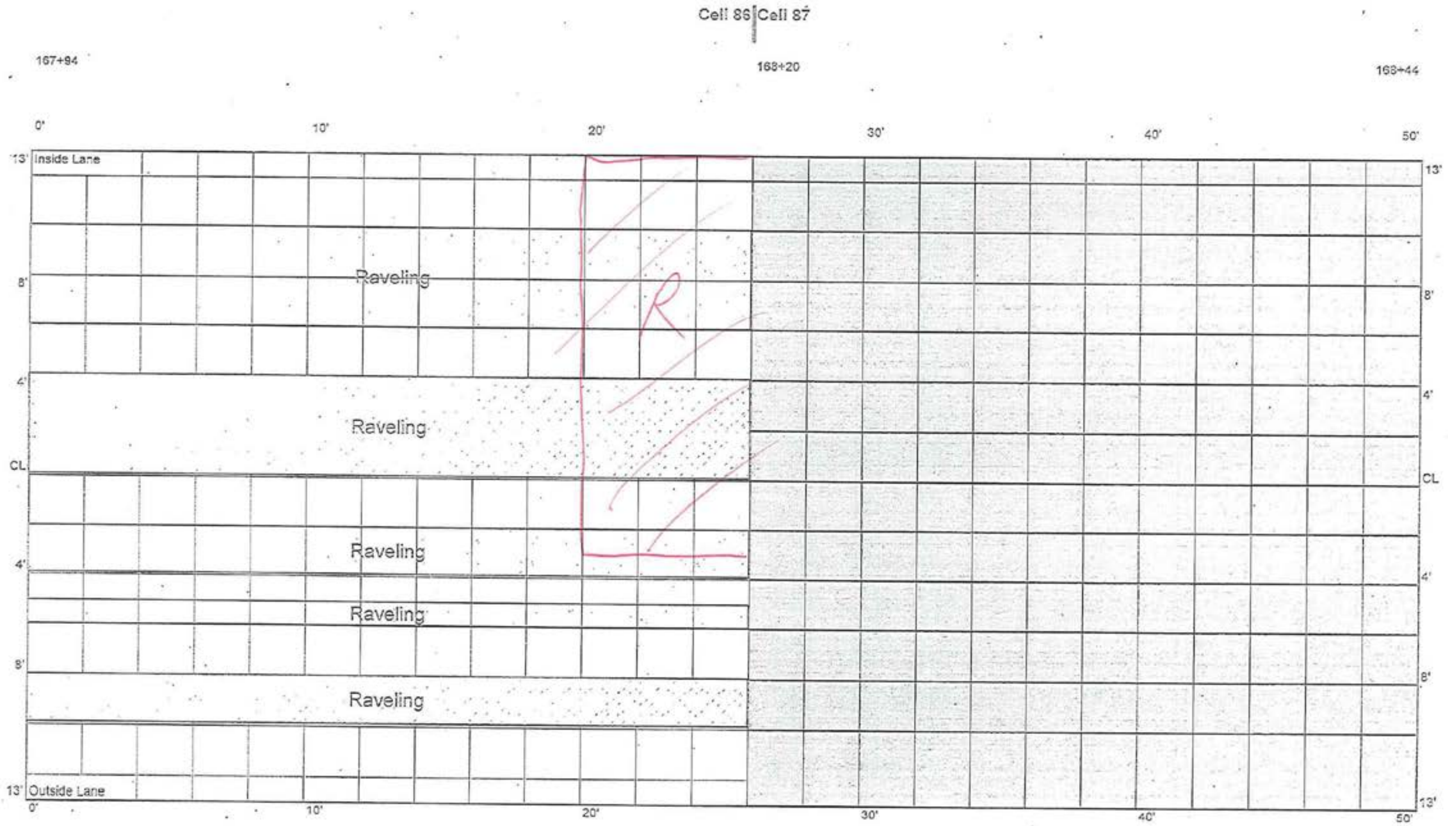


CELL 86
150 - 200 ft



CELL 86

200 - 250 ft

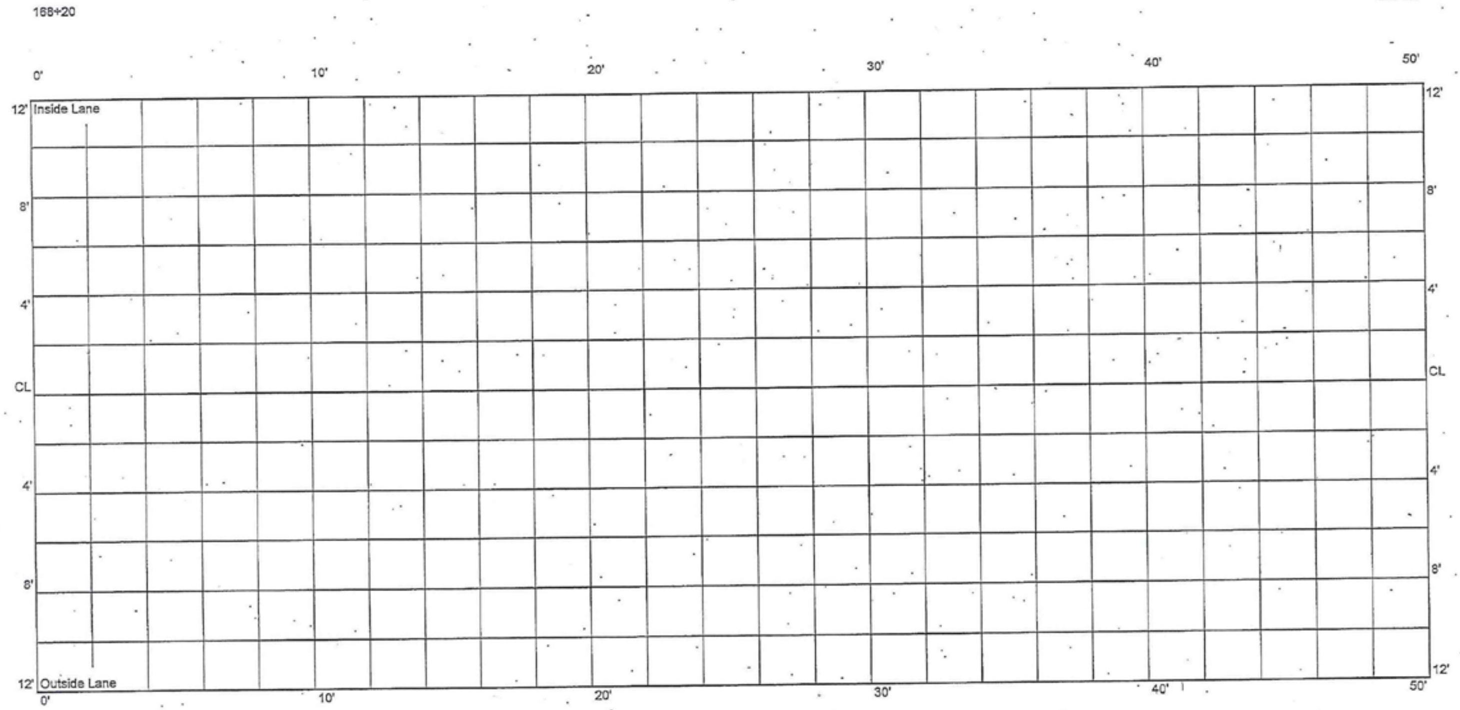


~~9/24/2010 MKC~~

~~4/25/2011 MKC~~

10/27/11
TRC

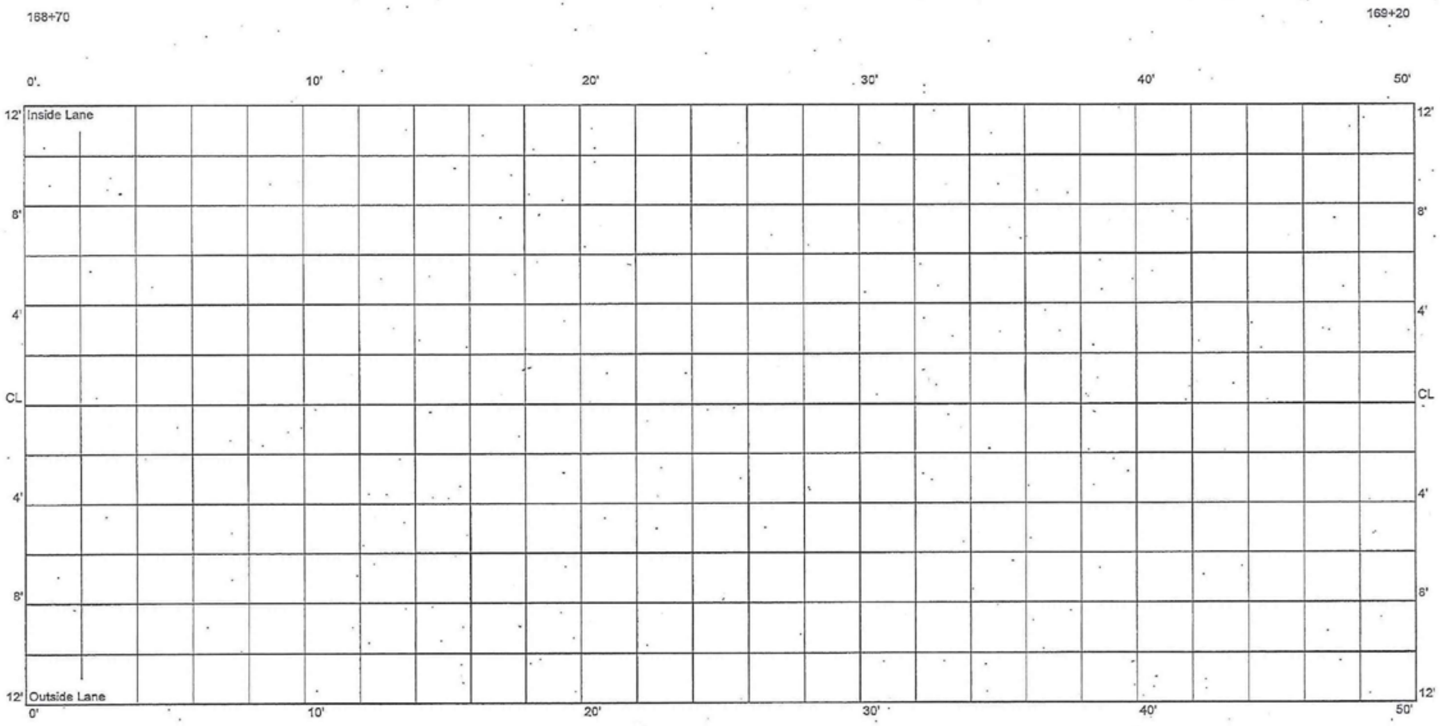
CELL 87
0 - 50 ft



4/13/10
TRC

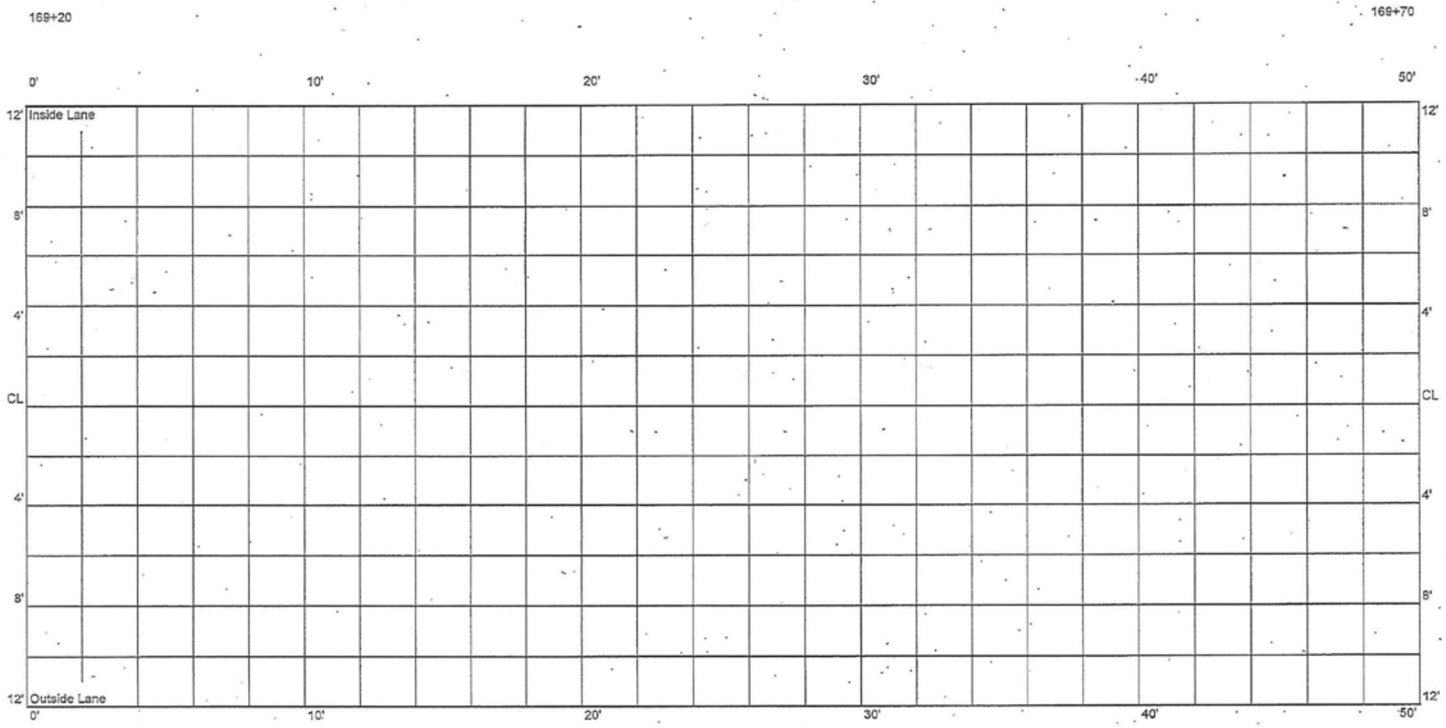
CELL 87

50 - 100 ft



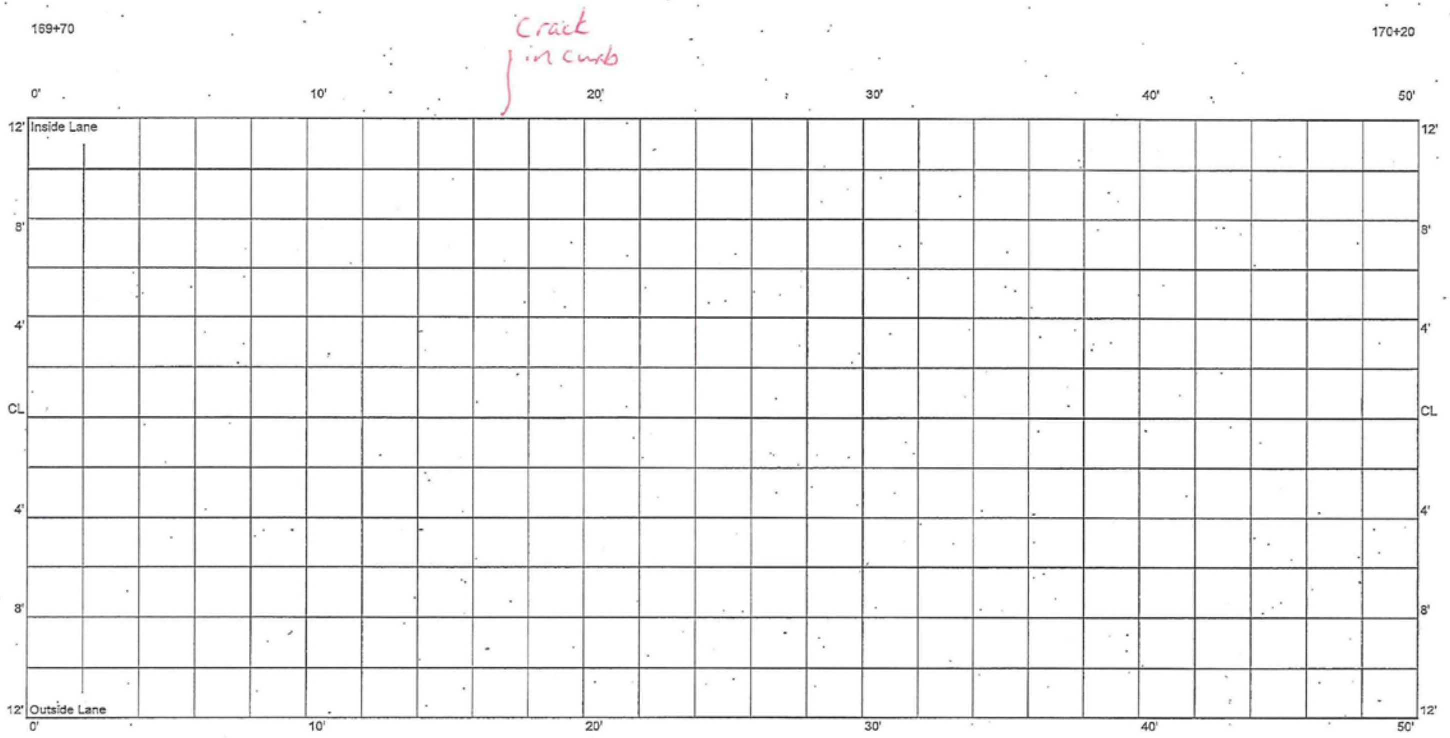
CELL 87

100 - 150 ft



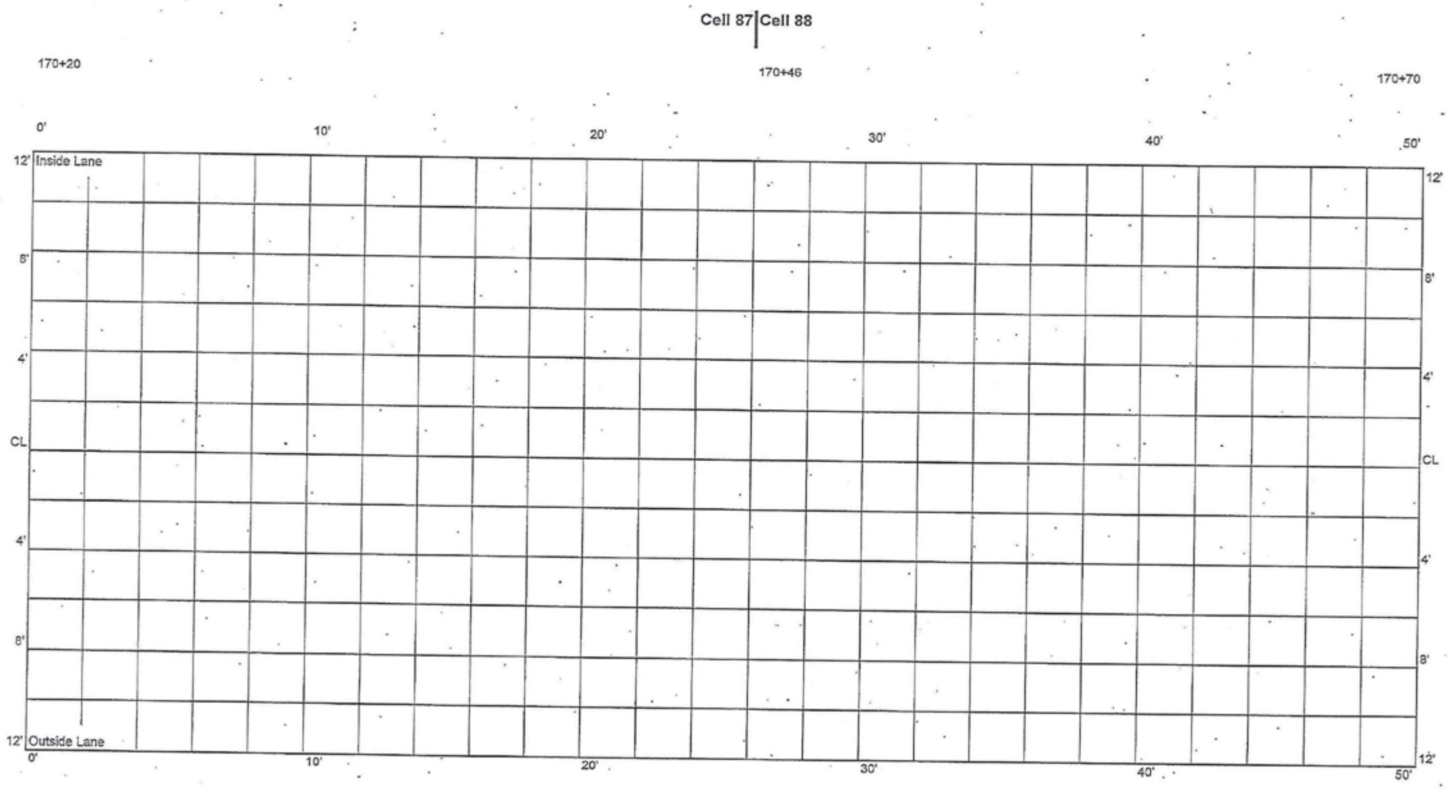
CELL 87

150 - 200 ft



CELL 87

200 - 250 ft

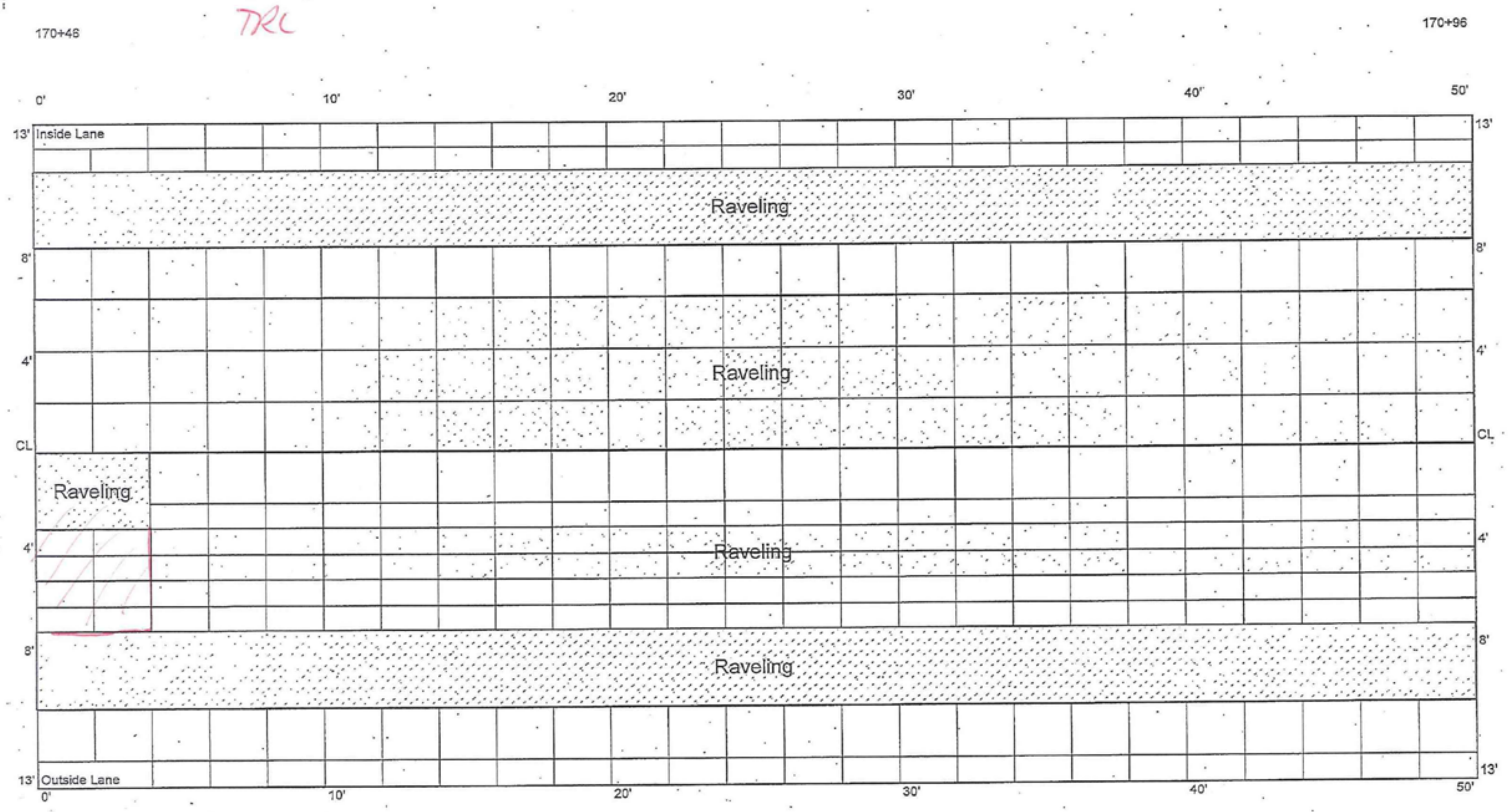


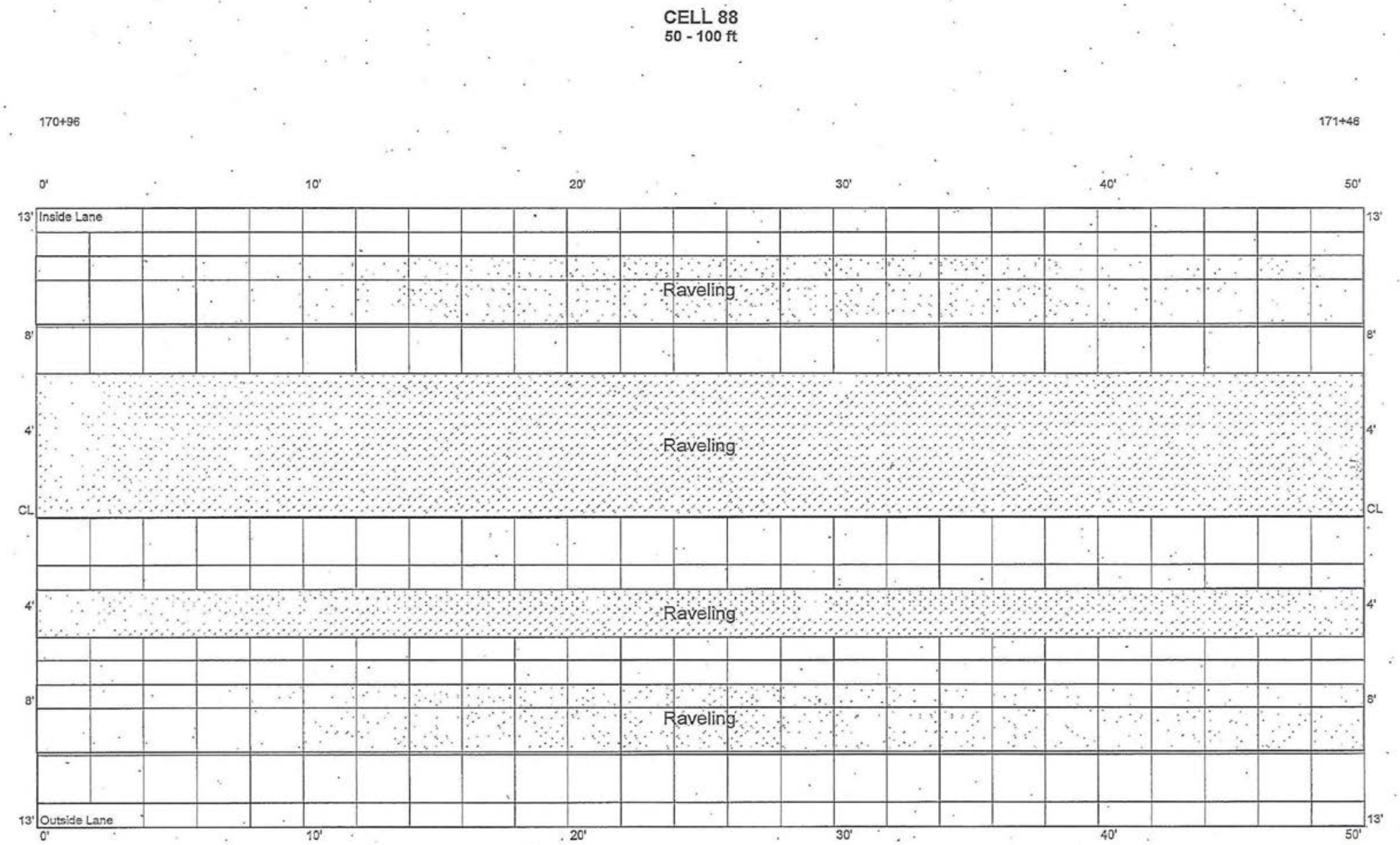
CELL 88
0 - 50 ft

9/24/2010 MKC

4/25/2011 MKC

10/27/11 TRC

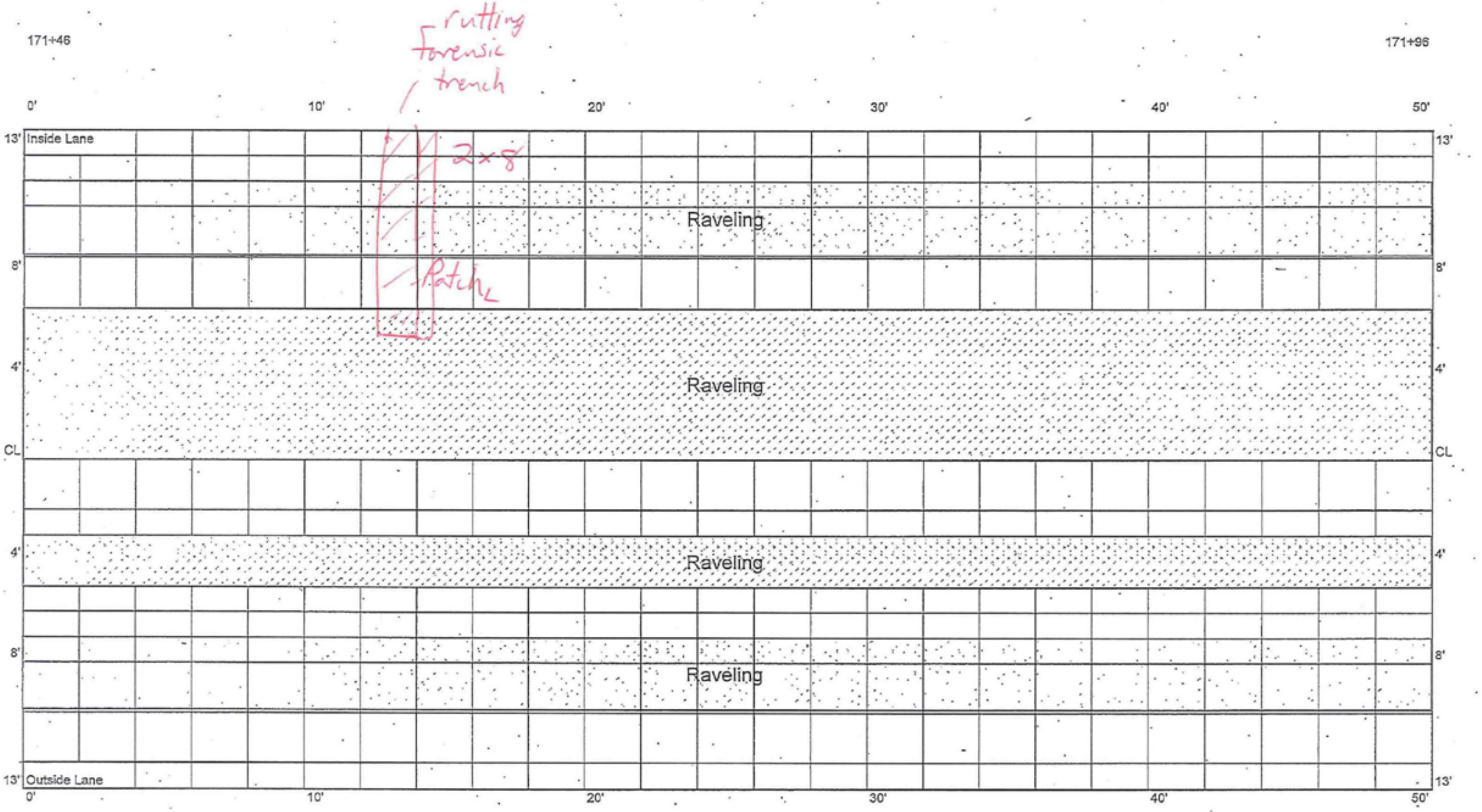



CELL 88
50 - 100 ft
170+96
171+46
0'
10'
20'
30'
40'
50'
13' Inside Lane
8'
4'
CL
Raveling
Raveling
Raveling
Raveling
13' Outside Lane

CELL 88

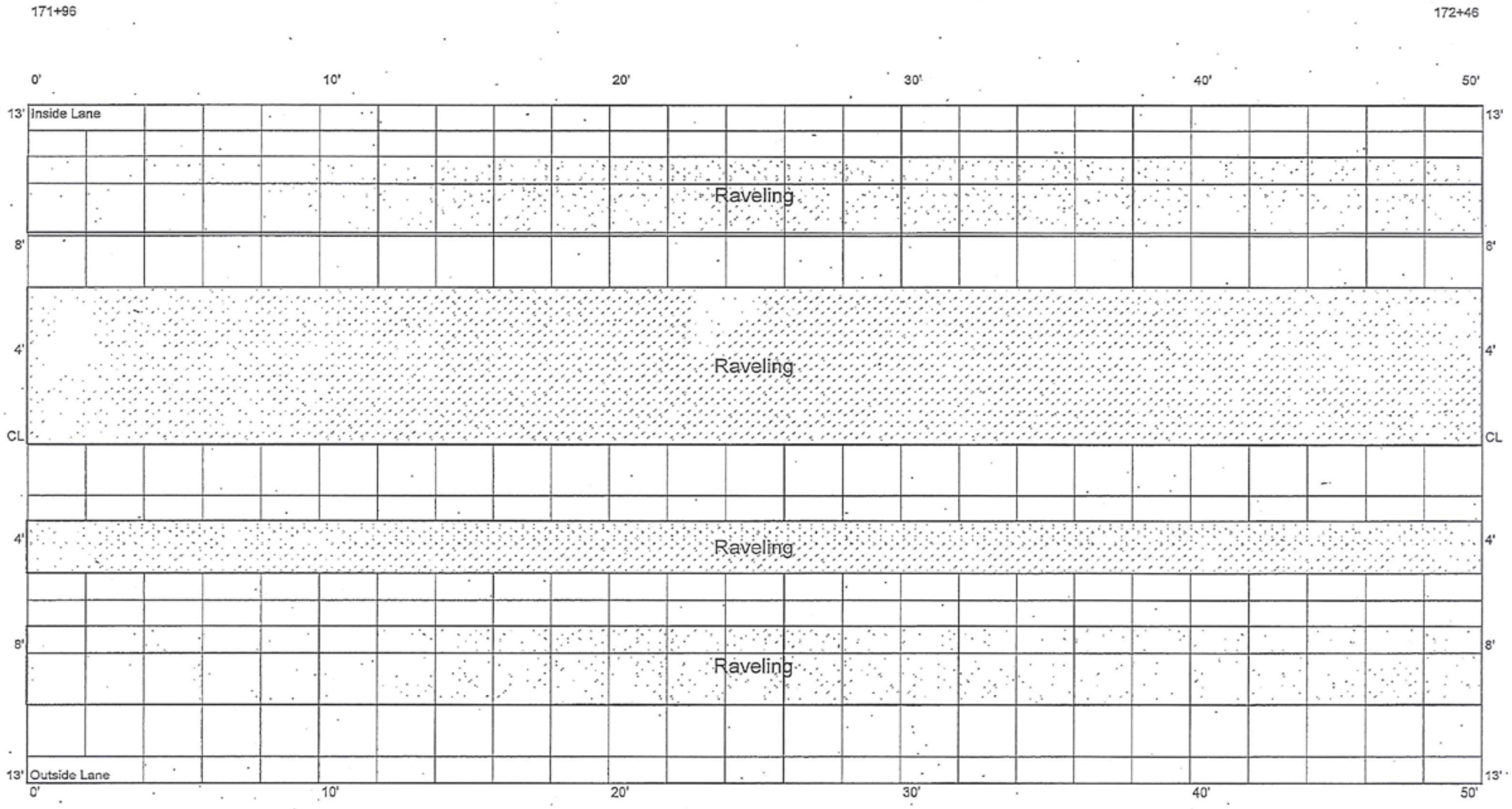
100 - 150 ft

(*enter into db)



CELL 88

150 - 200 ft



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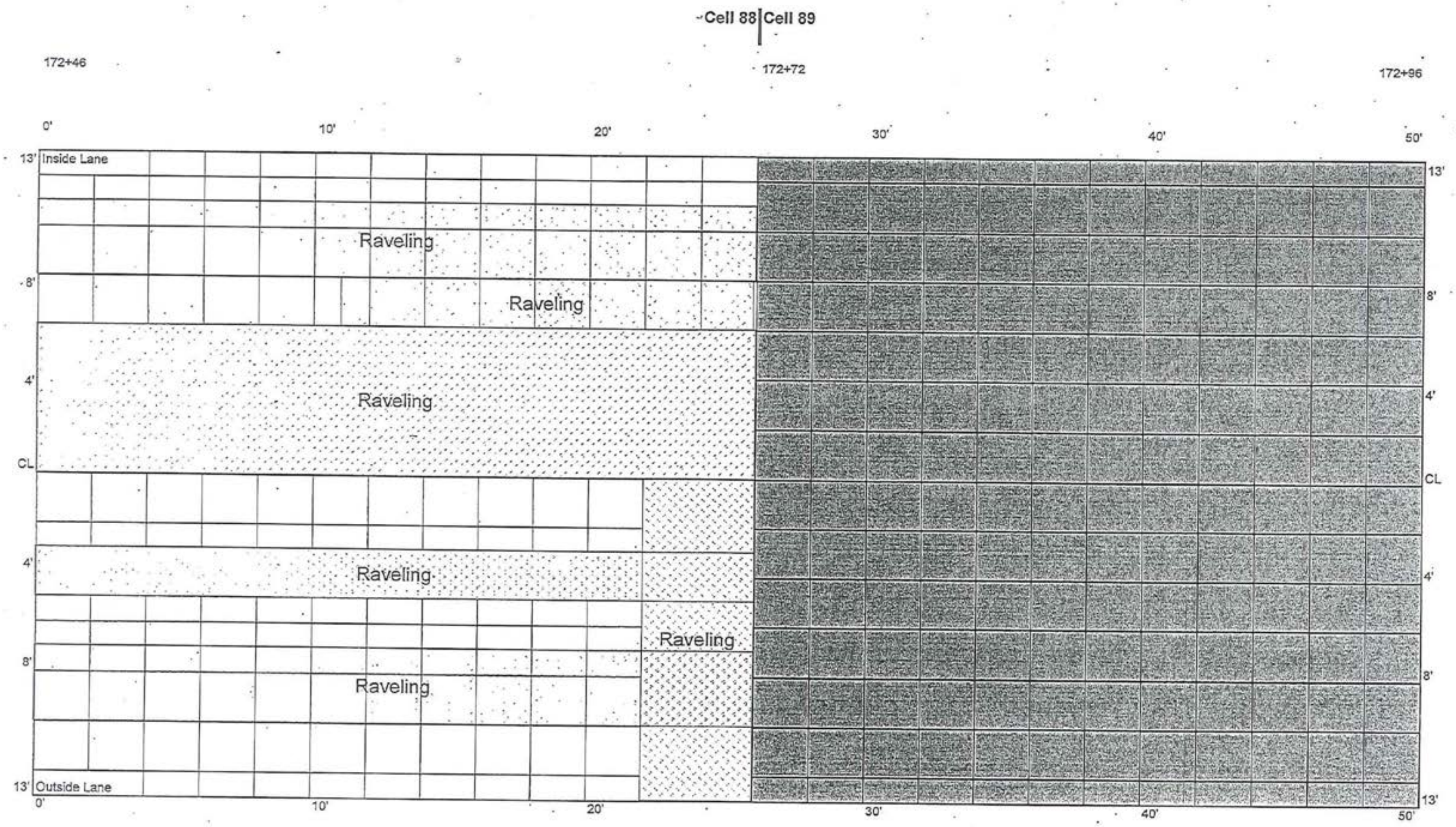
200 - 250 ft



APPENDIX O: SPECIAL CORE DENSITY AND VOIDS TESTING

Specimens 7 and 9 in Raveled Areas, Specimens 8 and 10 in OK Areas

	Full ht poros asphalt Speci			
Specimen I.D.	7(Rav)	8(OK)	9(Rav)	10(OK)
Bag Wt. (A)	58.6	59.0	58.7	59.3
Sample Dry Wt. (B)	4630.5	4570.9	4325.5	4306.0
Sealed Bag/Sample in Air (C)	4688.3	4629.1	4384.2	4363.8
Sealed Bag/Sample Under Water (D)	2167.3	2149.3	2026.6	2037.6
Sample Dry Wt. After Submersion (E)	4630.5	4570.8	4325.5	4305.1
Bag Volume Correction (Vc)	0.728	0.731	0.737	0.739
Gmb (B/[C-D-(A/Vc)])	1.897	1.905	1.899	1.917
Max. Spg. (Gmm)	2.518	2.518	2.518	2.518
Air Voids (Va)	24.6	24.3	24.6	23.9

APPENDIX P: RESILIENT MODULI – ALL LANES OF EACH CELL; 2009-2011

Cell 86 Layer Resilient Moduli - 2009

2009 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
5/6	61480	12106	19159	62210	15392	21313	59809	9868	22859	58340	10253	22111
6/17	137200	13791	22287	176311	14560	20680	174103	11484	23015	180486	10460	23465
7/27				64319	14143	23294	55006	10197	26487	52126	9628	26271
9/15	82955	15058	24326	124511	16076	22974	104740	11872	25084	107922	11394	24515
10/27	485293	15861	22349	599196	15384	21872	659862	10870	24002	663151	10906	23326
11/18	644498	17467	23294	714711	17466	22069	781436	11879	24923	451018	9810	24865

Cell 87 Layer Resilient Moduli - 2009

2009 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
5/5	311495	17768	24110	404831	18761	22058	325641	16599	25393	389362	13570	23509
6/17	980380	18542	23839	1324945	16578	22601	926518	17700	26024	1146566	14620	25664
8/24	274277	18854	24043	427532	18358	22707	227689	17768	25936			
9/15	568132	21168	26236	872701	18923	23784	582246	19495	28615	622629	16598	27190
10/27	4344975	17172	24532	4807621	14663	24051	4144449	16057	27225	4613251	14243	26724
11/18	4798451	19164	25941	5501324	16390	25761	4806385	17156	28558	5746016	13019	29121

Cell 88 Layer Resilient Moduli - 2009

2009 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
5/1	116451	6583	24298	125844	6522	24336						
5/5	79400	6427	21861	91750	6128	20543	70264	5006	23980	74528	5573	21531
6/17	148036	7766	23839	168400	7721	23326	146984	7441	24144	166999	7925	22751
7/8	55886	7258	25149	71576	7483	23235	54691	6028	28383	48102	6109	24983
9/15	117765	8565	25388	143969	8307	25141	108149	7913	26857	112281	8211	24697
10/27	526061	10738	27898	553072	10555	25878	557663	11091	28737	649113	10397	27682
11/17	357194	10849	26977	415763	11369	26286	422547	9910	28662			

Cell 86 Layer Resilient Moduli - 2010

2010 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
2/18	624885	148757	39486	757957	60687	32102	784729	141477	49702	794235	141197	47656
3/10	415073	17508	22790	540283	17102	22520	607275	10787	24541	606316	10536	23797
3/19				520588	13864	24820						
4/7	384829	19509	23148	461531	19614	22662	540179	12595	24659	526150	12270	23648
6/14	133510	16153	22503	181478	15775	22234	170710	12576	24128	178555	11095	23568
7/28	91536	18229	24303	154140	21589	20973	119094	14605	25608	108755	13491	24058
9/20	228865	19680	22535	283826	17756	21702	281675	14767	24244	268331	14180	23068
9/28				250947	16758	22313	246264	13791	23981	244578	12416	23505
11/12				476852	14452	23907	493681	10793	25583	553258	10768	25425
11/16	435498	18414	23480	654361	14075	22590	595967	12419	24678	632219	12170	24164

Cell 87 Layer Resilient Moduli - 2010

2010 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
2/22	3668517	45812	38598	4203724	33016	33492	3206063	46831	42505	3882890	40976	44611
3/10	3744907	17365	24176	4250034	16374	24205	3696582	13982	26330	4446132	10069	27710
3/19				4062170	16158	24981						
4/7	3581169	19217	25081	4134956	16558	24646	3242158	17412	26741	3962093	12695	27555
6/14	1097187	19138	24016	1378982	17654	22959	960990	17232	25933	1182226	13565	26414
7/28	545130	25003	26247	855204	21077	25111	549693	21474	28000	633287	17623	27324
9/20	228865	19680	22535	2904211	15780	23980	1867932	19699	27372	2168924	16700	27309
11/8							2309734	14957	27095	2872336	12820	28203
11/16	3994605	18961	24708	5034270	13789	24388	3951450	15961	26652	4592943	13768	27304

Cell 88 Layer Resilient Moduli - 2010

2010 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
2/18	592820	416377	76520	552529	329172	65939	523258	885183	81126	497436	1160638	72315
3/10	457775	13819	30077	477111	11603	27056	511136	17551	35615	603263	16670	32077
3/19				466120	6665	22538						
4/7	484467	8312	23547	499635	8313	22528	518247	7519	23928	594678	6624	23426
6/14	158443	7544	24932	178875	7432	25091	162260	7753	25398	183141	7109	24212
7/28	101331	8145	23521	137400	7686	23607	113207	8286	24268	112686	7694	22475
9/20	248960	8519	24261	242186	7846	22835	246097	9829	25563	283960	8440	25033
9/27	129041	9197	25277	147780	7515	24862	128789	9703	27059			
10/11	112628	8567	25482	137377	7822	25423	103727	9298	26510	122831	8418	25572
11/5	380824	7800	27230	397961	7563	25712	408052	8172	28682	516033	7790	29618
11/16	500633	9943	27611	622277	8492	26779	545475	10458	28623			

Cell 86 Layer Resilient Moduli - 2011

2011 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
3/1	602435	280285	50522	1250579	308572	37988						
3/16				339650	22693	35415				406576	12529	27062
3/29	219334	15586	22689	279557	15302	23108	315390	10839	22689	277025	10618	21950
4/6	300652	16951	21376	392360	15004	22014	346065	10822	22667	388403	10150	22030
4/29	172612	15801	22803	235850	15455	22522	216988	11276	24261	213723	11048	23507
6/6							59660	13495	25280	56044	12995	24367
6/27	96189	16721	24670	148542	17045	23465	107722	13378	24039	111717	9739	22346
9/6	120670	16993	27816	179851	18141	25680	139560	13880	25776	137660	11746	24601
11/4	350296	16837	27432	454161	14978	26981				417584	10899	26442

Cell 87 Layer Resilient Moduli - 2011

2011 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
3/1	2028528	376604	59189	3712743	217721	47690						
3/29	2064896	17897	23715	2503821	16629	22688	2212164	12247	25364	2573905	10557	26287
4/11	3852836	18800	23104	4457496	15605	22666	3521340	15495	25222	4190078	12961	26444
5/3	1371179	17826	22921	1900892	14673	22428	1327729	12489	25786	1516652	11024	26071
6/6							164243	19766	25606	158931	16781	24415
6/28	302006	21450	24657	471475	22336	23389						
9/6	1295091	20761	27950	1648226	19676	26724	1315476	15965	27491	1640072	12749	27911
11/4	2947215	19145	27750	3836589	14980	27862	3189066	13987	28747	3510415	11971	29391

Cell 88 Layer Resilient Moduli - 2011

2011 Date (Mo/Day)	Inside Lane						Outside Lane					
	Middle of Lane			Outer Wheel Path			Middle of Lane			Outer Wheel Path		
	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade	Asphalt	Base	Subgrade
3/1	701094	510540	73914	1097869	431705	60240						
3/16										384213	15797	32255
3/29	216216	6338	22098	216201	5855	22550	241274	5089	23018	315927	5033	22734
4/6										176146	4573	22342
4/11	431568	6712	23886	437933	7163	22170	435966	5869	24202	509559	5712	23771
5/2	407244	6673	23859	428971	6875	22626	443014	6060	26098	529821	5980	25034
6/6							53266	6013	22728	55813	6008	21686
6/28	88643	6263	22697	117601	6286	23520	86470	5485	23885	83766	5011	22417
9/6	201765	8424	25730	231633	7873	26762	192826	7110	25932	196157	6642	24231
11/4	338351	8561	27995	357373	8790	27294	400896	9025	30002	438730	8509	28344

APPENDIX Q: RAINFALL AND TIPPING BUCKET DATA FOR 2009-2011

Runoff Volumes (gallons)										
Day	Rainfall	Cell 86 surface runoff			Cell 87 surface runoff			Cell 88 surface runoff		
		Expected	tips	Actual	Expected	Tips	Actual	Expected	Tips	Actual
10/2/2009	1.41	1070	56	896	5500	180	2720	1070	9	128
10/6/2009	1.69	1282	66	1056	6592	258	4128	1282	10	160
6/11/2010	1.05	796	59	944	4096	12	192	796	31	496
6/25/2010	1.01	766	8	128	3940	0	0	766	7	112
7/17/2010	1.12	850	8	128	4369	0	0	850	14	224
8/13/2010	1.28	971	29	464		0	0	971	10	160
9/2/2010	1.34	1017	35	560		0	0	1017	20	320
9/15/2010	2.51	1905	47	752		0	0	1905	29	464
9/23/2010	1.12	850	80	1280		0	0	850	40	640
3/23/2011	2.14	1624	35	560	8348	32	512	1624	0	0
5/21/2011	1.06	804	78	1248		0	0	804	3	48
5/30/2011	0.9	683	48	768	3510	37	592	683	4	64
6/22/2011	1.06	804	41	656	4135	0	0	804	0	0
7/5/2011	1.50	1138	11	176	5851	4	64	1138	2	32
7/10/2011	1.17	888	2	32	4564	10	160	888	3	48
7/14/2011	1.75	1328	43	688	6826	6	96	1328	0	0
7/15/2011	1.48	1123	35	560	5773	8	128	1123	4	64
8/16/2011	1.41	1070	16	256	5500	44	704	1070	25	400

APPENDIX R: WATER QUALITY TESTING RESULTS

Sample Ports (SP 86 & SP 88)

Well #	SP 86								SP88	
Sample date	05/11/09	06/10/09	06/17/09	07/21/09	08/17/09	08/20/09	10/02/09	8/13/2010	06/10/09	07/21/09
Time	10:57	12:22	10:41	12:17	11:00	10:05	9:00	11:00	12:38	12:30
Conductivity umhos/cm)	680	650	740	780	750	810	880	1100	440	360
Turbidity (NTU)	3900	260	98	12	4.9	16	19	62	93	63
Suspended Vol.Solids (mg/L)	300	25	10	2.8	1.6	1.6	2.4	7.6	5.3	2.8
Suspended Solids (mg/L)	4600	350	140	25	11	27	20	130	81	37
Solids,Total Volatile mg/L)	320	110	130	93	82	87	190	170	67	79
Solids,Total(mg/L)	4900	780	600	490	470	520	600	760	400	330
Nitrate+Nitrite Nitrogen,Total(mg/L as N)	2.1	2.3	2.3	2.5	2.8	4	2.5	2.5	1.1	1.1
Kjeldahl Nitrogen, Total (mg/L)	3.19	0.54	0.3	0.42	0.66	0.35	0.24	0.36	0.92	0.65
Phosphorus Total, LL (mg/L as P)	2.95	0.46	0.173	0.213	0.089	0.088	0.075	0.149	0.321	0.305
Chloride,Total(mg/L)	72.9	70	80.7	82.5	96.7	115	127	182	50	21.8
Cadmium LL (ug/L)	4	0.5	0.17	0.18	<0.10	0.15	0.12	0.21	<0.10	<0.10
Chromium LL (ug/L)	150	25	9.2	10	4.1	6.6	6.7	9.17	11	10
Copper (ug/L)	290	41	10	17	37	18	8.4	16.8	39	17
Iron HL, Tot (ug/L)	190000	23000	4500	6300	830	490	1700	4220	3500	3500
Lead (ug/L)	89	10	2.1	3	<1.0	<1.0	1	2.46	1.6	1.8
Mercury (ug/L)	N/A	0.04	0.02	0.02	<0.01	<0.01	0.08	0.024	0.03	0.03
Nickel LL (ug/L)	210	31	9.6	12	4.5	2.7	6.6	10.3	6.3	5
Zinc HL (ug/L)	260	41	11	15	<10	<10	<10	11.8	10	<10
Temp (deg C)	13.49	17.62	19.09	22.09	21.52	21.74	19.72		16.82	24.69
PH	6.73	7.18	7.53	7.37	7.04	7.25	6.74		9.11	9.12

Runoff Water Quality

Sample Port #	TB Cells 88 & 89		TB Cells 86 & 87	
Sample date	6/9/2010	8/13/2010	6/9/2010	8/13/2010
Time	10:10	11:30	10:15	11:20
Pre-sample depth to water (ft.)				
Conductivity (umhos/cm)	56	49	96	71
Turbidity (NTU)	1.4	7	2.9	3.8
Suspended Vol. Solids (mg/L)	1.2	2.4	<1.0	2.8
Suspended Solids (mg/L)	2	10	1.2	12
Solids, Total Volatile (mg/L)	<10	11	18	21
Solids, Total (mg/L)	52	44	80	64
Nitrate+Nitrite Nitrogen, Total (mg/L as N)	0.18	0.2	0.78	0.29
Kjeldahl Nitrogen, Total (mg/L)	<0.20	0.34	0.43	0.55
Phosphorus Total, LL (mg/L as P)	0.032	0.071	0.037	0.05
Chloride, Total (mg/L)	<0.500	0.548	0.911	0.964
Cadmium LL (ug/L)	<0.10	<0.10	<0.10	<0.10
Chromium LL (ug/L)	0.76	1.17	0.9	1.25
Copper (ug/L)	<1.00	<10.0	1.79	<10.0
Iron HL, Tot (ug/L)	40.8	365	85.3	253
Lead (ug/L)	<1.0	<1.0	<1.0	1.18
Mercury (ug/L)	0.011	0.02	<0.010	0.025
Nickel LL (ug/L)	<1.0	<1.0	1.74	1.57
Zinc HL (ug/L)	46.2	18.4	75.6	30.2

Groundwater Water Quality

Well #	Well 1 (T3MW Cell 25)			Well 2 (T4MW Cell 25)		
Sample date	03/04/08	06/18/08	11/20/08	03/04/08	06/18/08	11/20/08
Time	11:45	12:00	12:20	13:15	12:45	13:00
Pre-sample depth to water (ft.)	9.55	6.75	8.4	21.45	10.65	12.42
Conductivity (umhos/cm)	710	730	740	1100	1500	1400
Turbidity (NTU)	78	92.4	na	100.3	7.9	178.1
Suspended Vol. Solids (mg/L)	6.7	16	32	4.7	5.2	3.3
Suspended Solids (mg/L)	75	240	540	68	90	80
Solids, Total Volatile (mg/L)	120	130	140	180	250	200
Solids, Total (mg/L)	560	930	1100	820	1200	1100
Nitrate+Nitrite Nitrogen, Total (mg/L as N)	<0.05	<0.05	<0.05	2.4	<0.05	0.55
Kjeldahl Nitrogen, Total (mg/L)	1.06	1.66	0.43	1.81	1.45	0.57
Phosphorus Total, LL (mg/L as P)	0.095	0.372	0.142	0.139	0.152	0.212
Chloride, Total (mg/L)	21	23	25	42	84	34
Cadmium LL (ug/L)	<0.10	0.7	0.24	<0.10	0.23	0.16
Chromium LL (ug/L)	4.7	14	7.2	4.4	4.2	2.9
Copper (ug/L)	53	21	9.6	65	66	6.9
Iron HL, Tot (ug/L)	3300	N/A	6300	3200	N/A	2600
Lead (ug/L)	2.2	12	3.8	1.6	2.5	1.3
Mercury (ug/L)	0.03	0.04	<0.01	0.05	0.03	0.01
Nickel LL (ug/L)	7.9	16	13	8.7	13	15
Zinc HL (ug/L)	15	36	19	14	<10	<10
Temp (deg C)	8.35	15.58	10.7	10.47	14.22	12.53
PH	6.67	6.83	6.03	6.08	6.85	6.73

APPENDIX S: WATER QUALITY STANDARDS

Water Quality standards taken from Minnesota Rules 7050								
			class 2a			Class 2b		
			CS	MS	FAV	CS	MS	FAV
Turbidity (NTU)			10			25		
Suspended Vol. Solids (mg/L)			NA	NA	NA	NA	NA	NA
Suspended Solids (mg/L)			See below					
Solids, Total Volatile (mg/L)			NA	NA	NA	NA	NA	NA
Solids, Total (mg/L)			NA	NA	NA	NA	NA	NA
Nitrate+Nitrite Nitrogen, Total (mg/L as N)								
Kjeldahl Nitrogen, Total (mg/L)			NA	NA	NA	NA	NA	NA
Phosphorus Total, LL (mg/L as P)			12			30		
Chloride, Total (mg/L)			230	860		230	860	
*Chromium LL (ug/L)			117	984		117	984	
*Copper (ug/L)			6.4	9.2		6.4	9.2	
Iron HL, Tot (ug/L)								
Lead (ug/L)			1.3	34		1.3	34	
Mercury (ug/L)			6.9			6.9		
*Nickel LL (ug/L)			88	789		88	789	
*Zinc HL (ug/L)			59	65		59	65	
Temp (deg centigrade above for stream				0		5		
Temp (deg centigrade above for lake)				0		3		
PH			6.5	8.5		6.5	8.5	
"CS" means the highest water concentration of a toxicant to which organisms can be exposed indefinitely without causing chronic toxicity								
MS" means the highest concentration of a toxicant in water to which aquatic organisms can be exposed for a brief time with zero to slight mortality.								
FAV = final acute value (96 hour) The FAV equals twice the MS value								

TSS water Quality Standards Criteria Table

Regional water quality criteria (Total Suspended Solids [TSS] mg/L)	Reference/least impacted	Biology	Combined
All Class 2A waters (Trout Streams)	10		10
Northern River Nutrient Region	16	14	15
Central River Nutrient Region	31	24	30
Southern River Nutrient Region	60	66	65
Red River mainstem – Headwaters to border		100	100
(Concentrations can be exceeded no more than 10% over a ten year data window; the assessment season is April through September)			
Lower Mississippi River – Pools 2 through 4 [through the Lower Mississippi River SAV draft SS WQS]		32	32
Lower Mississippi River main stem below Lake Pepin [UMRCC criteria report]		25	25
[summer average TSS concentration met in at least half of the summers, defined as June-September]			

APPENDIX T: TEMPERATURE BELOW PAVEMENT

Cell 19
Average temperatures below surface ((^{o}F)

	0.50	1.50	2.50	3.50	4.50	6.00	9.00	12.00	15.00	18.00	24.00	30.00	36.00	48.00	60.00	72.00
6/8/2009	54.1	54.7	55.5	56.1	57	57.7	59	60.3	61.5	62.3	63.5	64.1	64.2	62.9	60.5	57.9
7/21/2009	81.4	81.6	81.5	81.5	81.3	81	80.4	79.5	78.4	77.5	75.7	74.2	72.8	70.5	68.6	66.6
8/8/2009	78.8	78.5	78	77.7	77.2	76.8	76.2	75.7	75.4	75.3	75.1	74.9	74.4	72.7	70.6	68.5
8/19/2009	68.3	69.4	70.8	71.7	73	74	75.4	76.6	77.4	77.8	77.9	77.4	76.7	74.7	72.4	70
10/1/2009	51.6	52.7	54.1	55	56.3	57.4	59.2	60.9	62.4	63.5	65.3	66.6	67.8	69.3	69.5	69
10/6/2009	47.3	48.1	49.1	49.8	50.7	51.5	52.8	54.2	55.6	56.6	58.7	60.4	62	64.6	66.1	66.7
6/11/2010	70.9	71.1	71.2	71.3	71.4	71.5	71.8	72	72.3	72.5	72.7	72.5	72.1	69.8	67	64.1
6/25/2010	75.4	76.1	76.9	77.4	78	78.4	78.9	79	78.7	78.2	76.9	75.4	73.8	70.3	67.2	64.6
7/17/2010	83.1	83.7	84.3	84.7	85.2	85.5	85.6	85.4	84.8	84	82.3	80.5	78.7	75.1	72	69.2
8/13/2010	79.4	80.4	81.4	82.1	83.1	83.7	84.7	85.5	85.8	85.8	85.2	84.1	82.6	79.5		74
9/2/2010	70.5	152	73.4	74.5	75.9	77	78.8	80.3	81.5	82.1	82.8	82.7	82.1	79.8	77.2	74.7
9/15/2010	62.3		65.1	66.2	67.6	68.7	70.4	71.8	72.7	73.2	73.4	73.2	72.9	72.4	71.9	71.4
9/23/2010	62.8		63.8	64.2	64.7	65.1	65.9	66.7	67.5	68	68.9	69.4	69.8	70	70	69.6

Cell 88
Average temperatures below surface (^{o}F)

	0.50	1.50	2.50	3.50	4.50	6.00	9.00	12.00	15.00	18.00	24.00	30.00	36.00	48.00	60.00	72.00
6/8/2009	56.5		56.5	56.6	57.1	58	59	60.6	61.8	62.1	62.8	63.1	62.7	60.9	58.5	56.2
7/21/2009	80.2		80.3	80.3	80.2	79.8	79.2	77.8	76.3	75.9	74.7	73.1	71.6	69.2	67	64.9
8/8/2009	76.6		76.6	76.6	76.2	75.6	75.3	75.2	75.2	75.2	75.1	74.7	73.8	71.4	68.9	66.7
8/19/2009	73.3		73.3	73.5	74.2	75.3	76.1	77.1	77.3	77.3	77.1	76.3	75.2	72.9	70.4	68.2
10/1/2009	56.7		56.7	56.9	57.9	59.8	61.3	64	66	66.4	67.5	68.5	69.1	69.6	69.2	68.3
10/6/2009	50.9		50.9	51	51.8	53.2	54.5	57	59	59.6	61	62.6	63.9	65.6	66.4	66.5
6/11/2010	68.7	68.4	68.1	67.8	67.5	67.4	67.3	67.3	67.4	67.4	67.3	66.9	66.1	64	61.6	59.4
6/25/2010	77.6	78.6	79.6	80.1	80.9	81	80.5	79.1	77.1	76.5	74.8	72.7	70.5	66.9	63.7	61.2
7/17/2010	87.9	88.4	89	89.2	89.4	88.8	87.8	85.9	83.6	83	81.2	79	76.8	73.1	69.9	67.1
8/13/2010																
9/2/2010																
9/15/2010																
9/23/2010																

Cell 86
Average temperatures below surface (^{o}F)

	0.50	1.50	2.50	3.50	4.50	6.00	9.00	12.00	15.00	18.00	24.00	30.00	36.00	48.00	60.00	72.00
6/8/2009																
7/21/2009																
8/8/2009	75.3	75.3	74.4	75.3	74.8	75.2	74.3	74.4	74.5	74.5	74.4	74	73.1	71.1	69.1	67.1
8/19/2009	74	74	75.8	74	75	74.2	76.5	77	76.9	76.8	76.5	75.6	74.7	72.7	70.8	68.7
10/1/2009	49.5	49.6	50.6	51.7	54.2	55.4	60.1	63.1	63.3	64.5	65.8	66.6	67.1	67.4	67.4	66.9
10/6/2009	46	46	46.8	47.6	49.6	50.4	54.3	57.2	57.4	58.6	60.2	61.4	62.5	63.3	64.3	64.7
6/11/2010	68	68	67.7	67.3	66.4	66.2	65.7	65.6	65.6	65.5	65.3	64.9	64.2	63.5	61.6	59.7
6/25/2010	75.1	75.4	76.1	76.8	77.9	78	77.2	75	74.8	73.4	71.6	70	68.4	67	64.3	62
7/17/2010	84.5	84.6	85.5	85.6	85.9	85.2	83.6	80.7	80.4	78.9	76.9	75.3	73.8	72.5	69.9	67.6
8/13/2010																
9/2/2010																
9/15/2010																
9/23/2010																