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THE EFFECTS OF GRINDING ON PCC PAVEMENTS

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16. Abstract

This study investigated issues related to the effects of spot diamond grinding on the performance and material properties of concrete pavement, the safety aspects of continuously ground pavement and the public perception of pavement spot diamond grinding.

A field survey was conducted to assess the conditions of selected spot diamond ground PCC (portland cement concrete) pavement sites. Pavement distress data was collected on control and spot ground sections on 22 different highways and 34 different locations in Wisconsin. In addition, micro-surveys were completed for each of the spot ground sections. Utilizing the PDI (pavement distress index) values and results of the micro-surveys comparisons are made between sections that were spot ground and those that were not. Conclusions are drawn concerning the effects of spot grinding on the performance of the concrete pavements. The comparisons showed no significant differences between the spot ground and control sections.

To examine the safety aspects of longitudinal spot grinding, the crash rates of longitudinal continuously ground pavement were utilized. Crash rates on PCC pavements were compared between 290 km of continuously ground and 115 km of transversely tined pavements in Wisconsin. All 11,219 reported crashes on the study sites during the six-year period from 1988 to 1993 were analyzed. Continuously ground surfaces were found to have lower crash rates than tined surfaces under dry and wet conditions, during daytime and nighttime; also under all four wetness and light conditions combinations. Ground pavements had 58% the crash rates of tined pavements under dry and wet conditions; the ratio was 84% when snow or ice was present on the pavement, however, relatively limited vehicular travel occurred under such conditions and these results are viewed as preliminary. Ground pavements had 57% the crash rates of tined pavements during daytime; the ratio was 73% during nighttime. A hypothesis of increasing crash rates with time (based on frictional properties deterioration with pavement age and/or cumulative vehicle passes since construction) could not be confirmed for either type of pavement texture, based on the available data.

In the public perception portion of the study, three perceived problems related to spot grinding PCC pavements were investigated: (1) motorists' perception of the effects of spot grinding on ride quality, (2) public acceptance of grinding newly constructed PCC pavements, and (3) motorists experiencing glare and/or perceiving ground areas to be icy and/or slippery patches. The study was conducted using a police assisted intercept survey. According to the survey results, motorists driving the ground sections were not bothered by the glare or noticed any icy or slippery patch. However, 75% of the respondents indicated that they were bothered to see that a newly constructed PCC pavement would require spot grinding.

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ABSTRACT

This study investigated issues related to the effects of spot diamond grinding on the performance and material properties of concrete pavement, the safety aspects of continuously ground pavement and the public perception of pavement spot diamond grinding.

Diamond grinding was first used in California, in 1965 on a 19 year old section of I-10, to eliminate significant faulting. Since this first application, pavement grinding has grown to become a major element of portland cement concrete (PCC) pavement restoration. In addition, for new pavements, a number of states have adopted strict smoothness requirements of only a few inches of deviation per road mile. Diamond grinding is used to eliminate the "high" spots and insure a smooth ride on the newly constructed pavement.

A field survey was conducted to assess the conditions of selected spot diamond ground PCC (portland cement concrete) pavement sites. Pavement distress data was collected on control and spot ground sections on 22 different highways consisting of 34 different locations in Wisconsin. In addition, micro-surveys were completed for each of the spot ground sections. Utilizing the PDI (pavement distress index) values and results of the micro-surveys, comparisons were made between sections that were spot ground and those that were not. Conclusions were drawn concerning the effects of spot grinding on the performance of the concrete pavements. The comparisons showed no significant differences between the spot ground and control sections.

To examine the safety aspects of continuously ground PCC pavement, crash rates were compared between 290 km of continuously ground and 115 km of transversely tined pavements in Wisconsin. An effort was made to match ground and tined site characteristics in order to assure that all factors except surface texture were identical between the two site categories. All 11,219 reported crashes on the study sites during the six-year period from 1988 to 1993 were analyzed. Continuously ground surfaces were found to have lower crash rates than tined surfaces under dry and wet conditions, during daytime and nighttime; also under all four wetness and light conditions combinations. Ground pavements had 58% the crash rates of tined pavements under dry and wet conditions; the ratio was 84% when snow or ice was present on the pavement, however, relatively limited vehicular travel occurred under such conditions and these results are viewed as preliminary. Ground pavements had 57% the crash rates of tined pavements during daytime; the ratio was 73% during nighttime. A hypothesis of increasing crash rates with time (based on frictional properties deterioration with pavement age and/or cumulative vehicle passes since construction) could not be confirmed for either type of pavement texture, based on the available data.

In the public perception portion of the study, three perceived problems related to spot grinding PCC pavements were investigated: (1) motorists' perception of the effects of spot grinding on ride quality, (2) public acceptance of grinding newly constructed PCC pavements, and (3) motorists experiencing glare and/or perceiving ground areas to be icy and/or slippery patches.

The study was conducted using a police assisted intercept survey. According to the survey results, motorists driving the ground sections were not bothered by the glare or noticed any icy or slippery patch. However, 75% of the respondents indicated that they were bothered to see that a newly constructed PCC pavement would require spot grinding.

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INTRODUCTION

In the summer of 1994, a research contract titled, "The Effects of Diamond Grinding on PCC Pavements" sponsored by the Wisconsin Department of Transportation (WisDOT) was begun at Marquette University.

The study investigated issues related to the effects of spot diamond grinding on performance and material properties of concrete pavement, the safety aspects of continuously diamond ground pavement and the public perception of pavement spot diamond grinding. This report presents the results of that investigation and is presented in three parts:

1. effects of spot diamond grinding on the performance and material properties of concrete pavement
2. safety aspects of continuously ground pavement
3. public perception of pavement spot diamond grinding

I. EFFECTS OF SPOT DIAMOND GRINDING ON THE PERFORMANCE AND MATERIAL PROPERTIES OF CONCRETE PAVEMENT

LITERATURE REVIEW

An extensive literature search on the effects of spot diamond grinding on portland cement concrete was conducted and a complete report of this search is on file with the WisDOT Pavement Research Unit. Key findings of the literature search are summarized in this section.

Diamond grinding was first used in California in 1965 on a 19 year old section of I-10, to eliminate significant faulting. Since this first application, pavement grinding has grown to become a major element of PCC pavement restoration. According to the Rehabilitation Training Course Instructors Manual (*1*), diamond grinding is defined as patterns cut into hardened concrete with closely spaced diamond saw blades. The major purpose of diamond grinding is to remove surface defects to provide a smooth riding surface. If the amplitude of the pavement waves (difference between pavement crests and troughs) is large, motorists will hear a resounding thump every time their wheels encounter a high spot (*2*). This corresponds to a very rough ride. Diamond grinding removes these bumps and provides a smooth ride (*3,4*).

Diamond grinding equipment consists of diamond blades mounted on a horizontal shaft known as the cutting head. This cutting head is mounted under a machine that is specifically designed for this type of work. The front wheels of this machine pass over the bump or fault on the pavement surface. These irregularities are then ground off by a centrally mounted cutting head. The rear wheels track in the smooth path left behind. A typical width for a cutting head ranges from 914 to 965 millimeters (36 to 38 in.) with 164 to 193 blades per meter (50 to 59 blades per foot) of shaft. These blades produce a desirable "corduroy" texture on the surface of the pavement.

Rehabilitative Grinding

Grinding is a component of a comprehensive rehabilitative program known as Concrete Pavement Restoration (CPR). CPR is a restoration technique developed over a period of several years by members of the International Grooving & Grinding Association (IG&GA), the American Concrete Pavement Association (ACPA), several State Transportation Departments, and the Federal Highway Administration (FHWA). The technique is used to rectify pavements exhibiting distresses. CPR was developed to extend pavement life, improve riding quality, enhance safety, and reduce road maintenance costs (*5,6,7*). In Wisconsin, the main reasons diamond blade grinding is used in a CPR project is to remove transverse faulting and to improve ride due to roughness of new patches and repairs.

In the past it was found that grinding has been misapplied as a CPR technique. In 1985 Voight, Hall, and Darter (*8*) surveyed 76 grinding projects ranging in age from 1 to 9 years in 19 states. They found that grinding improves pavement ride, however joint faulting may recur at a faster rate than faulting of a new pavement if no other CPR techniques are performed to address other existing pavement deficiencies (e.g., loss of aggregate interlock, elongation of dowel sockets). They also found that a project which contains a large amount of cracking and other structural failures is not a good candidate for a CPR procedure.

The literature reviewed demonstrated that service life of a ground PCC pavement varies anywhere from 5 to 10 years (*3,9,10,11,12,13*). This service life depends upon many factors including rate of traffic loading, existing pavement design, climate, pavement condition at the time of restoration, CPR (additional work), and performance of the existing load transfer system (*3*).

Initial Pavement Diamond Grinding

A number of states have developed strict smoothness requirements of only a couple of centimeters of deviation per road kilometer for new pavements. In order to meet these standards, diamond grinding is performed to insure a smooth ride on a newly constructed pavement.

A profile measuring test is performed on the pavement to determine what pavement irregularities need to be ground in order to insure an acceptable ride. The most commonly used profile measuring device is the California profilograph (14). The California profilograph is essentially "a rolling straightedge". It is a 2.0 kilonewton (450 pound) aluminum truss which is 7.62 meters (25 feet) long by 1.07 meters (42 inches) high.

A profile is taken .92 meters (3 ft) from and parallel to each edge of pavement placed at a width of 3.66 meters (12 ft), or less. If the pavement is placed at a width greater than 3.66 meters (12 ft), the profile will be taken in the areas of the wheel tracks .92 meters (3 ft) from and parallel to each edge in the traveled direction and .92 meters (3 ft) from and parallel to each planned longitudinal joint on each side of the joint (15). The areas exceeding the acceptable surface roughness are diamond ground to meet the specification.

STATE PROFILOGRAPH SPECIFICATION SURVEY

As a part of this project, a survey of seven Midwestern states was conducted to determine rideability specifications, incentive/disincentive policies, and methods of profile measurement. The states surveyed included: Wisconsin, Illinois, Iowa, Indiana, Michigan, Minnesota, and Ohio.

Table 1 summarizes the grinding specifications for the states surveyed. As shown, with the exception of the Michigan Department of Transportation all of the states surveyed used the California profilograph. The incentive rideability specifications range between PI (profile index, mm/Km) <47 to PI $<$ 189 millimeters per kilometer (3 to 12 inches per mile), while the disincentive specifications range between PI$>$110 to PI$>$349 millimeters per kilometer (7 to 16 inches per mile). The maximum PI allowed by the states after which the work is considered unacceptable ranges between 158 to 475 millimeters per kilometer (10 to 30.1 inches per mile). The maximum high point allowed by the states after which grinding must be performed ranges between 7.6 to 12.7 mm (0.3 to 0.5 inches) per 7.63 meters (25 feet).

The American Association of State Highway and Transportation Officials (AASHTO) and the American Concrete Pavement Association (ACPA) have recommended pay schedules for projects based on the value of the profile index. These are shown in Table 2.

Typically, profilograph measurements are taken for the first several days of paving following initial startup or after a long shutdown period as soon as the concrete has cured sufficiently to permit the testing.

TABLE 1- Grinding Specifications for Midwestern States

STATE	PROPHILOGRAPH TYPE	INCENTIVE mm/Km* (in./mi)	NO INCENTIVE mm/Km* (in./mi)	DISINCENTIVE mm/Km* (in./mi)	MAX. HIGH POINT	MAX. PI mm/Km* (in./mi)
WISCONSIN	CALIFORNIA	PI < 110 (PI < 7)	110 < PI < 158 (7 < PI < 10)	PI > 158 (PI > 10)	10.2mm @ 7.63m (0.4" @ 25')	PI < 237 (PI < 15)
ILLINOIS	CALIFORNIA	PI < 67 (PI < 4.25)	PI < 158 (PI < 10)	PI > 158 (PI > 10)	7.6mm @ 7.63m (0.3" @ 25')	PI < 237 (PI < 15)
INDIANA <75.5 kmph	CALIFORNIA	-	PI < 252 (PI < 16)	252 < PI < 347 (16 < PI < 22)	7.6mm @ 7.63m (0.3" @ 25')	PI < 347 (PI < 22)
INDIANA >75.5 kmph	CALIFORNIA	-	PI < 189 (PI < 12)	189 < PI < 237 (12 < PI < 15)	7.6mm @ 7.63m (0.3" @ 25')	PI < 237 (PI < 15)
MICHIGAN	CALIFORNIA	PI < 63 (PI < 4)	63 < PI < 158 (4 < PI < 10)	-	7.6mm @ 7.63m (0.3" @ 25')	PI < 158 (PI < 10)
MICHIGAN	GM RAPID	RQI < 40.5	40.6 < RQI < 49.8	-	7.6mm @ 7.63m (0.3" @ 25')	RQI < 49.8
IOWA Sch.A	CALIFORNIA	(A) PI < 47 (PI < 3) (B) NO GRIND	49 < PI < 112 (3.1 < PI < 7.1)	PI > 112 (PI >7.1)	12.7mm @ 7.63m (0.5" @ 25')	PI < 159 (PI < 10.1)
IOWA Sch.B	CALIFORNIA	(A) PI < 189 (PI < 12) (B) GRIND TO 347 (22)	189 < PI < 349 (12 < PI < 22.1)	PI > 349 (PI > 22.1)	12.7mm @ 7.63m (0.5" @ 25')	PI < 475 (PI < 30.1)
MINNESOTA	CALIFORNIA	-	-	-	7.6mm @ 7.63m (0.3" @ 25')	-
OHIO	CALIFORNIA	PI < 110 (PI < 7)	79 < PI < 110 (5 < PI < 7)	PI > 110 (PI > 7)	7.6mm @ 7.63m (0.3" @ 25')	PI < 189 (PI < 12)

NOTES:PI = Profile Index

RQI = Ride Quality Index (no units)

IOWA SCH. A =Urban cross sections with posted speed limit of > 75.5 kmph (45mph) and all rural cross sections. Does not include ramps/loops.

IOWA SCH. B = All urban cross sections with posted speed limit of ≤ 75.5 kmph (45 mph.)

All PI and RQI measurements are made on a .16 km (0.1 mi) section unless otherwise noted.

* SI values are rounded conversion of U.S. customary units.

TABLE 2 - RECOMMENDED PAY SCHEDULE FOR CLASS A HIGHWAYS AASHTO AND ACPA (17)

PROFILE INDEX mm/km[1] (in/mi)	AASHTO PAY SCHEDULE*	ACPA PAY SCHEDULE*
47 or less (3 or less)	105	110
> 47 to 63 (>3 to 4)	104	108
> 63 to 79 (>4 to 5)	103	106
>79 to 95 (>5 to 6)	102	104
>95 to 110 (>6 to 7)	101	102
>110 to 158 (>7 to 10)	100	100
>158 to 174 (>10 to 11)	98**	98**
>174 to 189 (>11 to 12)	96**	96**
>189 to 205 (>12 to 13)	94**	94**
>205 to 221 (>13 to 14)	92**	92**
>221 to 237 (>14 to 15)	90**	90**
> 237 (>15)	CORRECTIVE WORK REQUIRED	CORRECTIVE WORK REQUIRED

* = Percent of pavement unit bid price
** = For cases where the Profile Index on a rural interstate or primary highway is between 158 and 237 millimeters per kilometer (10 to 15 inches per mile), the contractor should be given the option to correct the pavement to receive 100% pay.
[1] SI values are rounded conversion of U.S. customary units.

FIELD INSPECTION

Field inspection was used to determine whether initial spot diamond grinding on newly placed concrete has any effect on PCC pavement performance and material properties.

Although pavement performance is measured using pavement roughness test results (generally referred to as International Roughness Index or IRI) and pavement distress data (generally referred to as Pavement Distress Index or PDI), only the use of the PDI data was determined to be appropriate for this study. The use of IRI data, a continuous measure, was not considered to be appropriate since it represents the pavement roughness for the entire distance between two reference points, while spot diamond grinding is sporadic, covering only a small portion of the surveyed segment.

The following sections describe the PDI survey methodology and the results of the surveys conducted for the sites.

Methodology

The effects of spot diamond grinding on PCC pavements was assessed using the results of the PDI surveys of candidate sites containing spot diamond grinding and a micro-survey of only the spot diamond ground sections. Both spot diamond ground and control sites were selected and inspected. The control sections consisted of the non-ground sections of the candidate sites located adjacent to, before, or after the sections with a spot grinding section. Based on the field inspections, PDI values were calculated for both the candidate sites containing spot diamond grinding sections and the micro-survey sections (sections with 100% grinding) and analyzed to determine the effects of spot diamond grinding.

The PDI surveys were conducted according to the WisDOT standard procedure described in the Pavement Surface Distress Survey Manual (16). According to the WisDOT Pavement Distress Manual, .16 kilometers per 1.61 kilometers (0.1 mile per mile) of a highway is surveyed to develop the PDI value for the section (about 1.61 kilometer (1 mi) in length). The sections are defined according to the Reference Point (RP) system developed by WisDOT for the highways under the state jurisdiction. Although not all of the six PCC pavement distress indicators (surface distress, distressed joints/cracks, longitudinal distress, transverse faulting, and slab break up) are considered to be potentially related to spot diamond grinding, they were all included in the PDI calculations. The PDI value could range from 0, a newly constructed pavement, to 100, a totally failed pavement.

In addition to the standard .16 kilometer (0.1 mile) PDI survey, a micro-survey of only the diamond ground sections and an equal length of the non-ground sections was conducted. The conditions of the spot diamond ground sections were compared to the non-ground sections using only those pavement distress indicators that could potentially be related to spot grinding (e.g., distressed joint/crack, surface distress, and longitudinal joint distress). Since spot diamond grinding results in a negligible reduction in the pavement thickness, distress indicators not related to spot diamond grinding (e.g., patching, transverse faulting) were not included.

FIELD INSPECTION RESULTS

Selected Highway Locations

The PDI surveys were conducted on 22 highways consisting of 34 sites in Wisconsin. The selected sites produced 134 pairs (ground and control) of Reference Points (RP's) resulting in 268 PDI values for spot diamond ground and control sections. The selected sites are listed in Table 3.

The oldest sites were built in 1984 (about 11 years old) and the newest sites were built in 1991 (about 5 years old). A total of about 254 kilometers (158 mi) of highways were surveyed. The average age of the pavements was about 7 years old.

Survey Procedure

According to the WisDOT PDI Manual, the .16 kilometer (0.1 mi) survey segment is generally the segment from .48 to .64 km (0.3 - 0.4 mi) from the beginning of the section. However, since this segment may not include any spot diamond ground section (or may not be the section with the most spot diamond grinding), it was decided to select the .16 kilometer (0.1 mi) section with the most spot diamond grinding. Depending on the site, the amount of grinding in this section varied from 1% to 90%. An equal length of non-ground pavement section was selected and surveyed as the control section. The sections with a small amount of ground pavement may not be representative of the distresses that may only be occurring as the result of spot diamond grinding.

The micro-survey was limited to only the diamond ground sections regardless of the length of the spot diamond ground sections. In addition to considering the indicators related to spot diamond grinding, several factors based on visual inspection of the diamond ground and non-ground sections were recorded. These included a check on specific items such as popouts, spalling and cracking. Also, the conditions of the spot diamond ground sections were recorded using a video recorder and a camera.

TABLE 3 - Selected Pavement Sites with Spot Grinding

HIGHWAY	LIMIT	YEAR	LENGTH (km)
DISTRICT 1:			
1. USH 14	MIDDLETON - CROSS PLAINS	1988	12.88
2. USH 18 EB	CTH Y - EAST COUNTY LINE	1988	18.19
3. STH 33	FOX LAKE - BEAVER DAM RD	1990	11.43
DISTRICT 2:			
1. STH 50 WB	CTH W - I-94	1989	16.58
2. STH 50 EB	I-94 - CTH W	1989	16.58
3. STH 16 WB	SAWYER RD. - STH 167	1990	4.83
4. STH 16 EB	I-94 - STH 190	1990	4.83
5. STH 164 NB	I-94 - STH 190	1987	5.31
6. STH 164 SB	STH 190 - I-94	1987	5.31
7. STH 100	STH 32 - CH&NW RR STR	1984	2.58
8. STH 23 WB	CTH UU - CTH K	1989	6.44
9. STH 23 EB	CTH UU - CTH K	1989	6.44
10. STH 181 NB	COUNTY LINE RD. - STH 167	1988	3.22
11. STH 181 SB	STH 167 - COUNTY LINE RD.	1988	3.22
12. STH 167 WB	BUNTROCK RD. - STH 181	1989	1.61
13. STH 167 EB	STH 181 - BUNTROCK RD.	1989	1.61
14. STH 45 NB	STH 41 - WEST BEND	1989	20.93
15. STH 45 SB	WEST BEND - STH 41	1989	20.93
DISTRICT 3:			
1. STH 29	BONDUEL - ANGELICA	1986	8.86
2. US 141/41 SB	ABRAMS @ WEIGH STATION	1987	1.77
3. STH 172 EB	EAST OF FOX RIVER	1984	5.64
DISTRICT 4:			
1. STH 13	MARSHFIELD - SPENCER	1984	14.49
2. STH 21	REDGRANITE - STH 49	1988	9.66
3. STH 13 NB	STH 73 - WIS RAPIDS	1988	6.44
4. STH 13 SB	WIS RAPIDS - STH 73	1988	6.44
5. STH 13	SPENCER - COLBY	1989	16.10
6. STH 29 WB	152ND AVE - CTH O	1990	4.19
7. STH 29 EB	CTH O - 152ND AVE	1990	4.19
DISTRICT 5:			
1. STH 16 NB	MONEGAN OVERHEAD - GILLETTE	1986	2.42
2. STH 16 SB	GILLETTE ST. - MONEGAN	1986	2.42
3. STH 16 NB	OVERHEAD	1987	1.61
4. STH 16 SB	GILLETTE ST. - STH 157	1987	1.61
	STH 157 - GILLETTE ST.		
DISTRICT 6:			
1. I-94 EB		1991	3.22
2. I-94 WB	STH 35 - 11TH ST.	1991	3.22
	STH 35 - 11TH ST.		
DISTRICT 7: NO PROJECTS IDENTIFIED			
DISTRICT 8: NO PROJECTS IDENTIFIED			

PDI Survey Results

Tables 4 and 5 show the average PDI values for each site and the PDI values for each of the Reference Points of each site, respectively.

According to the survey results, a slight variation in the field survey may produce a ± 10 point variation in the PDI value (a 10% variation). This may include variations in assessing the distress severity level (e.g., slight severity level vs. moderate level) or the extent of distress (e.g., less than 25% vs. more than 25%). A ± 10 points variation in the PDI value for a test segment is considered reasonable, particularly for the PDI values less than 50 points.

As shown in Table 4, with the exception of STH 13 in Marathon County and STH 181 in Ozaukee County, the average PDI values for the ground and control sites were very similar (within 10 points). The survey results for STH 13 in Marathon County (about 5.5 miles) produced an average PDI value of 43 for the ground section and 30 for the control section (a difference of 13 points). The PDI surveys for STH 181 produced an average PDI value of 18 for the ground section and 6 for the control section (a difference of 12 points).

As shown in Table 5, the PDI values for the majority of the ground and control RP's were within ± 10 points. According to the survey results, 117 of the RP's produced PDI values within ± 10 points variation between the ground and control sections. Nine (9) of the RP's produced PDI values between 11 and 15 points variations between the ground and control sections, and another 7 RP's variations between 16 and 20. Only one RP produced a PDI value with variation of greater than 20 points between the ground and control section.

Statistical Analysis

A paired t-test statistical analysis method was used to determine the mean difference between the PDI values for the ground and control sections. The analysis indicated that the PDI mean values of the ground and control sections were statistically significantly different at 95% confidence. The analysis indicated that the mean difference is somewhere between 0.9 and 2.9 points (in 68% of the pairs the ground section had the same or lower PDI value), statistically different but the same in practical terms.

Micro-Survey Results

As indicated, in addition to the PDI surveys, a micro-survey of only the spot diamond ground and an equal length of non-ground section was conducted. The micro-survey consisted of recording pavement distresses (e.g., distressed joint/crack, surface distress, and longitudinal joint distress) that potentially may be caused by spot diamond grinding.

A total of 4,798 ground and non-ground (control) pavement slabs were surveyed. The results are summarized in Table 6. As shown, the spot diamond ground and control sections exhibited very similar pavement distresses. About 97% of the ground sections (1,168 joints out of a total of 1,200) exhibited no longitudinal joint distress as compared to 99% for the control sections. About 96% (2,308 slabs out of a total of 2,399 slabs) of the ground sections exhibited no distressed joints/cracks as compared to 98% for the control sections.

As shown in Table 6, the spot ground sections experience a slightly higher surface distress (popouts) than the control sections. About 89% of the ground sections (2,135 slabs out of a total of 2,399 slabs) exhibited no surface distress as compared to 96% for the control sections.

The micro-survey results were used to calculate PDI values for the survey sections. However, the procedure used for the calculations deviated from the WisDOT procedure in the following areas:

- Instead of generating a PDI value for each .16 kilometer (0.1 mi) section, a PDI value was generated for each surveyed slab.
- Only the three pavement distress indicators recorded in the micro-survey were used in the calculation.

The micro-survey resulted in 4,798 PDI values for spot diamond and control slabs.

Statistical Analysis

Similar to the PDI survey analysis, a paired t-test statistical analysis method was used to determine the mean difference between the ground and control slabs's PDI values generated as part of the micro-survey . The analysis indicated that the PDI mean values of the ground and control slabs were statistically significantly different at 95% confidence. The analysis indicated that the mean difference is somewhere between 0.6 and 0.9 point. The confidence interval (0.6-0.9) is within tolerable range.

As indicated, the spot ground slabs experienced a slightly higher surface distress than the control slabs. A paired t-test statistical analysis method was also used to determine the mean difference between the values for the ground and control slabs developed based on only the surface distress data. The analysis indicated that the mean values of the ground and control slabs were significantly different at 95% confidence. The mean difference is somewhere between 0.5 and 0.7, with a greater number of ground slabs having a higher level of distress than control slabs in most categories of distress.

TABLE 4 - Average PDI Values for Each Site

District	HWY	County	Year	AVG. PDI VALUE		
				Ground	Control	Difference
1	14	Dane	1987	11	10	1
	18 EB	Iowa	1988	3	7	-4
	33	Dodge	1990	0	0	0
2	164 NB	Waukesha	1988	7	0	7
	164 SB	Waukesha	1988	16	16	0
	16 WB	Waukesha	1990	6	3	3
	16 EB	Waukesha	1990	1	0	1
	100	Milwaukee	1984	34	30	4
	50 WB	Kenosha	1989	7	3	4
	50 EB	Kenosha	1989	11	10	1
	23 WB	Fond du Lac	1987	8	5	3
	23 EB	Fond du Lac	1987	13	9	4
	167 WB	Ozaukee	1990	0	0	0
	167 EB	Ozaukee	1990	0	0	0
	181 NB	Ozaukee	1987	5	11	-6
	181 SB	Ozaukee	1987	18	6	12
	45 NB	Washington	1985	6	6	0
	45 SB	Washington	1989	1	0	1
3	172	Brown	1984	12	14	-2
	29	Shawano	1986	4	1	3
	141/41	Oconto	1987	0	0	0
4	21	Waushara	1988	9	11	-2
	29 WB	Marathon	1990	0	0	0
	29 EB	Marathon	1990	4	0	4
	13	Marathon	1989	9	6	3
	13	Marathon	1984	43	30	13
	13 NB	Wood	1988	0	0	0
	13 SB	Wood	1988	0	0	0
5	16 NB	La Crosse	1985	13	11	2
	16 SB	La Crosse	1985	11	6	5
	16 NB	La Crosse	1986	20	11	9

District	*HWY*	*County*	*Year*	*AVG. PDI VALUE*		
	16 SB	*La Crosse*	*1986*	*5*	*10*	*-5*
6	*I-94 EB*	*St. Croix*	*1990*	*0*	*0*	*0*
	I-94 WB	*St. Croix*	*1990*	*0*	*0*	*0*

TABLE 5 - PDI Values for Control and Ground Sites

** - No Ground Section Found, ** No Control Section Found*

STH Characteristics	RP		Dist. (km)	% Ground	PDI Value		
	From	To			Ground	Control	Difference
STH - 14 DANE - 1987	200T	200D	1.75	4	15	11	4
	200D	198	2.24	4	11	11	0
	198	196	2.88	6	11	11	0
	196	194	1.71	1	6	6	0
	194	192	2.69	19	12	11	1
	200D	200T	1.75	1	11	11	0
STH - 18 IOWA 1988	101K	103G	2.24	2	0	0	0
	103G	106K	2.38	7	0	6	-6
	106K	108G	2.51	27	3	3	0
East bound only- West bound continously ground	108G	110M	1.72	16	0	3	-3
	110M	111K	1.56	4	0	0	0
	111K	112D	0.81	0	*	**	0
	112D	113K	2.06	1	3	3	0
STH - 33 DODGE - 1990	208	209	1.26	48	0	0	0
	209	211	2.00	45	2	0	2
	211	212	1.95	34	0	0	0
	212	213	1.63	56	0	0	0
	213	215	2.16	56	0	0	0
	215	217	1.56	67	0	0	0
STH - 164 WAUK. - 1988	145G	144K	1.29	7	12	19	-7
	146D	145G	1.87	0	19	12	7
	144K	145G	1.29	3	7	0	7
	145G	146D	1.87	0	*	0	0
STH - 16 WAUK - 1990	192G	190M	2.38	4	0	0	0
	194G	192G	2.50	2	1	0	1
	190M	192G	2.38	0	12	6	6

STH Characteristics	RP		Dist. (km)	% Ground	PDI Value		
	From	To			Ground	Control	Difference
	192G	194G	2.50	0	0	0	0
STH - 100 MILW. - 1984	001A	001P	1.32	4	32	38	-6
	001P	002A	1.22	1	36	21	15
STH - 23 FOND DU LAC 1987	225G	225K	1.11	1	11	**	11
	225K	226T	1.88	4	11	8	3
	226T	227M	0.93	16	17	11	6
	227M	228	1.13	4	11	8	3
	227M	226T	0.93	8	8	3	5
	226T	225K	1.88	27	11	6	5
	225K	225G	1.11	1	5	**	5
STH - 167 OZAUKEE 1990	22D	23K	1.71	21	0	0	0
	23K	22D	1.71	8	0	0	0
STH - 50 KENOSHA - 1989	47K	45T	1.61	2	6	3	3
	45T	44K	1.48	4	6	6	0
	44K	43M	0.95	1	11	6	5
	43M	42G	1.30	8	3	0	3
	42G	40K	1.90	33	6	3	3
	40K	39G	2.58	19	11	6	5
	39G	34G	2.69	7	3	3	0
	34G	33K	1.67	12	8	0	8
	33K	32G	1.32	90	11	**	11
	32G	30M	1.11	36	0	0	0
	30M	32G	1.11	15	3	6	-3
	32G	33K	1.32	29	5	0	5
	33K	34G	1.67	10	0	3	-3
	34G	39G	2.69	20	3	3	0
	39G	40K	2.58	38	29	6	23
	40K	42G	1.90	60	15	15	0

STH Characteristics	RP		Dist. (km)	% Ground	PDI Value		
	From	To			Ground	Control	Difference
	42G	43M	1.30	29	15	15	0
	43M	44K	0.95	15	10	17	-7
	44K	45T	1.48	13	16	15	1
	45T	47K	1.61	25	16	15	1
STH - 181 OZAUKEE 1987	14T	12T	1.64	3	21	8	13
	12T	11K	1.64	6	15	3	12
	11K	12T	1.64	1	3	11	-8
	12T	14T	1.64	2	7	11	-4
STH - 45 WASHINGTON 1985	60D	61K	1.63	0	0	0	0
	62M	63K	1.67	0	11	11	0
	63K	64G	1.67	0	11	11	0
	72G	73K	1.24	0	3	0	3
STH - 45 WASHINGTON 1989	74G	73K	1.50	9	0	0	0
	73K	72G	1.24	2	0	0	0
	72G	70M	1.26	2	0	0	0
	70M	68K	1.63	9	0	0	0
	68K	67T	1.40	4	0	0	0
	67T	65T	2.40	5	0	0	0
	65T	64G	2.54	12	0	0	0
	64G	63K	1.67	7	0	0	0
	63K	62M	1.67	2	8	0	8
	62M	61K	1.63	3	0	0	0
	61K	60D	1.63	6	0	0	0
STH - 172 BROWN - 1984	34	37	1.13	5	15	15	0
	37	39	1.93	2	11	15	-4
	39	40	1.01	2	11	11	0
STH - 29 SHAWANO 1986	262	263	1.95	2	0	0	0
	263	265K	1.96	17	0	0	0

STH Characteristics	RP		Dist. (km)	% Ground	PDI Value		
	From	To			Ground	Control	Difference
	265K	267D	2.05	8	5	0	5
	267D	268G	1.61	22	14	0	14
	268G	270D	1.93	3	1	3	-2
STH - 141/41 OCONTO - 1987	183	182	1.66	6	0	0	0
STH - 21 WAUSHARA 1988	139	141	2.24	12	12	11	1
	141	143	2.01	2	11	11	0
	143	144	1.34	3	6	11	-5
	144	146	2.01	2	3	11	-8
	146	148	1.87	12	11	11	0
STH - 29 MARATHON 1990	173D	172K	1.45	0	0	0	0
	172K	170G	3.22	6	0	0	0
	170G	172K	3.22	0	8	0	8
	172K	173D	1.45	1	0	0	0
STH - 13 MARATHON 1989	143	142	1.64	1	29	12	17
	142	143	1.64	1	28	11	17
	141	140	1.61	1	11	13	-2
	140	139	0.87	4	12	8	4
	139	140	0.87	10	0	11	-11
	137	139	0.81	4	0	0	0
	137	136	1.77	13	17	12	5
	136	135	1.61	1	8	0	8
	135	134	1.61	2	3	3	0
	134	133	1.64	11	0	11	-11
	133	132	1.61	7	0	0	0
	132	131	1.03	15	8	6	2

STH Characteristics	RP		Dist. (km)	% Ground	PDI Value		
	From	To			Ground	Control	Difference
	131	130	0.72	3	7	0	7
	130	131	0.72	7	0	0	0
	129	130	1.09	2	52	35	17
	128	126	2.27	1	51	35	16
	126	124	2.25	0	47	35	12
	124	123	2.25	1	48	29	19
	. 122	120	1.08	1	19	17	2
STH - 13 WOOD - 1988	71K	70M	1.45	2	0	0	0
	70M	69K	1.93	1	0	0	0
	69K	67G	1.61	1	0	0	0
	67G	65D	1.48	2	0	0	0
	65D	67G	1.48	1	0	0	0
	67G	69K	1.61	1	0	0	0
	69K	70M	1.93	1	0	0	0
	70M	71K	1.45	3	0	0	0
STH 16 LA CROSSE 1985	006D	007M	0.97	25	15	11	4
	007M	009D	1.59	9	11	11	0
	009D	007M	1.59	6	11	6	5
	007M	006D	1.22	2	11	6	5
STH - 16 LA CROSSE 1986	009D	012G	1.32	3	21	11	10
	012G	014M	2.06	33	11	11	0
	014M	016K	1.53	11	27	11	16
	016K	014M	1.53	4	0	0	0
	014M	012G	2.06	2	0	16	-16
	012G	009D	1.32	4	15	15	0

STH Characteristics	*RP*		*Dist. (km)*	*% Ground*	*PDI Value*		
	From	*To*			*Ground*	*Control*	*Difference*
I-94 ST. CROIX - 1990	*002D*	*003K*	*2.95*	*2*	*0*	*0*	*0*
	003K	*002D*	*2.95*	*5*	*0*	*0*	*0*

Table 6 - Results of Micro-Survey

DISTRESS SEVERITY LEVEL									
PCC DISTRESS	Total #	None		Slight		Moderate		Severe	
		Ground	Control	Ground	Control	Ground	Control	Ground	Control
Longitudinal Joint Distress	1,232	1,168	1,196	54	30	8	6	2	0
Distressed Joints/Cracks*	2,399	2,308	2,356	74	34	13	8	4	1
Surface Distress (popouts)**	2,399	2,135	2,297	244	100	18	2	2	0

* Units in Joints ** Units in Slabs

CONCLUSIONS

Based on the PDI surveys and the micro-survey, the following conclusions can be made:

1) The PDI and micro-survey results were consistent, indicating the mean values of the ground and control sections were statistically significantly different, but of no practical difference.

2) However, although statistically significantly different, according to the confidence interval, the spot diamond ground and control sites were very similar indicating that, for all practical purposes, spot diamond grinding does not adversely affect the performance and material properties of the pavement.

3) Therefore, it can be concluded that there was no observed relationship between the PDI values and the extent (percent of grinding) of surface grinding.

II. SAFETY ASPECTS OF SPOT GRINDING THROUGH THE ANALYSIS OF CONTINUOUSLY DIAMOND GROUND PAVEMENTS

INTRODUCTION

Spot ground sections are small and difficult upon which to make measurements. Therefore, long sections of longitudinal ground pavement, rehabilitated due to deteriorating ride quality, were used for comparisons with tined sections as a means of determining the safety of longitudinal spot grinding. Crash experience differences between Portland Cement Concrete (PCC) pavements that have been continuously ground during rehabilitation and standard PCC pavements with tined surfaces have not been well-established. The present study identified the existence and quantified the extent of crash characteristics differences between the two types of PCC pavement surface textures under a variety of environmental conditions; crash rate trends for the two surface textures over the six-year period from 1988 to 1993 were also examined.

BACKGROUND AND SIGNIFICANCE OF WORK

It is generally assumed that certain highway crashes (ex. crashes on wet pavement) are due-partially-to poor pavement surface friction. A frequently measured index of pavement surface friction is the Friction Number (FN). It has been documented in the literature that FN decreases with pavement age; also that concrete pavement surface texture treatment is directly related to friction properties.

Several studies have ascertained that certain pavement surface treatments (such as transverse and/or longitudinal tining or grinding) are associated with higher FN and "gentler" speed gradients (i.e., a lower drop in FN with increasing speed) than non-tined pavements (*18,19*), but no statistically sound studies have been found in the literature that quantify a relationship between FN and crash rates.

THE DATABASE

A total of 51 Wisconsin sites were identified for analysis, (30 ground and 21 tined) covering 405 km of concrete pavements. Test sites (ground surface) totaled 290 km and control sites (tined surface) 115 km. Figures 1 and 2 depict samples from a study ground site and a typical Wisconsin tined site respectively. The crash analysis was based on the six-year period from 1988 to 1993, during which 11,219 crashes were reported on all study sites. Geometric, traffic volume, truck presence, and percent of traffic during nighttime information was available for each study site. Crash, geometry and volume information was merged to produce one record for each crash. These records were aggregated to produce crash statistics for ground and tined sites.

STUDY OBJECTIVE

The study objective was to compare characteristics of crashes occurring on concrete pavements with continuous longitudinal grinding (test sites) with crashes on transversely tined concrete pavements (control sites) as a means of determining whether spot grinding was detrimental to

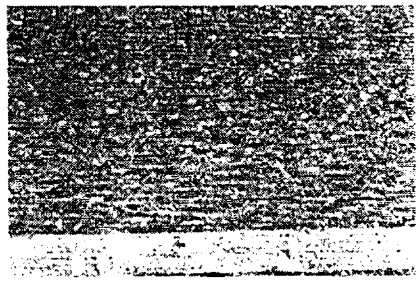

Figure 1

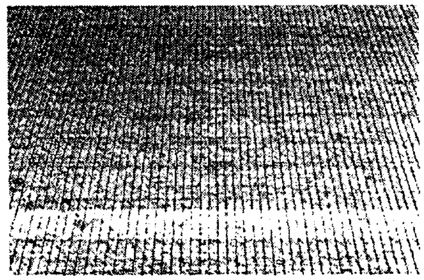

Figure 2

motoring safety. Because crash experience is influenced by roadway, vehicular, and environmental factors, an effort was made to match ground and tined site characteristics, in order to assure that all factors except surface texture were identical between the two site categories. In the absence of detailed weather information, and in order to account for weather differences among different parts of the state, it was attempted to maintain a balance in the lengths and functional classifications of ground and tined sites selected from each Wisconsin DOT geographical district. It was assumed that driving population characteristics would be identical between tined and ground sites.

ANALYSIS

Given the efforts described above to control for vehicular, environmental and roadway factors, it was assumed that any ground and tined site crash experience differences would be due to differences between the two pavement textures. The focus of the investigation was on factors that affect skid resistance (identified in a literature search), for example, pavement condition (dry, wet, snow/ice). The analysis proceeded from an overall comparison between the two site categories to more in-depth analyses of particular factors. The relation of each analyzed variable to skid resistance and possible implications for the crash experience are briefly introduced under each subheading, followed by a presentation of findings.

Overall Comparisons

The first question the study attempted to answer was whether overall crash experiences differed between tined and ground sites. A comparison of crash rates (crashes per 100 million vehicle kilometers traveled) between ground and tined sites during the study period, indicated that the crash rate for ground sites was lower than that of tined sites (86 and 135 crashes per 100 million vehicle-kilometers traveled respectively). Table 7 provides relevant information. Total vehicle kilometers traveled and total crashes were higher for ground sites. Ground site crash rates were 60% those of tined sites overall.

Pavement Condition

Coefficient of friction is lower on wet than dry pavements. It is therefore reasonable to expect a higher crash rate under wet pavement conditions. Although ground and tined site frictional properties were not expected to differ significantly on dry pavements, it is under wet conditions that any crash experience differences between the two textures were expected to emerge, since it is possible that tined and ground site textures may differ in their ability to maintain good friction properties when wet or when snow or ice is present on the pavement.

TABLE 7 Number of Crashes, Vehicular Travel and Crash Rates for Ground and Tined Sites

	N [a]	Vehicular travel [b,c]	Crash rate [c,d]
Ground sites	7085	82.40	86
Tined sites	4134	30.57	135
All sites	11219	112.97	**Overall rate**: 99

[a] Number of crashes
[b] 100 million vehicle-km of travel
[c] 1 km = 0.6 mi
[d] Crashes per 100 million vehicle-km

Areas where the two textures may differ are in their ability to allow rapid water displacement from the pavement/tire interface and their ability to drain water from (transversely to) the vehicle path. These characteristics may play a particularly crucial role in hydroplaning avoidance during wet pavement conditions. Another difference between the two textures may be in the ease with which snow-and particularly ice-can be removed from the roadway surface during snow plowing operations. All other factors being equal, a higher number of crashes due to loss of control could be expected for textures promoting a stronger ice/pavement bond.

Crash rates for each pavement condition are summarized in Table 8. Ground sites performed better than tined sites under all pavement conditions. Differences were greater under wet and dry conditions, during which ground sites had 58% the crash rates of tined sites.

Differences between ground and tined sites were less pronounced under snow/ice conditions during which ground sites had approximately 84% the crash rate of tined sites. Crash rates were lowest for dry pavement conditions and increased by 50% under wet conditions for both ground and tined sites. When snow or ice were present on the pavement, crash rates for ground sites were 2.6 times higher, and those for tined sites 1.85 times higher than rates on the same pavements when dry.

These findings were consistent with expectations of deteriorating crash experience as pavement conditions become progressively more slippery. It should be noted that findings for wet and snow/ice conditions on tined sites were based on relatively low vehicle-km of travel and should be used with caution. Comparisons between tined and ground sites for dry conditions, however, were based on significant vehicular travel and are reliable.

TABLE 8 Crash Rates for Different Pavement Conditions

	Crash Rate [a,b]		
Pavement Condition	Ground	Tined	Ratio Ground/Tined
Dry	65	112	58%
Wet	99	170	58%
Snow/Ice	173	205	84%

[a] Crashes per 100 million vehicle km
[b] 1 km = 0.6 mi

Light Condition

Pavement surface texture characteristics influence driver perception in a manner that can affect crash experience. For example, differences in pavement surface appearance may lead drivers to believe that ice is present on the pavement when it is not, making them more cautious and leading to lower crash rates. The opposite situation may involve a pavement texture that makes visual detection of ice on the pavement difficult, leading to a higher crash rate, since drivers are caught unaware of the dangerous situation. Perception of, but also actual, safety problems are exacerbated during poor visibility conditions such as poor weather and/or dark conditions.

Skidding problems due to the presence of snow\ice on the pavement can be expected to be more prevalent at nighttime during the winter months, when temperatures drop and ice formation is more likely. Snowplow operators unaware of the presence of ice on a certain pavement due to its texture (especially during nighttime, when ice detection may be particularly difficult), may reduce deicing agent dispersion rates, inadvertently increasing crash rates for this type of surface texture. These considerations led to an investigation of differences between daytime and nighttime crash rates.

Separate daytime and nighttime crash exposures were compiled, based on estimates of percentage of ADT occurring during daytime and nighttime. Crash rates were then calculated using number of crashes occurring during daytime and nighttime and the estimated vehicular travel during the same periods. For the purposes of this analysis, nighttime included crashes occurring during dark regardless of whether the roadway was/was not illuminated. Dawn and dusk crashes were excluded from consideration, eliminating 4.5% of all crashes. More crashes and more vehicle kilometers of travel were accumulated on ground than tined sites. A summary of findings is presented in Table 9.

Ground sites were safer overall, based on crash rates, both during daytime and nighttime. Differences between the two types of sites were more pronounced during daytime, when ground sites experienced 57% of the crash rate of tined sites. Nighttime differences were less pronounced with ground sites experiencing 73% of the crash rate of tined sites. Ground sites exhibited a higher nighttime/daytime crash frequency ratio than tined sites (68% compared to 51%). Both types of sites experienced approximately one-quarter of their vehicle kilometers of travel at night. Crash rates were much higher at night for both types of sites, but the ratio of nighttime to daytime crash rates was higher for ground sites for which nighttime crash rates were 262% those of daytime, compared to 203% for tined sites.

TABLE 9 Daytime and Nighttime Number of Crashes, Vehicular Travel, and Crash Rates

	Ground sites			Tined Sites			Ground/Tined Crash Rates	
	Day	Night	N/D	Day	Night	N/D	Day	Night
Crashes	3922	2670	68%	2580	1326	51%		
Vehicular Travel [a,b]	65.34	17.06	26%	24.3	6.16	25%		
Crash Rate [b,c]	60	157	262%	106	215	203%	57%	73%

[a] 100 million vehicle-km, [b] 1 km = 1 mi, [c] Crashes per 100 million vehicle-km

Light and Pavement Condition

Because crash rates for both light and pavement conditions were found to differ between tined and ground sites, crash rates were compiled for combinations of pavement conditions (wet, dry, snow/ice) and light conditions (daytime, nighttime). Results are presented in Table 10. Ground sites had lower crash rates than tined sites under all examined light and pavement conditions, except in the dark when snow or ice was present on the pavement. Crash rates indicated that ground sites performed better than tined sites during daytime for all pavement conditions.

Findings were consistent with expectations: crash rates increased as friction conditions deteriorated (dry → wet → snow/ice), and were higher for nighttime than daytime. This held true for both ground and tined sites. However, findings should be viewed with caution for categories with low vehicle-km of travel (snow or ice conditions).

TABLE 10 Crash Rates for Different Light and Roadway Conditions

Condition		Crash Rate [a,b]		
Light	Roadway	Ground Sites	Tined Sites	Ratio Ground / Tined
Day	Dry	52	93	0.55
Dark	Dry	119	182	0.65
Day	Wet	77	144	0.54
Dark	Wet	181	272	0.67
Day	Snow/Ice	106	154	0.69
Dark	Snow/Ice	430	403	1.07

[a] Crashes per 100 million vehicle-km, [b] 1 km = 0.6 mi

Pavement Friction Deterioration

Friction number deterioration with time is well-documented in the literature. For example, the Wisconsin DOT Facilities Development Manual (*20*) provides the following FN predictive equation for PCC pavements (transversely tined):

$$\ln(FN) = 3.99 - 0.0419\ln(LAVP) - 0.00129\,DOL + 0.00474\,HV \qquad (1)$$

where:

FN is the predicted friction number (tested at 60 km/h),
LAVP is the summation of all vehicles expected to pass over the design lane during the service life of the pavement (in millions),
DOL is the limestone, dolomite or ankerite content of coarse aggregate material expressed as percent by weight,
HV is the percent of heavy vehicles in the design lane as a percent of lane ADT.

Equation (*1*) allows the estimation of FN at the end of a pavement's service life as a function of pavement materials and cumulative vehicle passes. Furthermore, it establishes a (negative) FN time gradient: FN is shown to decrease over the service life of a pavement, as vehicle passes accumulate on the pavement. A similar concept was documented in a 1971 Federal Aviation Administration report (*21*) which quantified FN deterioration for concrete pavements as a function of cumulative vehicle passes since construction.

Researchers studying surface treatment FN characteristics, have determined that pavement surface treatments are indistinguishable in terms of FN after a period of two to five years. Specifically, a 1979 Louisiana Department of Transportation evaluation of 10 different surface treatments (*22*), documented significant differences in FN at construction/rehabilitation time, depending on pavement surface texture. However, a decrease in FN with time for all surface textures was documented, which continued until, within a period of approximately five years, all tested surface treatments approached identical FN values. Evaluated textures were constructed using burlap drag, a variety of broom types, and metal tines of various spacings to create longitudinal or transverse textures. Another study concluded that, although grinding increased FN initially, pavements returned to their initial FN within a period of two years in rehabilitated pavements (*23*).

These findings can be summarized in the following expectations for ground pavements: in the short term (two-to-five years) grinding provides a higher FN--which should lead to a lower crash rate for skid-related crashes--after which FN for ground surfaces can be expected to be equal to that of other surface treatments, at which point crash rates for skid-related crashes should be equal among surface treatments. In the long term (five years-to-pavement life), pavements can be expected to exhibit identical FN that will continue to decline throughout the life of the pavement. The decline of FN as a pavement ages (FN **time** gradient) can reasonably be expected to lead to higher crash rates with time--especially for skid-related crashes--regardless of initial pavement surface treatment.

The number of study sites for which crash information was available for the first two-to-five years after construction was insignificant, thus no attempt was made to validate above-stated short term expectations of lower crash rates for longitudinally ground compared to tined study sites. Various attempts to validate long-term crash rate expectations using the available data are described under the following subheadings.

Cumulative Vehicle Passes and Pavement Age

Based on the above discussion, accumulation of vehicle passes over time is expected to be related to a FN (and, consequently, crash experience) deterioration with time. A variety of regression models (both linear and higher order) using crash rate as the dependent variable and cumulative vehicle passes or pavement age as the independent variable were calibrated in an effort to verify the validity of these expectations. Dependent variables were crash rates for: all crashes, and crashes under dry, wet and snow/ice pavement conditions. Independent variables were: cumulative vehicle passes since construction, heavy vehicle passes since construction, and pavement age. Models were calibrated separately for ground and tined sites, and all sites simultaneously. All calibrated regression models had very poor fit. This poor fit may be partially explained by the lack of a continuous crash history for study sites (no crash information was available for most years since construction for the majority of sites), and imprecise volume information. Estimations of cumulative volume since construction were based on linear extrapolations from study data, and may have contained significant inaccuracies for pavements with many years in service, since daily volumes and heavy vehicle presence may have deviated significantly from the assumed linear trends since construction.

The most accurate crash experience trends available, were those for the study years 1988 through 1993, and were investigated next.

Six-year Trends

Crash rates were calculated for the years 1988 through 1993. Based on the above discussion, friction-related crash experience could be expected to worsen with time, since FN was expected to decrease with time. Separate crash rates were established for ground and tined sites in an attempt to identify differences between the two site categories. Tined sites had consistently higher crash rates than ground sites for all analyzed years (Figure 3).

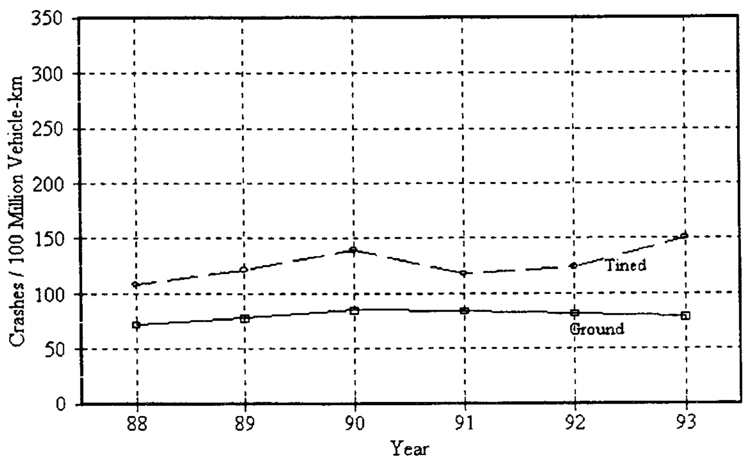

Figure 3 Crash Rates Years 1988-1993 - All Crashes

Year-to-year crash rate variation was lower for ground than tined sites. No consistent crash rate deterioration with time was evident for either group of sites, and no consistent crash rate divergence or convergence (i.e., increasing or decreasing crash rate differences with time) could be observed between ground and tined sites.

Daytime and nighttime crash rates for tined and ground sites are presented in Figure 4. Ground sites had consistently lower crash rates than tined sites throughout the study period, both during daytime and nighttime. Nighttime crash rates were higher than daytime for each year. This was consistent with the pattern observed in Table 9 summarizing crash rates for all years.

Ground sites had consistently lower crash rates than tined sites for dry pavements (Figure 5)-and wet pavements (Figure 6); crash rates for dry pavements were lower than those for wet pavements.

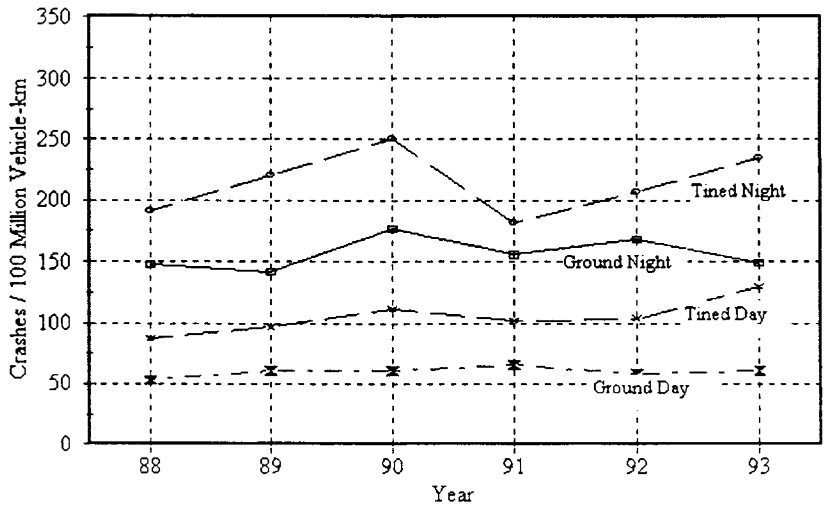

Figure 4 Crash Rates Years 1988-1993 - Daytime and Nighttime

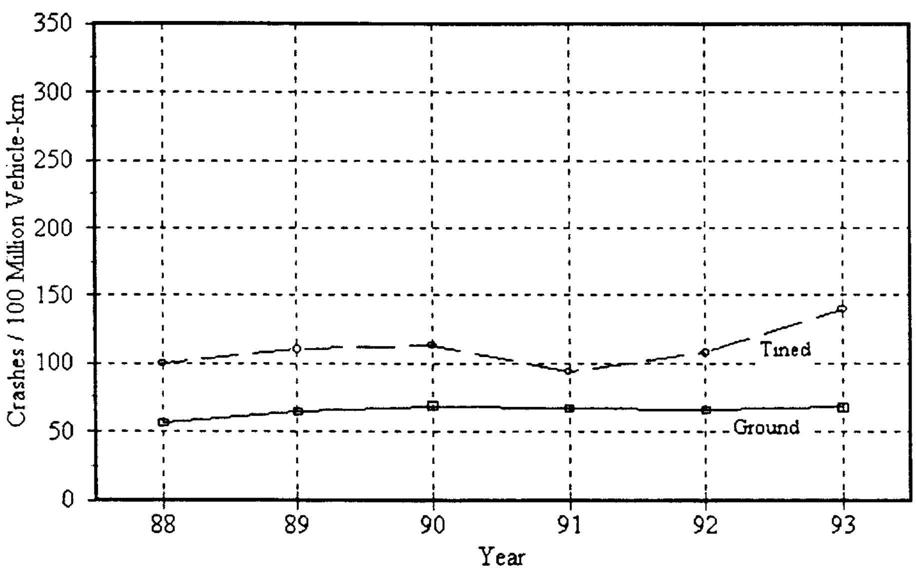

Figure 5 Crash Rates Years 1988-1993 - Dry Pavement

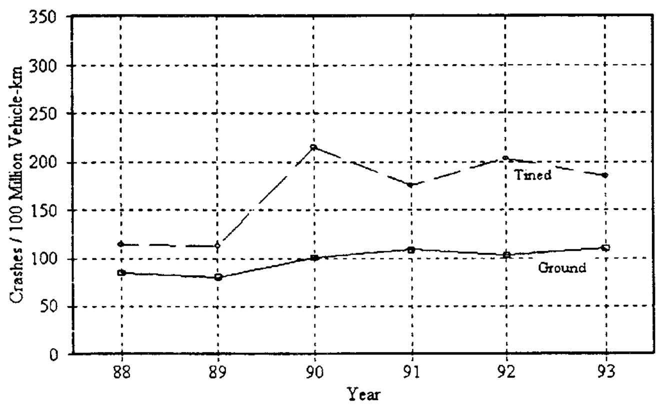

Figure 6 Crash Rates Years 1988-1993 - Wet Pavement

Figures 7 through 10 present comparisons between ground and tined crash rates for crashes on: dry pavements during daytime; wet pavements during daytime; dry pavements during nighttime; and, wet pavements during nighttime, respectively. In all cases ground sites were shown to outperform tined sites, and results were consistent with those presented in Table 10, but significant crash rate fluctuations with time were evident for crash categories with small sample sizes.

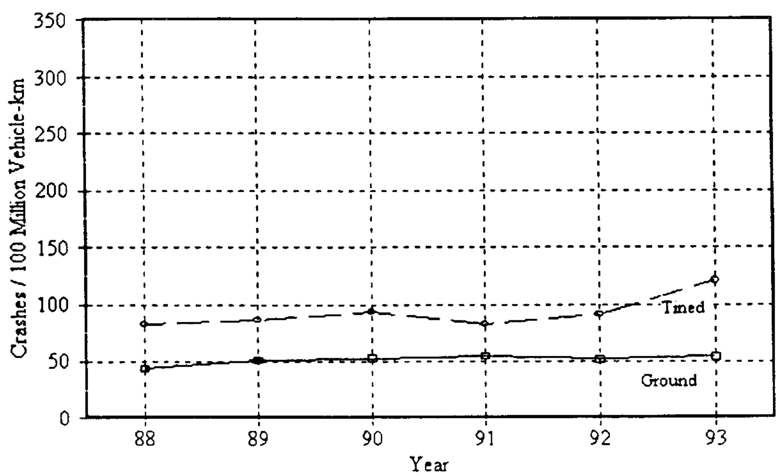

Figure 7 Crash Rates years 1988-1993 - Daytime Dry Pavement

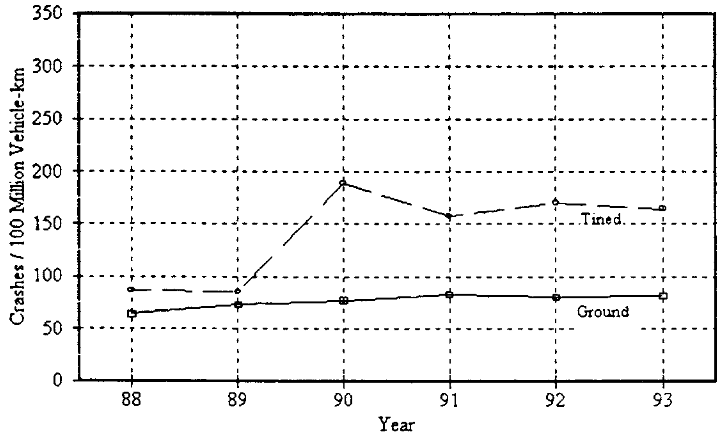

Figure 8 Crash Rates Years 1988-1993 - Daytime Wet Pavement

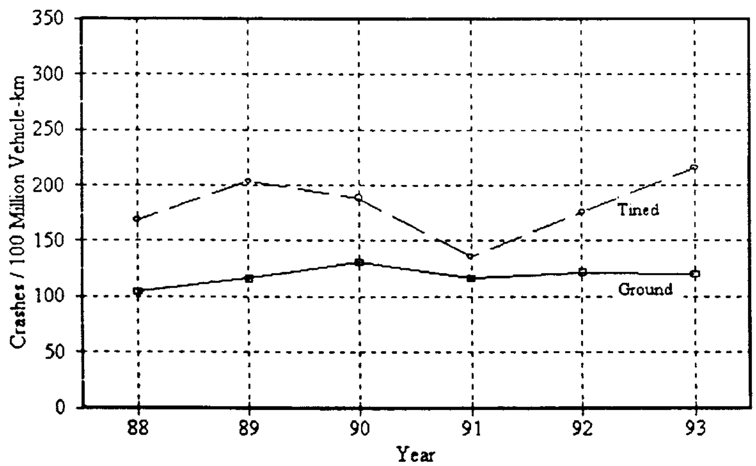

Figure 9 Crash Rates Years 1988-1993 - Nighttime Dry Pavement

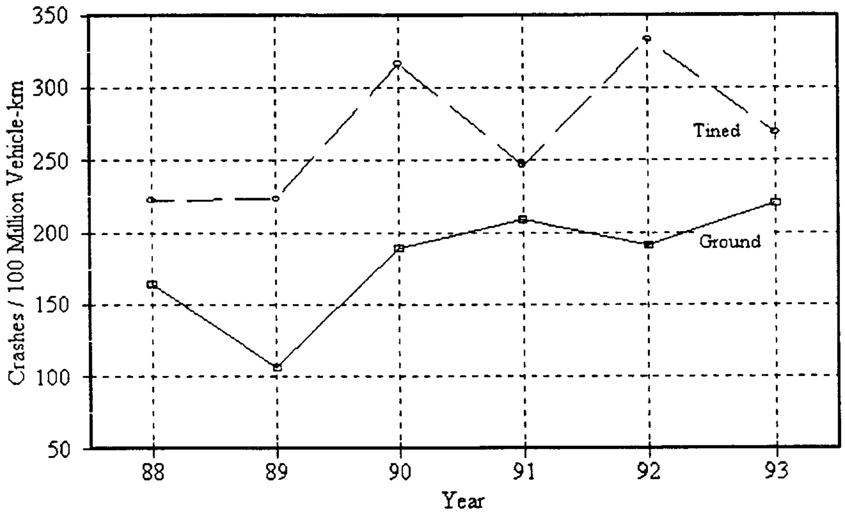

Figure 10 Crash Rates Years 1988-1993 - Nighttime Wet Pavements

SUMMARY OF FINDINGS

This section presents a general description of findings. A summary of the most reliable crash rates (i.e., results based on significant vehicular travel) can be found in Table 11.

- Continuously ground sites were found to have lower overall crash rates than tined sites.
- Ground sites were found to have lower crash rates than their tined counterparts under all pavement conditions. Crash rates were lowest for dry conditions, increased for wet pavements and further increased when snow or ice were present on the pavement. Ground sites had 58 percent the crash rates of tined sites under dry and wet pavement conditions; the ratio was 84 percent when snow or ice were present on the pavement.
- Crash rates were lower in daytime than nighttime; ground sites performed better under both conditions (57% and 73% respectively of tined site daytime and nighttime crash rates).
- Results for the combination of pavement condition (dry or wet) and light condition (daytime or nighttime) showed that ground sites had lower crash rates than tined sites in every category. Nighttime crash rates for dry or wet pavements were higher than any daytime category (dry or wet pavement) for a given pavement surface treatment.
- The analysis of crash rate relations with pavement age and cumulative vehicle passes since construction was inconclusive. Crash rates for the period 1988 to 1993 verified the above findings for light and pavement conditions for each year individually.

TABLE 11 Most Reliable Crash Rate Findings

		Crash Rate [a,b]
All sites	Ground sites	86
	Tined sites	135
Pavement condition	Ground sites: dry pavement	65
	Tined sites: dry pavement	112
	Ground sites: wet pavement	99
	Tined sites: wet pavement	170
Light condition	Ground sites: daytime	60
	Tined sites: daytime	106
	Ground sites: nighttime	157
	Tined sites: nighttime	215
Pavement and Light condition	Ground sites: daytime, dry	52
	Tined sites: daytime, dry	93
	Ground nighttime, dry pavement	119
	Ground sites: daytime, wet	77
	Ground sites: daytime, snow/ice	106

[a] Crashes per 100 million vehicle-km
[b] 1 km = 0.6 mi

CONCLUSIONS AND RECOMMENDATIONS

Longitudinally ground PCC pavements were found to have lower overall crash rates (measured in crashes per 100 million vehicle-km of travel) than transversely tined PCC pavements under all pavement conditions and therefore spot longitudinal grinding can be considered safe. Areas of concern that need to be addressed in future research efforts were identified and are described below.

- Although direct friction measurements were not part of this evaluation, improved friction properties for continuously ground pavements may provide a plausible explanation for the lower crash rates associated with this particular surface treatment in Wisconsin. Expectations of identical crash rates between ground and tined PCC pavements, based on previous research findings (according to which different PCC pavement surface treatments were expected to have identical FN five years after construction) were not confirmed here; ground pavements were found to exhibit lower crash rates regardless of pavement age. Ground PCC pavements also had consistently lower crash rates than tined ones for each of the six years for which crash rate information was available.

- Expectations at the outset of this study were that, if one surface treatment was superior to the other, differences would be more prevalent during wet pavement conditions. However, these expectations were not confirmed here: ground pavements had 58% the crash rates of tined pavements under both dry and wet surface conditions; differences were less pronounced (84%) under snow and ice conditions. Results for wet and dry conditions were based on an adequate accumulation of vehicular travel, however, additional data are necessary for reliable conclusions on the relative performance of ground and tined PCC pavements under snow/ice conditions.

- Crash rate comparisons between continuously ground and tined PCC pavements reveal that, although ground pavements are preferable to tined ones in terms of crash occurrence, the benefits of grinding are less pronounced during nighttime. The ratio of nighttime to daytime crash rates is 2.62 for ground pavements, but only 2.03 for tined pavements. Furthermore, ground pavements have 57% the crash rates of tined pavements during daytime, but 73% the crash rates of tined pavements during nighttime.

- It is reasonable to assume that the source of this nighttime difference for ground PCC pavements would not be surface texture or environmental factors, since ground surfaces have superior performance during daytime-their friction properties will not deteriorate during nighttime, and environmental factors are identical for ground and tined surfaces both during daytime and nighttime. The difference thus, may originate with driver perceptions during nighttime, that affect driving behavior, however, an investigation of driver perceptions is beyond the scope of this study.

- Based on major findings of this research project, grinding PCC pavements is a safety enhancement, notwithstanding preliminary findings of higher crash rates for ground concrete pavements during nighttime when snow or ice is present on the pavement. Grinding of PCC pavements can be expected to lead to lower crash rates both on wet and dry pavements during daytime and nighttime.

Additional research is necessary into comparisons of nighttime crash rates between ground and tined pavements, in order to:

i) explain the higher proportion of nighttime (compared to daytime) crashes on ground pavements, and

ii) answer conclusively the question of whether ground pavements have, indeed, a higher crash rate at nighttime when snow or ice is present on the pavement.

III. PUBLIC PERCEPTION OF SPOT DIAMOND GRINDING PCC PAVEMENTS

OVERVIEW

This section presents the results of a glare study that was based on the intercept surveys of motorists along two sections of State Trunk Highway 50 (STH 50), Kenosha County, Wisconsin. The surveys were taken by the Wisconsin Survey Lab (WSRL).

The purpose of the study was to assess three perceived problems identified by the WisDOT Research Panel:

1. Motorists perception of the effect of grinding on ride quality.
2. Public acceptance of grinding newly constructed PCC pavements.
3. Motorists experiencing glare and/or perceiving ground areas as icy spots (referred to as "ice" phenomenon).

The three elements are described in the original work plan. According to the work plan, a study design was prepared by the Research Team for approval by the panel. The following section briefly describes the original study design and the subsequent revisions.

Study Design

Prior to the preparation of the study design, at the direction of the Panel, the assessment of public acceptance of grinding newly constructed PCC pavements was eliminated from the study. A study design consisting of six subtasks was developed for assessing the effects of grinding on ride quality and glare and perceived icy/slippery spots phenomenon. Subsequently, the panel also eliminated the ride quality assessment from the study and only approved the glare and "ice" study.

Study of Glare and/or "Ice" Phenomenon

The objectives of the study were to determine:

- Whether motorists would notice spot ground areas, and;
- Those noticing the ground areas:
  - What do they perceive to notice?
  - Does their perception adversely affect their driving ability?
  - What precautionary measure(s), if any, they take as they approach the ground areas.

The study of glare an/or "ice" was planned to be assessed by administering a questionnaire. Motorists (either test drivers or truck and bus drivers) would have answered specific questions by an observer seated in the vehicle next to them, as they drove over the test section. The observer would have asked questions such as lane avoidance and perception of glare and ice while they traversed a given section with known conditions.

The work plan included three general tasks for studying the glare and/or "ice". The tasks consisted of developing a survey form, conducting field surveys, and preparing a report. The Panel tentatively approved the work plan and requested detailed information about he survey content, procedure, locations and the conditions under which they would be conducted. The study is discussed in the following section.

Other Atmospheric Phenomena

Other atmospheric phenomena can lead to situations that cause ground pavements to appear icy, but they could not be documented as part of this task. They are mentioned here for further reference should they be of interest. During overcast days, following deicing operations, where topography is snow covered, ground spots can appear like ice. Although not black ice (generally refers to nighttime viewing), spot ground areas appear shiny and hence could be perceived as icy spots. This condition could not be documented, and certainly is difficult to survey to obtain motorists opinions.

STUDY OF GLARE AND/OR "ICE" PHENOMENON

Background

Spot diamond grinding affects the pavement surface appearance and its color. The ground areas could be noticed by the approaching motorists, under certain atmospheric conditions, from a relatively long distance (sometimes over 1000 feet). In freezing temperature and/or wet pavement conditions, motorists may perceive the ground areas to be icy and/or slippery patches. Also, spot ground sections may have a glaring effect (creating blinding light) through the reflection of the sun (in the afternoon) when driving in the westerly direction and/or through the reflection of the headlights (at night).

Study Design

A study design (consisting of three tests (surveys No. 1 to 3) was designed for assessing the glare and "ice" phenomenon (see Attachment A, Description of Survey Tests). The three surveys are summarized in Table 12.

As shown, the objective of Survey No. 1 was to examine whether the reflection of the sun on the spot ground areas would create glare or appear as icy spots when the temperature is below freezing. The objective of Survey No. 2 was to examine whether the spot ground areas would create glare or appear as icy spots at night when the temperature is below freezing. The objective of Survey No. 3 was to examine whether the reflection of the on-coming vehicles on the spot ground areas (not directly from headlights) would create glare at night.

Table 12 -- Public Perception of Glare and/or "Ice" -- Field Survey

	SURVEY NO. 1	SURVEY NO. 2	SURVEY NO. 3
LOCATION	STH 50	STH 50	STH 100
CONDITIONS	· Late afternoon · Clear sky · Below freezing	· Night · Dry pavement · Below freezing	· Night · Dry pavement · Above freezing
PUBLIC PERCEPTION	· Glare and/or "ice"	· Glare and/or "ice"	· Glare from headlights

Revised Study Design

The WSRL was subcontracted for soliciting volunteer drives and conducting Survey No. 2. However, after 800 telephone call attempts, only 15 volunteers committed to the survey for the evening of March 27, 1996. Only 8 of the 15 volunteers actually showed up and completed the survey. Subsequently, an attempt was made to recruit volunteers from the City of Kenosha employees and from Marquette University students. After an extensive effort (e.g., phone calls, e-mail, and posting of flyers) only two volunteers were recruited. As a result, the survey was canceled.

Because of the weather dependency of the survey and the difficulty of arranging for stand-by volunteers, the Research Team recommended a police assisted intercept survey. The panel concurred with the recommendation, but approved only Survey No. 1.

The observations of "ice" at night requires an opposing light source. Hence the third test was on a two-lane highway where oncoming vehicle's headlights could be observed. The problem with surveying this phenomena was the difficulty of being at the right place with an observer positioned to notice the ground spot without pre-disposing the subject to its existence. If the observer and the subject are moving, the oncoming vehicle must be in just the correct place to have the headlights reflect on the ground spot. Therefore, eliminating the survey had more to do with the difficulty of obtaining it. It is still a phenomenon, but the resources of the project were insufficient for funding such a survey.

RESULTS

The intercept surveys were conducted in February 1997, along two sections of STH 50 of which one contained significant spot ground areas, and the other contained none (control section).

The surveys were conducted at sundown on two separate days and had a very short window of opportunity to complete when the sun was low in the sky before sunset. The motorists surveyed on the control section were probably entirely different drivers than those surveyed on the ground section.

The Wisconsin State Highway Patrol provided traffic control and assisted in the surveys. Motorists were intercepted in advance of the ground and control sections and asked to participate in the survey. The participants were given a brief instruction and then stopped and asked to respond to the questions after they drove the section.

Based on a 5% margin of error for a sample size of 60, it could not definitely be concluded that there was a difference, or otherwise no difference, between the survey results for the ground and control sections. A sample size of at least 395 would be needed to draw definite conclusions. However, the project budget did not allow such a large sample size.

The survey results are shown on pages 37-39. According to the survey results, motorists driving neither section experienced glare from the pavement or noticed any icy spot. Although some drivers indicated that they changed lanes or slowed down as they approached the ground or non-ground areas, their action(s) was not influenced by the surface condition. Two of the many pictures taken showing the solar glare phenomena are shown in Figure 11.

About 70% (41 respondents) of the motorists driving the ground section and about 76% (44 respondents) of those driving the non-ground section noticed glare directly from the sun.

Another goal of the survey was to find motorists perceptions of ground pavements in general. When asked "If a pavement has patches or is spotty in places, how much does that bother you?", 35 - 40% of the respondents indicated it did bother them some or a great deal. If the responses in the category of "just a little" are added to the above, approximately 3/4 of the respondents answered indicating it did bother them. All of the responses are shown on pages 37-39.

CONCLUSIONS

The survey results indicate that the reflection of the sun on the spot ground areas did not cause glaring effect or appear as "ice" to the motorists in the afternoon when the temperature is below freezing. Furthermore, the motorists' behavior or ability to operate their vehicles was unaffected by the presence of spot ground areas.

As indicated, the Research Team was unable to complete the surveys for assessing the glare and/or "ice" phenomenon at night when the temperature is below freezing (survey no. 2). However, the 8 drivers surveyed did not experience glare or notice icy spots along the ground or control sections. Since Survey No. 3 was eliminated, the headlight effect could not be assessed.

SURVEY RESULTS

Question 1 - Did you change your driving pattern (e.g., slow down, change lane) in any way as you drove over this road, such as slowing down, hitting your brakes, change lanes, or some other change?

SECTION	YES		NO		TOTAL
	Number	%	Number	%	
TEST SECTION	11	18.3%	49	81.7%	60
CONTROL SECTION	8	13.3%	52	86.7%	60

Question 2 - What did you do?

RESPONSE	TEST SECTION		CONTROL SECTION	
	Number	%	Number	%
Slowed down	5	8.3%	6	10.0%
Hit brakes	0.0	0.0	1	1.7
Changed lane	6	10.0	0	0.0
Other	0.0	0.0	1	1.7
Nothing*	49	81.7	52	86.7
TOTAL	60	100.0%	60	100.0%

*Did not change driving pattern.

Question 3 - What caused you to make this change? (Open-ended)

RESPONSE	TEST SECTION		CONTROL SECTION	
	Number	%	Number	%
Glare from sun	0	0.0%	1	1.7%
Icy patch	0	0.0	0	0.0
Other	11	18.7	7	11.7
Made no change	49	81.7	52	86.7
TOTAL	60	100.0%	60	100.0%

SURVEY RESULTS

Question 4 - Did you feel glare from the sun directly at you, did it seem to come from the pavement, or both?

RESPONSE	TEST SECTION		CONTROL SECTION	
	Number	%	Number	%
Directly at me	0	0.0	0	0.0
From pavement	0	0.0	1	1.7
Both	0	0.0	0	0.0
Don't know	0	0.0	0	0.0
Did not feel glare	60	100.0%	59	98.3%
TOTAL	60	100.0%	60	100.0%

Question 5 - Did you think the pavement was icy at any point?

RESPONSE	YES		NO		TOTAL
	Number	%	Number	%	
TEST SECTION	0	0.0%	60	100.0%	58
CONTROL SECTION	0	0.0%	60	100.0%	58

Question 6 - While you were driving did you notice any glare from the sun?

RESPONSE	YES		NO		TOTAL
	Number	%	Number	%	
TEST SECTION	41	70.0%	17	29.3%	58
CONTROL SECTION	44	75.9%	14	34.1%	58

SURVEY RESULTS

Question 7 - Did you feel glare came directly at you, did it seem to come from the pavement, or both?

RESPONSES	TEST SECTION Number	%	CONTROL SECTION Number	%
Directly at me	28		23	39.7%
From pavement	2		4	6.9
Both	11		17	29.3
Don't know	0		0	0.0
Inapp.	17		14	24.1
TOTAL	58	100.0%	58	100.0%

Question 8 - How did the pavement appear to you? Did it appear to be smooth or to have rough spots in places?

RESPONSE	TEST SECTION Number	%	CONTROL SECTION Number	%
Smooth	19	31.7%	26	43.3%
Rough	41	68.3	34	56.7
TOTAL	60	100.0%	60	100.0%

Question 9 - If a pavement has patches or is spotty in places, how much does that bother you?

RESPONSE	TEST SECTION Number	%	CONTROL SECTION Number	%
A great deal	5	8.3%	7	11.7%
Some	19	31.7	14	23.3
Just a little	20	33.3	25	41.7
Not at all	15	25.0	14	23.3
Don't know	1	1.7	0	0.0
TOTAL	60	100.0%	60	100.0%

Figure 11 Photographs Showing the Solar Glare Phenomena

MAJOR FINDINGS OF STUDY

1. Spot diamond grinding does not adversely affect the performance and material properties of the pavement.

2. Grinding PCC pavements is recommended as a safety enhancement, notwithstanding preliminary findings of higher crash rates for ground concrete pavements during nighttime when snow or ice is present on the pavement.

3. Grinding of PCC pavements can be expected to lead to lower crash rates both on wet and dry pavements during daytime and nighttime.

4. Motorists did not perceive spot ground areas to be "ice" when driving on pavements during times when the temperature was below freezing and there was glare from the sun. However, some respondents to the survey indicated that they were bothered to see that a newly constructed PCC pavement would require spot grinding.

RECOMMENDATION

Spot grinding of new concrete pavements should be continued as presently performed. Although the appearance of spot grinding on new concrete pavements appears to bother some motorists to a degree, spot grinding has been found to enhance ride quality, motoring safety and does not cause structural harm to the pavement.

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