**Impact of Diamond Grinding on Pavements Exhibiting Materials Related Distress (MRD)-Page4**

Historically D-Cracking and Aggregate Silica Reaction (ASR) were the materials related distresses that impacted concrete pavement performance. Today, joint associated distress may have overcome these as the most common MRD. Although the causes of MRD are now believed to be known and the prevention in new concrete pavements possible, many miles of MRD pavements exist on the highway. When it becomes time to conduct pavement preservation activities one consideration is whether the MRD pavement can be successfully diamond ground as part of the preservation activities. There is a need to develop guidance and perhaps test procedures which would allow determination of the suitability of diamond grinding on an MRD pavement.

**Impact of Longitudinal Grooving on Safety and Vehicle Control—Page 5**

Significant impacts on wet weather related accidents can occur through the application of net-work level preservation strategies that address both friction aspects and hydroplaning potential. Tools exist that can address these issues both from a theoretical and experience basis. Over a half century of data is available to demonstrate the benefits of longitudinal grooving of pavements.

Due to the enhanced lateral stability provided by diamond grooving, some vehicle response results in apparent steering input to the driver. This problem was recognized by Caltrans early and they subsequently developed a narrower groove (i.e. 0.95”) to mitigate this effect. The California research conducted in the 1960s and 70’s employed bias ply tires and vehicle suspensions quite different than modern car fleets. There is a need to research the impact of groove width and groove spacing on vehicle control to optimize the performance of this safety treatment. Old I-94 at MnROADs has longitudinal grooved test sections and instrumented vehicles now exist which can now measure the impact of groove width and groove spacing.

**Repair of Joint Associated Distressed Pavements--Page 10**

Joint associated distress has seriously impacted some existing concrete pavements in the mid-western United States. These pavements can experience considerable transverse and longitudinal joint associated distress. Although some agencies have successfully conducted repairs of these distresses, some agencies continue to experience performance issues with the repairs. There is a need to establish procedures and training which will ensure long term performance of MRD repairs.

**Effectiveness of Surface Hardeners on Texture Durability--Page 11**

In locations where polishing aggregates exist it is not uncommon for texture wear to occur prematurely. This can be particularly true when the surface is diamond ground exposing more of the coarse aggregate prone to polishing. This results in some CDG textures diminishing in 4 to 7 years.

There are products now available which purport to be able to provide more wear resistant textures once topically applied. Recent research by Chico State suggests that multiple periodic applications of such products may provide this kind of benefit. Old I-94 WB at MnROADs has two test sections of one of these treatments. There is a need to establish the efficacy of these types of products and if successful the cost-benefit as a preservation strategy.

**Effectiveness of Penetrating Sealers on Preventing/Mitigating Joint Associated Distress—Page 12**

In recent times, concern has developed regarding joint associated distress that is evident in many wet-freeze states. The distress oftentimes begins at a joint and progresses outward as the deterioration increases. Current research suggests that the adverse effects of both the saturation level and the formation of calcium oxychloride can be mitigated by the use of penetrating sealers. The penetrating sealer limits the contact between the salt solution (winter maintenance chemicals) and the calcium hydroxide present in the concrete.

Penetrating sealers are applied using hand or equipment mounted sprayers and are simply sprayed across a narrow joint from the top of the pavement. Since often times only a narrow joint configuration exists, the spray application needs to cover the inside of a joint that is only 1/8 to ¼ inch in width and can be three to four inches in depth. There is a need assess the performance of these types of treatments and the application methods to ensure their effectiveness.

**Determining the Impact of Water Infiltration through Transverse Joints on Base Erosion and Jointed Concrete Pavement Performance—Page 14**

The Texas Transportation Institute recently improved upon a mechanistic-empirical fault prediction model, previously developed for the National Ready Mixed Concrete Association (NRMCA), under contract to the Seal No Seal group. The impact of joint seal effectiveness was directly employed within the fault prediction model.

One important factor that was addressed in the model was a means to evaluate the number of wet days per year that water exists underneath the slab at the slab/subbase interface. This number is not only a function of annual rainfall but also a function of surface inflow, sealant effectiveness and subbase drainability. The number of wet days was determined with respect to probability functions that can be used for each site to evaluate the number of days that water exists underneath a slab.

The erosion resistance of materials, number of wet days, and traffic load were defined and coupled in this model to effectively analyze the potential for faulting and erosion in jointed concrete pavements. The model can be calibrated for local conditions as a function of distinct characteristics of the subbase or subgrade, which is an important capability in life cycle analysis.

Suggested Approach to Scoping Research for Each Project

* Prepare a white paper defining the problem, its extent and severity, and summarizing relevant past and on-going research and their outcomes (past and future).
* Develop the project scope such that both short term and long term implementation can occur. This may include development/promotion of satellite research sites and programs in collaborator efforts as well as MnROAD research.

Diamond grinding is the process of removing a thin layer of hardened concrete or asphalt concrete pavement surface using a self-propelled machine outfitted with a series of closely spaced diamond saw blades mounted on a rotating shaft. Typical highway diamond grinding units employ approximately 240 blades across a four-foot wide head to remove the surface material. This removal, although a cutting process, applies pressure and torque to the surface of the roadway.

Diamond grinding originated in California in the late 1950s and early 1960s with the first reported major highway project constructed on a section of I-10. Since its first diamond grinding in 1965, this section of I-10 has been ground three times in total and is performing well after a half century in service after being diamond ground. Over the last half century, diamond grinding has proven to be one of the most effective strategies in the preservation tool kit when installed on pavements consisting of competent concrete.

However, with the preponderance of joint associated distress in some Midwest states, concern exists regarding its efficacy when used on pavements exhibiting MRD. The concern is whether the diamond grinding process will exacerbate the MRD over time due to the stresses imposed during the construction process.

The low volume roads test location at MnROAD had the curves constructed with aggregates that were assumed to promote ASR in the pavement. This was done to evaluate the deterioration rates over time. As such, these sections could be used to construct diamond ground sections over different periods in time to assess if there is an acceleration in the MRD and, more importantly, if there is some procedure by which to determine when a pavement could be ground and when it should not be ground.

Since 2008 the FHWA has been actively promoting the placement of high friction surface treatments (HFST) in locations such as sharp horizontal curves and where vehicles may brake excessively. This program was created with the recognition that although horizontal curves made up only 5 percent of our Nation’s highway miles in 2008, more than 25 percent of highway fatalities in the United States occurred at or near horizontal curves each year.

At these locations the road surface of standard pavements may become prematurely polished, thereby reducing available pavement friction and contributing to loss of vehicle control or skidding. Negotiating a sharper curve requires increased friction demand, which subsequently creates greater shear forces on the surface aggregate leading to increased polishing of the surface aggregate.

The FHWA further promoted the HFST technology in EDC-2 and today, 39 states have successfully used HFST. The HFST have proven valuable in reducing accidents and ensuring motorist safety.

High friction surface treatments (HFST) are site specific applications of very high-quality, durable aggregates using a polymer binder. As a result, installation costs typically range from $20 to $50 per square yard. Due to their expense, HFSTs cannot be used for corridor type applications and their use has been limited to spot applications.

However, accidents happen at many locations and there is a need for additional tools which can be applied to larger areas enhancing safety even more. Building upon the success of the HFST program, there is a need to develop additional and less expensive tools to facilitate accident reduction and safer travel.

Once such tool is longitudinal diamond grooving which can be applied to either asphalt or concrete pavements. Longitudinal grooving typically costs on the order of $2 to $3 per square yard which allows it to be more cost effectively applied to larger areas and at many more locations.

Treatment service lives for HFSTs have been estimated at 10 years while diamond grooving service lives range between 10 to 20 years providing additional long term benefit for network level application.

Longitudinal grooving is a process that uses diamond cutting blades to saw longitudinal grooves into the roadway surface within the driving lanes. The installed grooves are typically 1/8 inch wide and 3/16 to ¼ inch deep spaced typically on ¾ inch centers. Figure 1 is a photo of a longitudinally grooved roadway.



Figure 1 Roadway with Longitudinal Grooving

**National Impact:**

The following paragraphs are excerpts from studies depicting the national accident and safety statistics. They clearly spell out the extent and severity of the situation. In addition, it is also evident that accident events are wide spread and frequent. As such, techniques such HSFT which are spot applications cannot solve the problem alone. Instead, a comprehensive approach using more widely applied and cost-effective preservation treatments are needed. The use of longitudinal diamond grooving is one such preservation strategy.

It has been estimated that weather-related crashes cause between 94 million and 272 million hours of delay each year. The annual cost of weather related crashes is estimated to be between $22 billion and $51 billion (FHWA Pisano et al).

“The vast majority of most weather-related crashes happen on wet pavement and during rainfall: 73% on wet pavement and 46% during rainfall. A much smaller percentage of weather-related crashes occur during winter conditions: 17% during snow or sleet, 13% occur on icy pavement and 14% of weather-related crashes take place on snowy or slushy pavement. Only 3% happen in the presence of fog. (FHWA-Source: Ten-year averages from 2004 to 2013 analyzed by Booz Allen Hamilton, based on NHTSA data).”

“Nearly 5,700 people are killed and more than 544,700 people are injured in crashes on wet pavement annually. Every year, over 3,400 people are killed and over 357,300 people are injured in crashes during rainfall.” (FHWA Road Weather Management Program Web site)

**Game Changing:**

As indicated previously, there are many causes of wet weather accidents that span from visibility issues, to driver behavior, to roadway geometrics, to roadway conditions. However, the most easily controlled cause is roadway condition and its improvement can be addressed by effective pavement preservation strategies. Longitudinal grooving is one of the most effective preservation strategies for preventing hydroplaning.

For roadway condition, safety is commonly described in terms of friction values; the higher the friction value the safer the roadway. Under dry pavement conditions this assumption is an acceptable characterization. Under wet weather conditions, friction alone may not be sufficient to prevent accidents. Under wet weather conditions the ability to evacuate water from the tire-pavement contact becomes critical to preventing hydroplaning. If sufficient water becomes trapped between the roadway surface and the tire, hydroplaning can occur no matter what the friction level of the pavement.

Oftentimes preservation strategies do not address the hydroplaning potential but instead assume increased friction as a solution. From a theoretical approach, current analysis procedures were developed between the 1970s and 1990s and are now under evaluation in NCHRP project 15-55 for improvement. This study is identifying the short comings of the current design procedures which rely on both empirical data and one-dimensional analysis.

With computer capability today, 2-D and 3-D analysis is now possible and hopefully in the near future will provide more robust and accurate hydroplaning analysis. Perhaps the most significant work to date is by Ong et al (2005). An excerpt from Dr. Ong’s paper best describes his work: “This paper presents a numerical model to simulate the hydroplaning phenomenon and conducts a systematic study on the effectiveness of various designs of longitudinal grooving against hydroplaning. The analysis covers groove widths of 2 to 10 mm, grove depths of 1 to 10 mm, and groove center-to-center spacing of 5 to 25 mm. Groove dimensions are found to have significant effects on the effectiveness of a grooving design against hydroplaning. The results show quantitatively how the use of larger groove width and depth, and smaller groove spacing would reduce hydroplaning risk by computing the changes in the expected hydroplaning speed.”

One additional benefit that is derived from longitudinal grooving is the impact of anisotropic friction behavior. That is, many surface types exhibit the same or similar friction in all directions. Longitudinal based textures exhibit different friction in different directions. This is the phenomena known as lateral stability that is associated with longitudinal oriented textures. When a vehicle attempts to deviate from the direction of travel the friction can actually increase (i.e. embedment of tire tread in grooves). This attribute is not accounted for by typical agency friction testing (i.e. ASTM E274) which can only test in the direction of travel.

Through the use of longitudinal grooving, the potential for and the prevention of, hydroplaning can be addressed both from a theoretical standpoint as well as practical experience. Longitudinal grooving as a preservation strategy was originally developed by the California Highway Department in the early 1960s to improve friction and reduce wet weather accidents. Prior to the 21st century, computer simulations of the impact of longitudinal grooving were not conducted. Now, both the technology and applications exist. With the completion of the NCHRP 15-55 work even more powerful tools will be available for the journey to improve safety.

**Urgency and Scale:**

“On average, there are over 5,760,000 vehicle crashes each year. Approximately 22% of these crashes – nearly 1,259,000 – are weather-related. ….. On average, nearly 6,000 people are killed and over 445,000 people are injured in weather-related crashes each year. (Source: Ten-year averages from 2004 to 2013 analyzed by Booz Allen Hamilton, based on NHTSA data).”

Significant impacts on wet weather related accidents can occur through the application of net-work level preservation strategies that address both friction aspects and hydroplaning potential. Tools exist that can address these issues both from a theoretical and experience basis. Over a half century of data is available to demonstrate the benefits of longitudinal grooving of pavements.

Caltrans has successfully used longitudinal grooving to combat wet weather accidents for over half a century. The following excerpt is from one of their early studies; “…Longitudinal grooving is particularly effective in preventing hydroplaning accidents on curved sections of roadways, bridges, and tangent section of roadways subject to high cross winds. During an emergency stop, the longitudinal grooves also help hold the vehicle within its own traffic lane, a factor which is extremely important on multiple-lane roadways.”

Due to the enhanced lateral stability provided by diamond grooving, some vehicle response results in apparent steering input to the driver. This problem was recognized by Caltrans early on who developed a narrower groove (i.e. 0.95”) to mitigate this effect. The California research conducted in the 1960s and 70’s employed bias ply tires and vehicle suspensions quite different than modern car fleets. There is a need to research the impact of groove width and groove spacing on vehicle control to optimize the performance of this safety treatment.

Joint associated distress has seriously impacted some existing concrete pavements in the mid-western United States. These pavements can experience considerable transverse and longitudinal joint associated distress. Although some agencies have successfully conducted repairs of these distresses, some agencies continue to experience performance issues with the repairs. There is a need to establish procedures and training which will ensure long term performance of MRD repairs.

Minnesota DOT has been a leader in the investigation of the causes and prevention of joint associated distress across their network. By combining the previous research where MRD was found to occur on pavements constructed prior to 1995, it may be possible to evaluate the performance of selected MRD repairs over time.

In locations where polishing aggregates exist it is not uncommon for texture wear to occur prematurely. This can be particularly true when the surface is diamond ground exposing more of the coarse aggregate prone to polishing. This results in some CDG textures diminishing in 4 to 7 years.

There are products now available which purport to be able to provide more wear resistant textures once topically applied. Recent research by Chico State suggests that multiple periodic applications of such products may provide this kind of benefit. Old I-94 WB at MnROADs has two test sections of one of these treatments. There is a need to establish the efficacy of these types of products and, if successful, the cost-benefit as a preservation strategy.

Surface hardeners generally rely on a chemical process where a reaction between a surface treatment’s hardening agent and the concrete creates a denser surface texture, which is harder than plain concrete in the near surface region. Lithium silicate is a common, reliable agent to harden the surface of Portland cement concrete. It has been used successfully to extend the service lives of concrete floors in industrial settings where low speed vehicular traffic is present. It works by reacting with the calcium hydroxide produced by cement hydration. The reaction produces calcium silicate hydrate. This is the same product that is produced by adding water to Portland cement, which develops the strength and hardness in Portland cement concrete. During hydration, the calcium hydroxide is dissolved in the water; migrates to the surface where the lithium silicate reaction occurs; and the newly formed calcium silicate hydrate deposits itself in the pores and voids on the concrete’s surface. The lithium part’s function of the silicate is to stabilize and solubilize the silicate so it can remain in solution until it penetrates the concrete and then can react with the abundant calcium hydroxide found in the concrete.

Lithium silicate has two main advantages over other; first, it forms a dust rather than a crust when it dries. Second, when the lithium silicate penetrates the pores in the concrete, a reaction with calcium hydroxide occurs and creates both chemical hardening and densifying, increasing the concrete's surface strength and resistance to wear to traffic abrasion. A recent highway study of a Portland cement concrete pavement (PCCP) found that the treatment made the pavement more rut resistant and resistant to wear from snow plow abrasion. The reaction is greatest on a porous concrete surface because the porosity promotes penetration of the hardening agent, which in turn results in a deeper hardened surface.

Traditionally, sealing of transverse and longitudinal joints in concrete pavements has been accomplished through the use of formed in-place or compression type sealants installed shortly after pavement construction or during rehabilitation efforts. The common sealant types are hot pour and silicone sealants, and neoprene compression seals placed in varying geometric joint designs.

In recent times, concern has developed regarding joint associated distress that is evident in many wet-freeze states. The distress oftentimes begins at a joint and progresses outward as the deterioration increases (see photo in notes). Several national studies have investigated this issue which is best characterized by the C.P. Tech Center as follows: “This joint deterioration is problematic because it compromises the performance and service life of an otherwise healthy concrete pavement. Repairing these joints can be expensive, and these repairs are disruptive to the travelling public.”

Joint associated distress is attributed to two primary actions; freeze thaw damage and chemical attack, through the formation of expansive calcium oxychloride. Freeze thaw damage may be attributable to more aggressive de-icing and anti-icing programs implemented to provide enhanced roadway safety. In addition to greater quantities of salt being consumed, more varieties of salt types are also being used. Some calcium and magnesium based salts have been implicated in increasing the saturation level of concrete pavements.

Weiss has shown that there is a critical saturation level (i.e. 85%) at which concrete can survive freeze thaw conditions. At saturation levels above this, concrete loses its ability to resist freeze thaw actions due to the amount of water within the system when freezing occurs.

The second cause of joint associated distress is chemical, and that is the development of expansive calcium oxychloride. This was first reported by Sutter (4) and has more recently been indicated as a major contributing factor to distress. The formation of calcium oxychloride is the result of calcium hydroxide (within the concrete) reacting with calcium chloride used for winter maintenance operations. The resulting calcium oxychloride is an expansive product that subsequently deteriorates the concrete.

Current research suggests that the adverse effects of both the saturation level and the formation of calcium oxychloride can be mitigated by the use of a penetrating sealer. The penetrating sealer limits the contact between the salt solution (winter maintenance chemicals) and the calcium hydroxide present in the concrete.

As a result, there has been increasing interest in the use of penetrating concrete sealers, in lieu of sealants, to better protect the concrete from ingress of water and chemicals at the surface and into the joint.

Sealer technology has steadily improved and sealers generally can be classified as two types; reactive and non-reactive. Non-reactive sealers do not chemically react with concrete and perform similar to coatings with a typical service life of 3 to 5 years. These products are typically petroleum based, silicone oils, or linseed oil. Reactive sealers chemically react with the concrete and as a result are considered to be a more permanent solution. Reactive sealers are typically siloxanes and silanes and are often times specified as penetrating sealers.

Even though the use of penetrating sealers in lieu of, and in addition to, conventional joint sealants is becoming more common, there is still a need to develop practices for specifying, inspecting and testing penetrating sealers.

Currently penetrating sealers are applied using hand sprayers or equipment mounted sprayers and are simply sprayed across a narrow joint from the top of the pavement. Since often times only a narrow joint configuration exists, the spray application needs to cover the inside of a joint that is only 1/8 to ¼ inch in width and can be three to four inches in depth.

There is a need to develop a synthesis of practice on the specifying, inspection, and testing of penetrating sealers. If the synthesis indicates additional research is necessary, test sections should be constructed to further evaluate the performance. The following activities should be considered:

1. Specifications: Develop a summary of currently used specifications. Since these products are typically proprietary in nature, is it possible to develop a successful generic specification? How is the application rate/product determined in the design phase? Are there different categories of products with different applications? Are they selected from an approved product list and if so, what testing is required to meet the APL requirements? Are the agencies specifying the use of both a penetrating sealer followed by application of a conventional sealant?
2. Installation: Prepare a summary of installation methods such as hand sprayer, specialty equipment, etc. How are the joints prepared prior to application? If conventional sealants are applied in addition to the penetrating sealer, how much delay is specified between the processes and how is the ability of the sealant to bond to the treated surface ensured (i.e. testing or ?).
3. Inspection: How is the rate of application and coverage inspected? Are there field tests used to verify this? Product application at the top of the joint does not ensure adequate coverage of the joint face which cannot be seen. How is joint face coverage assured or inspected?
4. Laboratory Tests: What tests are the agencies specifying? Are they relying on manufacturer certification or conducting actual tests? If testing, what is the frequency of sampling and testing? What procedures are being used, etc.?
5. Performance assessment: Develop a summary of the performance to date of projects incorporating penetrating sealers.
6. Construct additional necessary test sections.

The Texas Transportation Institute recently improved upon a mechanistic-empirical fault prediction model, previously developed for the National Ready Mixed Concrete Association (NRMCA), under contract to the Seal No Seal group.

A focus of the SNS effort was to link joint seal effectiveness at an age beyond the initial performance period (during which the sealant is fully bonded) to when faulting would initiate through the ultimate advancement of a prediction model addressing the potential for erosion as a precursor to faulting and support related issues. The erosion resistance of materials, number of wet days and traffic load were defined and coupled in this model to effectively analyze the potential for faulting and erosion in jointed concrete pavements.

One important factor that was addressed in the model was a means to evaluate the number of wet days per year that water exists underneath the slab at the slab/subbase interface. This number is not only a function of annual rainfall but also a function of surface inflow, sealant effectiveness and subbase drainability. The number of wet days was determined with respect to probability functions that can be used for each site to evaluate the number of days that water exists underneath a slab.

The erosion resistance of materials, number of wet days, and traffic load were defined and coupled in this model to effectively analyze the potential for faulting and erosion in jointed concrete pavements. The model can be calibrated for local conditions as a function of distinct characteristics of the subbase or subgrade, which is an important capability in life cycle analysis. As such, MnRoads is a unique setting in which different structural sections and sealant conditions have existed whose performance have been evaluated and perhaps could be used as input to the models.