Performance of Diamond Grinding

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Although diamond grinding of jointed concrete pavements has been used in the United States since 1965 to remove faults and improve rideability, no documentation of its performance nationwide has been available until now. As part of a study of eight concrete pavement rehabilitation techniques conducted by the University of Illinois for FHWA, 76 diamond grinding projects in 19 states were surveyed and analyzed. Diamond grinding is an effective means of improving ride quality on pavements with faulted joints, cracks, and repairs. The rideability of a newly ground pavement is typically as good as or better than that of a newly constructed pavement. However, if no other restoration work except grinding is performed on pavements with poor subdrainage, slab support, and load transfer, faulting after grinding recurs at a faster rate than for newly constructed pavements. Other factors found to significantly affect the performance of diamond grinding include traffic, slab thickness, joint spacing, base type, subgrade type, and climate. Surprisingly, dowel bar diameter was not found to be significant to the prediction of faulting after grinding. By the time faulting reaches objectionable levels, dowels may already be so loose that they contribute little to load transfer. More than 20 percent of the grinding projects surveyed had large amounts of cracking (more than 825 ft/lane-mi), and probably should have been overlaid or reconstructed rather than restored. The full benefit of diamond grinding, in terms of pavement life extension and cost effectiveness of repair, is not likely to be achieved on such pavements, which are likely to require major structural rehabilitation long before appreciable faulting recurs.

This investigation of the performance of diamond grinding on jointed concrete pavements is part of a study entitled "Determination of Rehabilitation Techniques for Rigid Pavements," conducted between 1985 and 1988 by the University of Illinois for FHWA. The objective of the study was to improve procedures for evaluating and rehabilitating concrete pavements. Five concrete pavement restoration techniques (diamond grinding, load transfer restoration, edge support restoration, full-depth repair, and partial-depth repair) and three types of overlay (bonded concrete, unbonded concrete, and crack and seat AC overlay) were investigated. The results of this study are fully reported elsewhere (*1–4*).

DIAMOND GRINDING

Diamond grinding of jointed portland cement concrete (PCC) pavements has been part of experimental and routine restoration work since 1965 (*5–7*). The first major project ground in that year was recently reground to restore rideability. Within about the last 10 years, the amount of diamond grinding work completed has increased. The capabilities of diamond grinding equipment have also improved during this time period (*5*).

To date there has been no nationwide documentation of the performance of diamond grinding. Several specifications exist and the technique has proven effective in several states. Diamond grinding has been effective in removal of faulting and surface wear; however, the overall effectiveness of the technique in terms of extending pavement life has not been determined and verified through country-wide field performance.

Available references on diamond grinding of jointed concrete pavements were reviewed. Some new publications are available that have added considerable knowledge to the design, construction, and performance of diamond grinding (*5,6,8–12*).

The development of an extensive data base containing information on original pavement design, traffic, environmental conditions, and performance was required to determine the effectiveness of grinding. This data base was developed to allow analysis of many factors that might affect performance.

To obtain all of the necessary data base elements, the following methods and sources were used:

- A field survey was conducted on each project to document its current condition. The surveys included crack mapping, faulting measurements, distress data collection, and subjective ratings of pavement condition and rideability.
- The design of each original pavement structure was determined from "as built" plans and verbal communication with state DOT personnel.
- Environmental data of temperature and precipitation were obtained from historical records kept by the National Oceanic and Atmospheric Administration.
- Traffic estimates, including average daily traffic and percent commercial trucks, were obtained from the state DOTs. For calculation of accumulated axle loads on each project, FHWA historical W–4 tables on axle load distributions for the corresponding states and pavement classifications were used.

Physical test data were not collected. The most useful tests would have been heavy load deflection testing, coring, and laboratory testing. These tests would have greatly increased the ability to analyze and interpret the pavement deterioration observed in the visual surveys. An understanding of the physical properties of the pavement layers, quality of support, load transfer, and base gradations would have permitted structural, material, and drainage evaluations.

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DATA BASE AND DATA COLLECTION

A total of 76 diamond ground pavement sections in 19 different states were included in the data base. Two sample units about 1,000 ft in length were surveyed on as many sections as possible; so the data base contained a total of 114 sample units. Included in the data base are many of the projects on which diamond grinding was done after 1976, when this type of work began in earnest throughout the country. These pavements were field surveyed between June 1985 and July 1986. Figure 1 shows the general location of the diamond grinding projects. A fair distribution exists among the different geographic and climatic zones.

The field and office data collection procedures are described in detail by Reiter et al. (*4*). For the purposes of developing performance prediction models and improving design and construction procedures, the following types of data were necessary:

- Field condition data,
- Original pavement structural design and improvement data,
- Rehabilitation design data,
- Historical traffic volumes and classifications, W-4 load tables and calculated 18-kip equivalent single axle loads (ESAL), and
- Environmental data.

A complete list of all of the variables considered in the field surveys are as follows:

- General
  - —Sample unit,
  - —Foundation of sample unit,
  - —Condition of drainage ditches,
  - —Subsurface drainage present and functional, and
  - —Number of transverse joints in sample unit.
- Slab distress variables
  - —Transverse cracking,
  - —Transverse D cracking,
  - —Longitudinal cracking,
  - —Longitudinal D cracking,
  - —Longitudinal joint spalling, and
  - —Scaling, crazing, map cracking, shrinkage cracking.
- Joint distress variables
  - —Transverse joint spalling,
  - —Corner spalling,
  - —Pumping,
  - —Faulting (mean over sample unit),
  - —Joint width (mean over sample unit),
  - —Corner breaks,
  - —D cracking along joint,
  - —Reactive aggregate distress,
  - —Joint sealant condition, and
  - —Incompressibles in joint.

The following are design variables for the original pavement that are contained in the data base.

- General
  - —Identification (highway, milepost, direction);

FIGURE 1 Location of diamond grinding sections included in the data base.

—Beginning and ending mile posts and stations;
—Number of through lanes;
—Type of original pavement, jointed plain concrete pavement (JPCP), or jointed reinforced concrete pavement (JRCP);
—Layer descriptions, material types, thicknesses;
—Date of original pavement construction; and
—Dates and descriptions of major improvements.

- Joints and reinforcement
  —Average contraction joint spacing,
  —Skewness of joints,
  —Expansion joint spacing,
  —Transverse contraction joint load transfer system,
  —Dowel diameter,
  —Type of slab reinforcement,
  —Longitudinal bar/wire diameter, and
  —Longitudinal bar/wire spacing.
- Subgrade, shoulder, and drainage
  —Type of subgrade soil (fine-grained, coarse-grained),
  —Outer shoulder surface type,
  —Original subsurface drainage type, and
  —Original subsurface drainage location.

The data base is comprehensive, containing as many projects as could be included within available resources. This was done to provide a wide range of data to facilitate regression analysis for development of performance models.

Figures 2 and 3 show the distributions of age and accumulated 18-kip ESALs since grinding. The age distribution indicates the relative newness of the grinding technique, with a mean of 4 years and a range of 1 to 9 years. The ESAL distribution shows a mean of 2 million ESALs and a range of 0.22 to 7.81 million ESALs after grinding in the outer traffic lane. The physical designs of the pavements are summarized as follows:

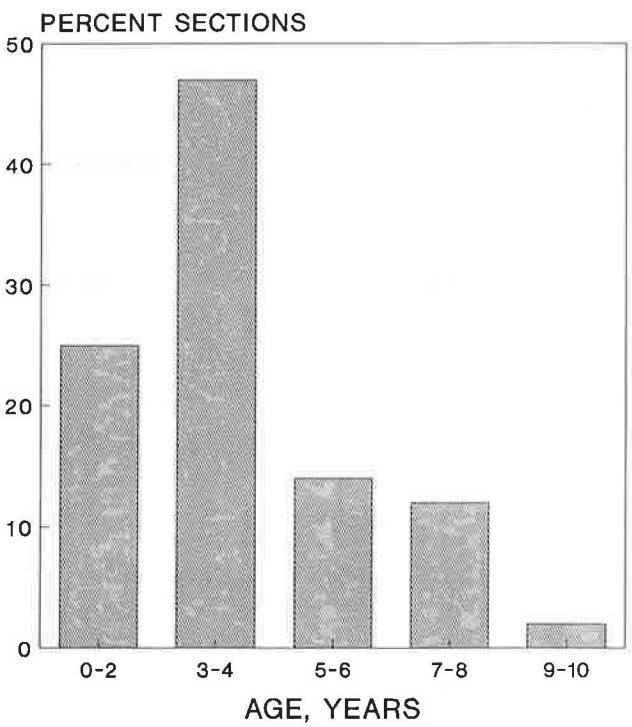

FIGURE 2 Age distribution of diamond grinding sections.

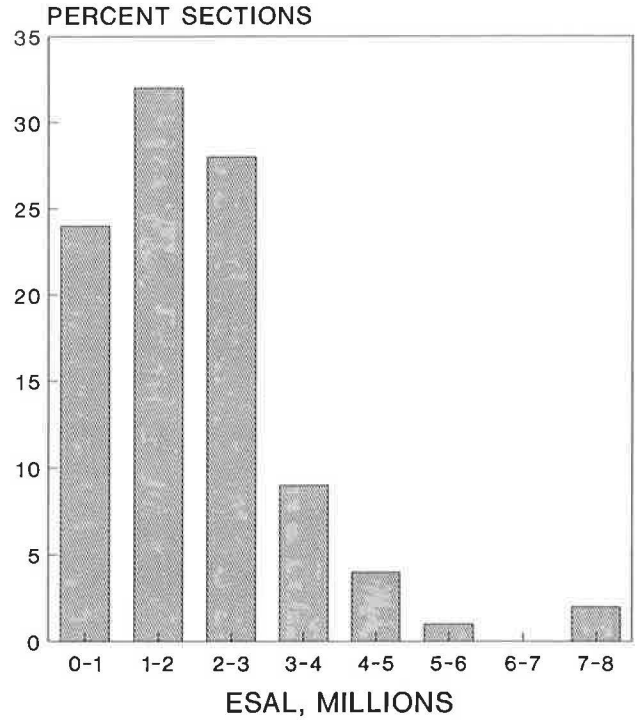

FIGURE 3 ESAL distribution of diamond grinding sections.

- Pavement type: 39 JRCP, 75 JPCP.
- Slab thickness: 7 to 12 in.
- Joint spacing: 15 to 100 ft.
- Base type: 54 percent granular, 46 percent stabilized.
- Load transfer: 38 percent dowelled, 62 percent undowelled.
- Shoulder type: 95 percent AC, 5 percent tied PCC.
- Subdrainage: 82 percent with none, 18 percent with edge drains.

Subgrade and climate variables had the following ranges:

- Subgrade type: 53 percent fine-grained, 47 percent coarse.
- Precipitation: 9 to 61 in. per year.
- Freezing Index: 0 to 1,750 freezing degree-days.

About 50 percent of the projects were diamond ground in both lanes, and the other 50 percent were ground in the outer lane only. For 29 percent of the projects, the age of the pavement at the time of grinding is unknown; in nearly all cases this is because the year of original construction is unknown. For the remaining projects, the range of ages was 11 to 32 years, and the average age was 19 years.

FIELD PERFORMANCE AND EVALUATION

Diamond grinding greatly improves the rideability of the pavement by removing faulting. Diamond grinding also

TABLE 1 SUMMARY OF DISTRESS TYPES IDENTIFIED FOR DIAMOND GRINDING PROJECTS (OUTER TRAFFIC LANE ONLY)

Distress Type	Severity	Mean	Range
Transverse Cracking	Medium and High	459	0 to 2928 ft/mile
Longitudinal Cracking	Medium and High	91	0 to 1900 ft/mile
Corner Breaks	All	7	0 to 222 /mile
"D" Cracking	All	6 percent of sections	
Pumping	Low	99 percent of sections	
	Medium	1	
	High	0	
Joint Spalling	Low	96 percent of sections	
	Medium	4	
	High	0	

Notes: 1 mile = 1.609 km
1 ft/mile = 0.1894 m/km

increases the friction of the surface for a short time after grinding (*5,12–14*). An evaluation of distresses that may affect the structural capacity, rideability, and friction of ground pavements is presented in this section.

Distresses that may directly affect the structural integrity of the ground pavement are transverse and longitudinal cracking, corner breaks, joint spalling, joint faulting, pumping, and D cracking. Rideability is affected by most of these distresses. Friction is decreased by wear and polish of the surface texture. Table 1 presents a summary of the mean and range of major distresses measured in the grinding section outer lanes, expressed on a per-mile basis.

The severity levels used in describing distresses correspond to standard definitions given in the concrete pavement evaluation system (COPES) distress manual (*15*). For example, a low-severity crack is a hairline crack, a medium-severity crack is working (spalled and faulted), and a high-severity crack is badly spalled and faulted, in need of immediate repair.

Transverse Cracking

Deteriorated (medium- and high-severity) transverse cracks on jointed concrete pavements are largely caused by a combination of traffic loading fatigue damage and thermal curling stresses. For JRCP, an additional contributing factor may be lock-up of transverse joints caused by dowel bar corrosion or misalignment. The distribution of deteriorated transverse cracks in the outer lane for the ground pavements surveyed is shown in Figure 4. Of the pavement sections, 43 percent had no deteriorated transverse cracks. However, 21 percent had over 825 ft of deteriorated cracks per mile. This level of cracking is considered indicative of a pavement in need of structural rehabilitation. This value of approximately 825 ft/mi was found to be the average of all projects in the NCHRP 1–19 COPES data base that had a present serviceability rating less than 3.0. It corresponds to a working crack every 77 ft.

Without historical distress data, it is impossible to determine how much of the cracking on these sections was present at the time of grinding and how much developed afterwards. In either case, these sections were probably structurally inadequate before grinding and should have been overlaid or reconstructed rather than restored.

Longitudinal Cracking

Longitudinal cracking is usually caused by late sawing, shallow saw cuts, or the use of plastic inserts that do not create an adequate weakened plane for longitudinal joint. Figure 5 shows a distribution of the deteriorated (medium- to high-severity) longitudinal cracking on the diamond ground sections. Of the sections, 75 percent had no deteriorated longitudinal cracking. Only 5 percent had more than 500 ft of deteriorated longitudinal cracking per mile. Three sections had over 1,500

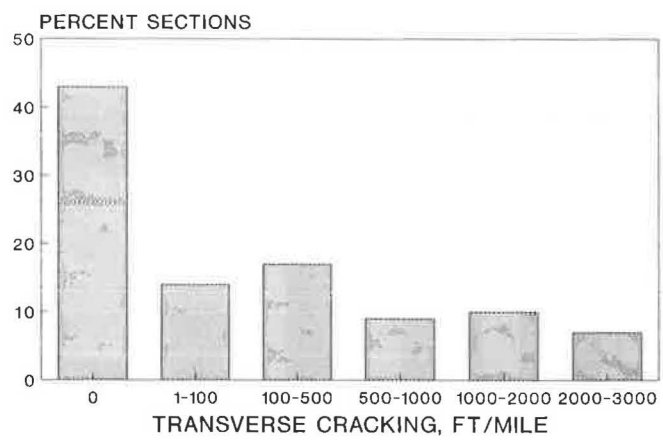

FIGURE 4 Transverse cracking distribution of diamond grinding sections.

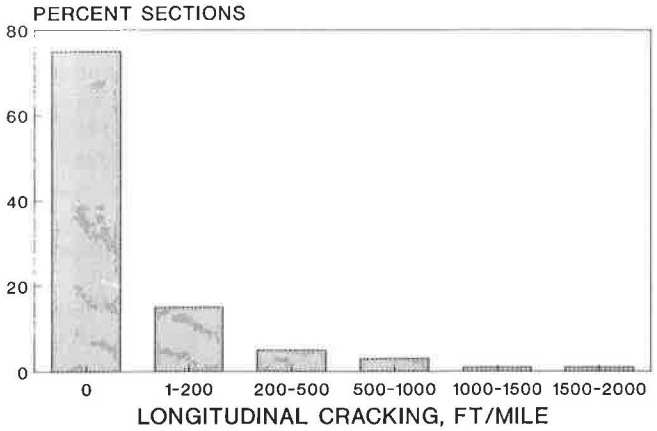

FIGURE 5 Longitudinal cracking distribution of diamond grinding sections.

ft/mi of deteriorated longitudinal cracking. It is impossible to determine whether this cracking occurred before or after grinding.

Corner Breaks

Corner breaks are the result of loss of support beneath the slab caused by erosion of the base course or subgrade. Projects that are diamond ground for faulting (which is indicative of pumping) frequently have some loss of support. Significant faulting cannot occur without some erosion of the underlying layers of the concrete pavement (*11*). Corner breaks are a good indicator of structural deficiency.

These breaks were observed on 19 percent of the sections. However, only 6 percent of the sections had more than 25 corner breaks per mile, a level that is considered serious. Three sections had more than 100 corner breaks per mile. Whether the breaks occurred before or after diamond grinding is not known. In either case, that many of the sections were diamond ground without consideration or determination of support conditions is evident.

Joint/Crack Faulting and Pumping

Faulting develops from pumping and erosion of underlying materials through the combination of factors:

1. The movement of heavy wheel loads across the joint or crack,
2. The presence of free moisture in either the base or subgrade, or both,
3. An erodible base or subgrade material (high in fines), and
4. Poor load transfer across joints and cracks (*9,13,14*).

If these factors are present, the base or subgrade materials, or both, have the potential to pump beneath the approach slab as wheel loads cross joints and cracks. Pumping forces water and fines from under the leave side and either deposits the fines under the approach side or force them out through the longitudinal joint. This action depends on the deflection of the slab corners, and is more severe on pavements that exhibit poor load transfer. The accumulation of fines lifts the approach side and leaves a void under the leave side, resulting in faulting (*9*).

The distribution of transverse joint faulting for the diamond grinding sections is shown in Figure 6. The average faulting in the outer lane was 0.065 in., with individual sections ranging from 0.01 to 0.33 in. Faulting detracts significantly from ride quality on JPCP when it exceeds about 0.13 in., which occurred on 7 percent of the sections (*16*).

Low-severity pumping (water bleeding, blowholes, some pumped fines) was observed on many of the diamond grinding sections. However, only one section exhibited medium-severity pumping (substantial amount of fines pumped on to the shoulder). Edge drains and tied PCC shoulders on several sections probably reduced the occurrence of visible signs of pumping.

D Cracking

D cracking is caused by freeze-thaw damage to either the aggregates or the paste in PCC, and is evidenced by fine hairline cracks near and parallel to joints and cracks that eventually spall out. Only 6 percent of the diamond grinding sections exhibited D cracking.

Wearout of Grinding Texture

The texture developed by grinding provides good friction immediately (*5,12,17*). The ridges produced improve the surface macrotexture and provide an escape route for water under tires.

Data on friction numbers were not available for any of the sections. On some, wear of the grinding texture in the wheel paths was evident. This concern warrants further detailed study because loss of texture could result in loss in friction. The Georgia DOT has used the sand patch method to measure

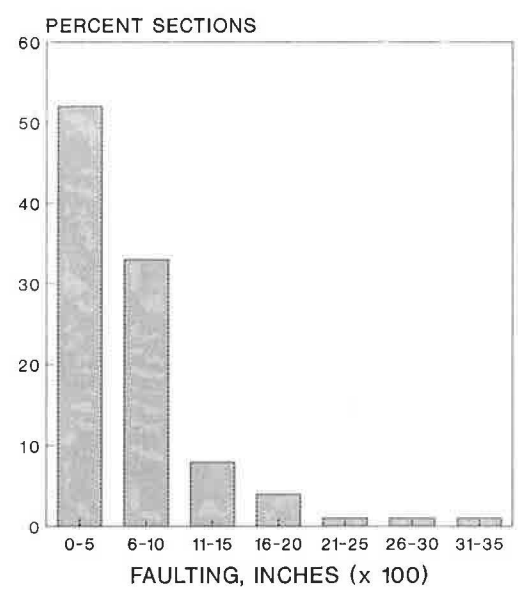

FIGURE 6 Faulting distribution of diamond grinding sections.

texture depths on grinding projects (*17*) and observed the effect of traffic on wearout of grinding texture. Texture depths between 0.04 and 0.06 in. have been measured on several projects shortly after grinding. These values compare favorably to the 0.035-in. depth required on newly constructed pavements. The texture depths on many projects dropped off to 0.03 in. or less after about 5 million vehicle passes, but decreased more slowly after that. They did not reach the specified minimum level requiring correction until after about 25 million vehicle passes (in the Georgia study a truck pass was considered to be approximately equal to 8 passenger car passes in terms of wearout of grinding texture). Most of the projects included in the Georgia study had granite aggregates; wearout of grinding texture on pavements with softer aggregates would probably be more rapid. The width of the land area between the grinding blades is also likely to be a factor in the rate of texture loss.

PERFORMANCE MODEL

Model Development

Faulting is a major distress type that develops after grinding on most jointed concrete pavements. A predictive model was developed for transverse joint faulting using nonlinear regression techniques available in the Statistical Package for the Social Sciences (SPSS) (*18*).

As a first step in analyzing the data, all independent variables that were believed to have a significant influence on the faulting of ground pavements were identified. These variables were then considered in the development of a nonlinear regression model for faulting.

In addition to the regular 114 diamond grinding sections, data from dowelled joint load transfer restoration sections were added so that this work, when done concurrently, could be considered. These sections were also diamond ground.

A great deal of time was spent trying to develop a faulting model for diamond ground pavements, with only limited success. As diamond grinding is applied in more states with differing climates and designs, the initial model can be revised to include more variables and wider ranges of applicability.

Faulting Model

The factors that entered into the faulting model included design, traffic, subgrade, climate, and additional restoration work. The model obtained is as follows:

$$\begin{aligned} \text{FAULT} = {} & -5.62(\text{ESAL} + \text{AGE})^{0.54}\,[5.85(1 \\ & + \text{DRAIN} + \text{SUB})^{0.0529} \\ & -3.8 * 10^{-9}(\text{FI}/100)^{6.29} + 0.484\,(\text{THICK} \\ & + \text{PCCSH})^{0.335} + 0.1554\text{BASE} \\ & - 7.163\text{JSPACE}^{0.0137} + 0.1136\text{LTR}]/100 \end{aligned} \quad (1)$$

where

FAULT = outer-lane mean transverse joint faulting after grinding (in.),
ESAL = outer-lane accumulated 18-kip ESALs after grinding (millions),
AGE = time since diamond grinding (years),
DRAIN = 0 if no edge drains were present after grinding, 1 if edge drains were present after grinding,
SUB = 0 for fine-grained subgrade soil (A4 to A7), 1 for coarse-grained subgrade soil (A1 to A3),
FI = Freezing Index (mean Fahrenheit degree-days below freezing),
THICK = original slab thickness (in.),
PCCSH = 0 if no tied concrete shoulder was present, 1 if tied concrete shoulder was present,
BASE = 0 if existing base is granular material, 1 if existing base is stabilized material (asphalt, cement),
JSPACE = mean transverse joint spacing (ft),
LTR = 0 if no retrofit dowels were placed when ground, 1 if retrofit dowels were placed.

The statistics were as follows:

R^2 = 0.38,
Standard error = 0.027 in., and
n = 114 sections (diamond grinding without load transfer restoration plus 72 joints with diamond grinding and load transfer restoration).

The mean and ranges of factors are as follows:

Factors	*Mean*	*Range*
Faulting, in.	0.06	0.01 to 0.33
ESALs, millions	1.94	0.22 to 7.8
Age, years	4	1 to 9
Slab thickness, in.	9.0	7.0 to 12.0
Joint spacing, ft	38	15 to 100
Dowel diameter, in.	—	0 (no dowels) to 1.25
PCC shoulder	—	0 (no PCC shoulder), 1 (tied PCC shoulder)
Base type	—	0 (granular), 1 (stabilized)
Edge drains	—	0 (none), 1 (yes)
Subgrade type	—	0 (fine-grained), 1 (coarse-grained)
Freezing Index, degree-days	436	0 to 1,750
Annual precipitation, in.	33.5	9.3 to 61.1
Pavement type	—	JRCP, 39 sections JPCP, 75 sections

Several factors were identified that affect the rate of faulting of a ground pavement. Two typical or standard pavements were defined. Each factor was varied over a typical range and the change in faulting determined. The ratio of the higher faulting value to the lower value was computed. The results are as follows:

JRCP Factor	*Range*	*High/Low Range*
ESALs, million	1 to 10	5.9 Increase
Slab thickness, in.	8 to 12	1.6 Decrease
Joint spacing, ft	25 to 75	1.4 Increase
Base type	Granular, stabilized	1.2 Decrease
Subgrade soil	Fine, coarse	1.4 Decrease
Freezing Index	0 to 1,500	1.2 Increase
Concrete shoulder	No, yes	1.1 Decrease
Edge drains	No, yes	1.4 Decrease
Load transfer restoration	No, yes	1.6 Decrease

JPCP Factor	*Range*	*High/Low Range*
ESALs, million	1 to 10	6.0 Increase
Slab thickness, in.	8 to 12	3.0 Decrease
Joint spacing, ft	8 to 20	1.7 Increase
Base type	Granular, stabilized	1.2 Decrease
Subgrade soil	Fine, coarse	2.0 Decrease
Freezing Index	0 to 1,500	1.3 Increase
Concrete shoulder	No, yes	1.2 Decrease
Edge drains	No, yes	2.0 Decrease
Load transfer restoration	No, yes	1.6 Decrease

These results indicate that the variables in the faulting model are affecting faulting in the logical direction, and that some of them have a much larger effect than others. The variable having the greatest effect is traffic, and the design factor showing the most effect is slab thickness. The subgrade soil type also has a major effect, probably because of better subdrainage with a coarse-grained soil. One factor that did not enter the equation was the presence of dowels in the original pavement. It appears that after a pavement has faulted badly enough to require grinding, the dowels are too loose to have any impact on future faulting after grinding. Additional restoration work, including concrete shoulders, edge drains, and load transfer restoration, also has a significant effect on reducing faulting.

Figure 7 shows faulting development for the standard JRCP (see Table 2) over its initial life (using the NCHRP 1–19 faulting model) and after diamond grinding (Year 20) when no additional restoration work is done. The results show that the recurrence of faulting after grinding is more rapid than when the pavement is new.

Figures 8 and 9 show predicted faulting for the standard JRCP and JPCP designs respectively (see Table 2) after diamond grinding, with and without edge drains. The faulting of the pavement over its initial performance period, labeled "new," is also shown for comparison.

Figures 10 and 11 show faulting development for grinding alone, grinding with tied PCC shoulders, grinding with load transfer restoration (using dowels) and grinding with tied PCC shoulders and load transfer restoration.

The results clearly indicate the importance of concurrent restoration work to the success of a grinding project when deficiencies such as poor subdrainage and joint load transfer exist. These results are for only two standard or typical designs, and other design parameters would produce different results. Therefore, the designer should apply judgment when using the faulting prediction model for determining whether or not to do other restoration work.

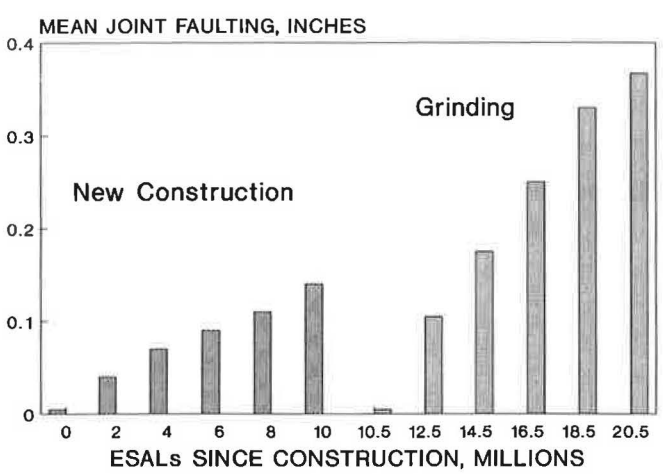

FIGURE 7 Projected faulting for standard JRCP section for new construction and after diamond grinding.

TABLE 2 TYPICAL STANDARD PAVEMENT CHARACTERISTICS FOR FAULTING SENSITIVITY ANALYSIS

Factor	JRCP	JPCP
ESAL	0.5 million/year	0.5 million/year
Age (since grinding)	0 to 20 years	0 to 20 years
Edge Drains	None	None
Subgrade Soil	Fine grained	Fine grained
Freezing Index	250	0
Slab Thickness	9 in	8 in
Shoulder Type	Asphalt Concrete	Asphalt Concrete
Base Type	Granular	Stabilized
Joint Spacing	50 ft	15.5 ft
Load Transfer (retrofit dowels)	No	No

Notes: Sensitivity analysis was conducted by varying one factor at a time over the range of age with corresponding change in ESAL.
1 in. ≐ 2.54 cm
1 ft = 0.3048 m

CONCLUSIONS AND RECOMMENDATIONS

Overall Effectiveness

Diamond grinding has been successful in producing a smooth ride and extending the service lives of jointed concrete pave-

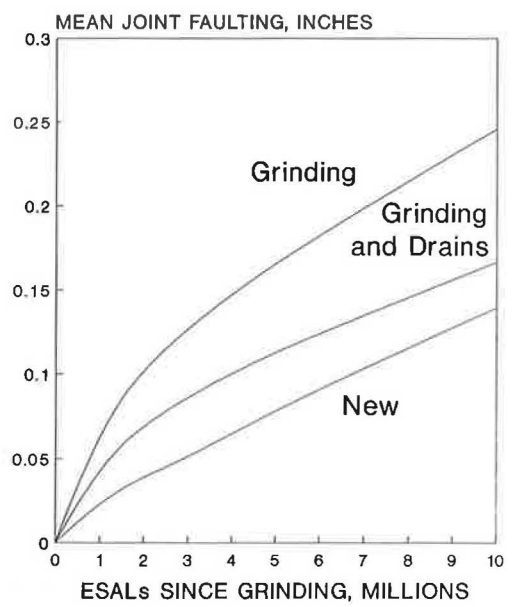

FIGURE 8 Effect of grinding and retrofit edge drains on JRCP faulting.

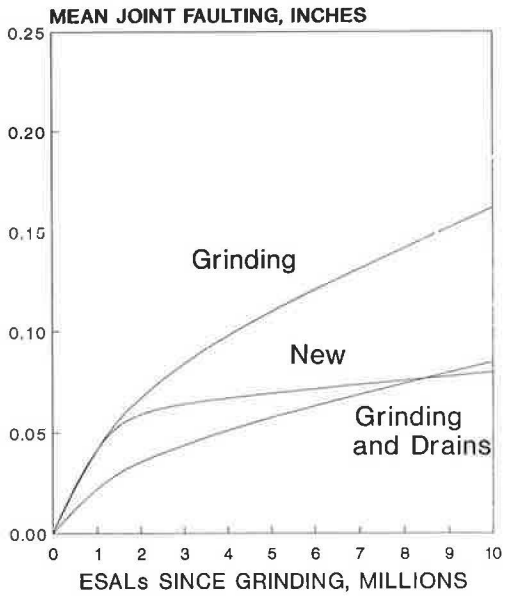

FIGURE 9 Effect of grinding and retrofit edge drains on JPCP faulting.

ments. About one out of five grinding projects surveyed in this study had substantial quantities of structural distress (cracking and corner breaks) and probably should have been overlaid or reconstructed rather than restored. Diamond grinding does not contribute to the structural capacity of a pavement, and its benefits will be short-lived on any pavement with extensive structural damage.

Transverse Cracking

About 21 percent of the ground sections showed a large amount of deteriorated transverse cracking (over 825 ft/lane-mi). This amount is for pavements having an average life after grinding of four years and 2 million accumulated 18-kip ESALs. Of the sections, 57 percent had minor amounts of deteriorated cracks.

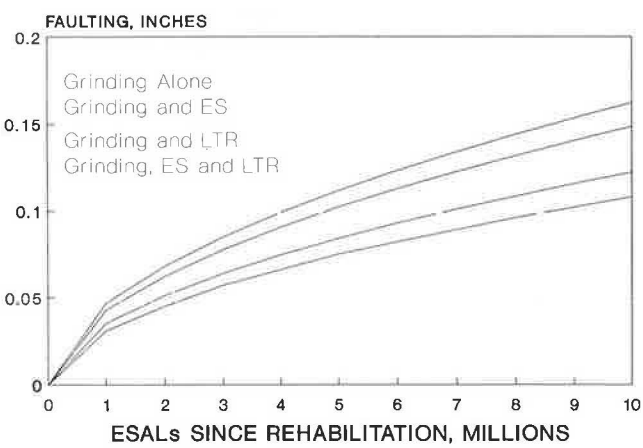

FIGURE 10 Predicted faulting of JPCP after grinding and other restoration work.

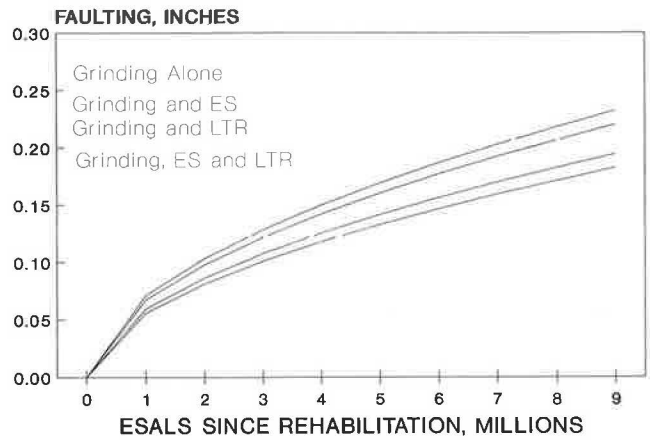

FIGURE 11 Predicted faulting of JRCP after grinding and other restoration work.

Longitudinal Cracking

About 90 percent of the ground sections showed little or no deteriorated longitudinal cracking. Only 2 percent of the sections showed a serious amount of longitudinal cracking (greater than 1,000 ft/mi).

Corner Breaks

About 19 percent of the ground sections showed minor corner breaks, and only 6 percent showed a serious amount (greater than 25/mi).

Faulting of Transverse Contraction Joints

The rate of faulting after grinding generally is higher than for newly constructed pavements if no other restoration work is accomplished. However, this accelerated development of faulting can be largely overcome by reducing the pumping potentials with concurrent work such as load transfer restoration, sealing joints, and retrofitting tied PCC shoulders and subdrainage. Some key factors that affect faulting were determined to be the following:

- Future traffic—Truck traffic after diamond grinding (accumulated 18-kip ESALs) has a large effect on the amount of faulting that develops. Faulting after grinding develops rapidly at first and then levels off, similarly to faulting of new pavements (*15*).
- Existing pavement design—Pavements with thicker slabs, stabilized bases, and shorter joint spacings fault less after grinding.
- Drainage—Edge drains and coarse-grained subgrade soils reduce faulting after grinding.
- Climate—The colder the climate where the pavement is located, the greater the amount of faulting after grinding.
- Tied concrete shoulder—Tied concrete shoulders reduce faulting after grinding.
- Load Transfer Restoration—Retrofitting dowels to restore load transfer at transverse joints and working cracks reduces faulting after grinding.

• Prediction of Faulting After Grinding—The prediction model for faulting after grinding can be used with caution to estimate the life of the technique (number of years until faulting again reaches an unacceptable level) and to examine the potential impact of concurrent work such as edge drain installation, load transfer restoration, and tied concrete shoulders.

Wearout of Grinding Texture

The surveys revealed that there was some wear of the texture in the wheel paths. The rate of wearout and the factors involved could not be determined. It is likely that the hardness of the aggregate, the level of traffic, and the land area width are major factors involved. It is important to maximize the land area between grooves, while still providing an adequate number of grooves for surface drainage.

ACKNOWLEDGMENT

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