Technical Report Documentation Page

1. Report No.	2. Government Accession No.	Recipient's Catalog No.
4. Title and Subtitle Concrete Pavement Rehabilitation – Guide for Diamond Grinding		5. Report Date June 2001 6. Performing Organization Code
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9. Performing Organization Name and Address Federal Highway Administration Southern Resource Center 61 Forsyth St, SW, Suite 17T26 Atlanta, GA 30303		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Highway Administration 400 7th Street S.W. Washington, DC 20590		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This Technical Bulletin recommends procedures for selecting, designing, and construction of diamond grinding in Portland cement concrete pavements. Diamond grinding consists of removing surface irregularities from concrete pavements that are often caused by faulting, curling, and warping of the slabs. The main benefits of properly using this technique include smoother ride, reduced road noise, and improved friction. Diamond grinding can be used as a stand-alone rehabilitation technique. However, FHWA recommends its use as part of a comprehensive Concrete Pavement Rehabilitation (CPR) program. Information regarding cost and performance is also included in this document.

This document has been prepared in part with information collected under the sponsorship of FHWA's Special Project 205, Quality Concrete Pavement Rehabilitation. Other documents to provide similar guidance in other CPR techniques will follow.

17. Key Words Concrete Pavement Rehabilitation, CPR, Diamond Grinding, Pavement Smoothness, Ride		18. Distribution Statement No restrictions	
19. Security Classification (of this report) None Unclassified	20. Security Classification (of this page) None Unclassified	No. of Pages	22. Price

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Concrete Pavement Rehabilitation Guide for Diamond Grinding

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INTRODUCTION

Diamond grinding is a concrete pavement restoration technique that corrects irregularities such as faulting and roughness on concrete pavements. Diamond grinding should be used in conjunction with other Concrete Pavement Rehabilitation (CPR) techniques. A full CPR job can restore structural and functional capacity of a pavement to acceptable levels for a specific traffic need. Full-depth repair, load transfer restoration, and in special situations, addition of edge drains and/or slab stabilization may be appropriately used to restore structural integrity to the pavement. Partial-depth repair may be used to repair spalled areas at joints and cracks. Diamond grinding restores rideability by removing surface irregularities caused by construction curling, slab warping, faulting, and roughness caused by CPR construction work. The most immediate effect of diamond grinding is a significant improvement in the riding smoothness of a pavement. Another very important effect of diamond grinding is the significant increase in surface macro-texture and consequent noise reduction and safety improvement. Safety is improved by a temporary increase in skid friction resistance and a reduction in the potential for hydroplaning. Safety may also be improved by grooving the pavement surface. Grooving consists of cutting deeper channels that provides better drainage of water between the tires and the pavement surface and thus preventing skidding and hydroplaning. Grooving is not covered in this technical guide. For more information about grooving the reader may contact the International Grooving and Grinding Association at 518-731-7450.

Some of the advantages of a diamond ground pavements and its construction include:

- Provides a smooth riding surface that is often as good or better than a new pavement. Smooth ride is achieved by removing faulting at joints and cracks, removing construction curling and moisture-gradient warping of the slabs, and other construction or environmental related roughness.
- Enhances surface texture and friction, consequently reducing road noise and improving safety.

- May reduce accident rates in wet weather conditions by providing adequate macrotexture and removing studded tires wheel-path rutting. These improvements reduce the potential for small-vehicle hydroplaning.
- Does not significantly affect fatigue life of a pavement.
- Does not affect material durability unless the coarse aggregate is a soft stone subject to polishing.
- Does not raise the pavement surface elevation.
- May be applied only where is needed, however, spot grinding is generally not recommended.
- Can be constructed during off-peak hours.

Pavement friction may be improved through grinding by enhancing surface macrotexture. Adequate macrotexture reduces the potential for hydroplaning, especially in cases where studded tire wear has produced "ruts" in the concrete pavement. The increased macrotexture initially provides high skid numbers, but this improvement may be temporary, particularly if the pavement contains aggregates susceptible to polishing. This effect may be offset by properly spacing the diamond saw blades, creating more land area between the grooves on softer coarse aggregate.

Diamond grinding re-textures worn surfaces with a longitudinal texture and provides a quieter surface. Diamond grinding also removes faults by leveling the pavement surface, thus eliminating the thumping and slapping sound created by faulted joints. However, the thumping sound may also be related to wide joints, which will not be affected.

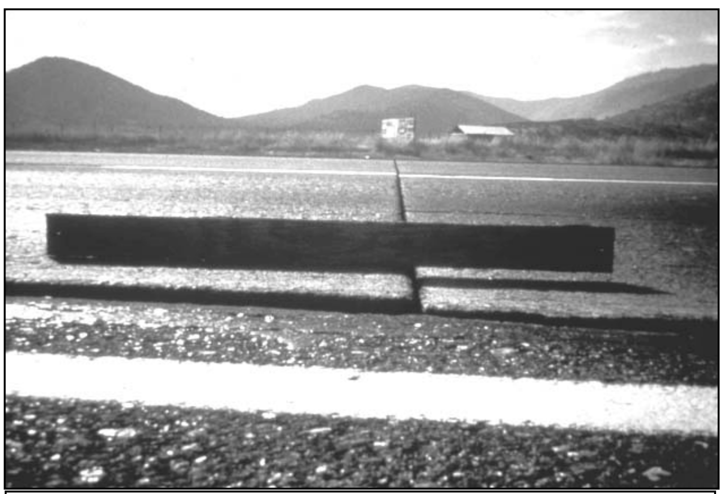


Figure 1. Diamond grinding can be used to correct surface irregularities such as faulting (difference in elevation across a joint or crack).

Measurements on highways in Belgium indicate a reduction of up to 5 dbA in pavement noise levels. Also, there may be a considerable difference in the frequency of noise, resulting in a more pleasant ride after diamond grinding. Michigan DOT found an after grinding noise reduction of up to 5dbA in peak frequencies of 500 Hz and the first harmonic of 1000 Hz (DeFrain 1989). This is particularly true of pavements that were transversely tined with uniformly spaced groves.

Diamond grinding generally reduces slab thickness by 4 to 6 mm ($^{3}/_{16}$ to ¼ in). Since slab thickness is one of the most sensitive factors affecting cracking performance of concrete pavements, any reduction can be a concern. A cracking model was used to determine the fatigue life of jointed plain concrete pavement (Rao, Yu, Darter). The result indicated that a 5-mm (¼ in) reduction in slab thickness results in about 30 percent reduction in fatigue life if the concrete strength remains constant. However, long-term strength of concrete is significantly higher than the design strength, which is typically the 28-day strength. The strength of conventional concrete after 1 year can be up to 20 percent higher than 28-day strength. If the increase in concrete strength is considered, the small reduction in slab thickness has negligible effect on service life. These results suggest that a typical concrete pavement may be ground up to three times without compromising its fatigue life. In practice, some States have ground concrete pavements up to three times without reporting any problems (i.e., California and Georgia).

Not all concrete pavements with excessive roughness or faulting are good candidates for diamond grinding. For example, a pavement with medium traffic and a roughness IRI (International Roughness Index) value above 3 m/km (190 in/mi) may be beyond the window of opportunity for cost-effective diamond grinding. In such cases, other procedures such as an overlay may be a better alternative to restore the pavement's smooth ride. In some cases diamond grinding alone may not be enough to address an existing problem. Structural distresses such as pumping, loss of support, corner breaks, working transverse cracks, and shattered slabs will require repairs before grinding is conducted. A high percent of shattered slabs (more than 5 percent) indicates a structural deficiency in the pavement. The cause of roughness due to faulting needs to be addressed before grinding to avoid its redevelopment. Severe levels of material durability problems such as D-cracking, reactive aggregate, and freeze and thaw damage indicate that diamond grinding is not a suitable restoration technique and that a more comprehensive rehabilitation strategy should be used to improve the pavement.

DESIGN CONSIDERATIONS

Diamond Grinding in the CPR Program

As more highway agencies have used diamond grinding to restore ride and texture of their concrete pavements, there have been some cases of misapplication of the technique. Structurally deficient pavements should not be ground without repairing major distresses of the pavement. A properly structured CPR program should thoroughly evaluate the existing condition of the pavement, and then implement a CPR strategy to upgrade the pavement condition to acceptable levels. The pavement evaluation is done in a multi-step process. First, design and condition data is collected by reviewing as constructed plans and making field reviews. This data is then evaluated to determine the probable cause and extent of existing deterioration. Laboratory and/or field testing is often necessary to complete the pavement evaluation. The pavement designer should use the evaluation data to design a CPR strategy that will correct the particular distresses in the concrete pavement. A CPR strategy may include two or more individual techniques. The techniques are almost always more effective when used together, but can also be applied individually to

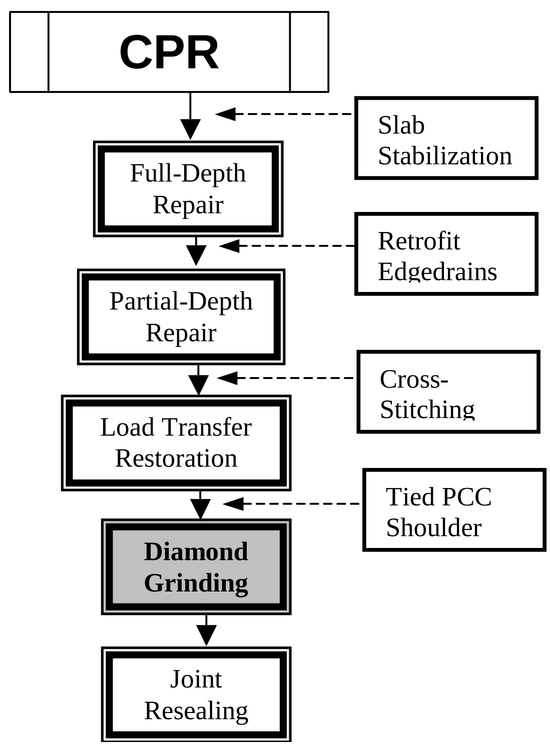


Figure 2. Typical sequence of a concrete pavement rehabilitation program

address a single distress. A full CPR job can restore structural capacity to levels near those of new construction. Within the CPR strategy selected, diamond grinding restores ride by blending the old slabs with new repairs into a uniform profile. The pavement joints are generally resealed after diamond grinding. Figure 2 shows the typical sequence of CPR work. As indicated above, only those techniques required to address a particular pavement problem need to be included in a strategy. The CPR techniques that are more commonly used are shown in the left column of Figure 2.

Selection of Candidate Projects

The long-term effectiveness of diamond grinding depends upon a number of factors. However, the most significant factors are the condition of the existing pavement structure, traffic and level of CPR applied. It is important for the designer to recognize that diamond grinding addresses functional problems of the pavement only. If the existing pavement is structurally deficient, an overlay or reconstruction may be more appropriate. Pavements with moderate to advanced material related distresses such as alkali-silica reaction or D-cracking are not good candidates for diamond grinding. The use of diamond grinding in pavements with severe material related distress may lead to accelerate pavement failure. However, in some cases when the pavement is in poor condition, diamond grinding may be used as a short-term solution for a roughness or poor friction characteristics until a more comprehensive repair or reconstruction of the pavement can be undertaken.

The selection of a good candidate project for diamond grinding, and CPR in general, involves both engineering and economics. Construction of a CPR technique too early may not produce significant improvement. Likewise, a late stage CPR may produce significant improvement, but at a very high cost, and may not perform very well. This proper timing for CPR with diamond grinding is better known as the “window of opportunity.” The “window of opportunity” describes the time frame in a pavement’s life when CPR can be applied effectively and economically. The best method for determining if a pavement is in this time frame is by performing annual pavement condition surveys and selecting trigger and limit values for the application of each CPR technique. Trigger values indicate when a highway agency should consider diamond grinding and CPR to restore rideability. Limit values for diamond grinding define the point when the pavement has deteriorated so much that it is no longer cost effective to grind. Tables 1 and 2 provide an example of trigger and limit values for diamond grinding for different type of pavements and traffic volume levels.

Other factors should be considered when selecting a diamond grinding project. These factors may include:

- If there is evidence of severe drainage or erosion problem, normally indicated by severe faulting (> 6 mm, or ¼ in) or pumping, actions should be taken to alleviate this problem before grinding.
- The presence of progressive transverse slab cracking and corner breaks in jointed pavements indicate a structural deficiency. Slab cracking and faulting will continue after grinding, and will reduce the life of the rehabilitation project.
- Joints and transverse cracks with a load transfer of less than 60 percent should be retrofitted with dowels prior to diamond grinding (see publication FHWA-SA-97-103 for more information on load transfer restoration). An effort should be made to restrict total deflection of slabs at the joints to less than 0.8 mm ($^{1}/_{64}$-inch). Slab stabilization can be used to restrict the total deflection of slabs.
- The hardness of the aggregate and depth of cut has a direct relationship on the cost of the diamond grinding. Grinding of pavements with extremely hard aggregate (such as quartzite) takes more time and effort that projects with softer aggregate (such as limestone). Projects with harder aggregates are more expensive to diamond grind.
- Significant slab replacement and repair may be indicative of continuing progressive deterioration that grinding would not remedy.

Table 1. Trigger Values for Diamond Grinding

	JPCP			JRCP			CRCP		
Traffic Volumes*	**High**	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**
Faulting mm-avg (inches avg)	2.0 (0.08)	2.0 (0.08)	2.0 (0.08)	4.0 (0.16)	4.0 (0.16)	4.0 (0.16)	N.A.		
Skid Resistance	Minimum Local Acceptable Levels								
PSR	3.8	3.6	3.4	3.8	3.6	3.4	3.8	3.6	3.4
IRI m/km (in/mi)	1.0 (63)	1.2 (76)	1.4 (90)	1.0 (63)	1.2 (76)	1.4 (90)	1.0 (63)	1.2 (76)	1.4 (90)

*Volumes: High ADT>10,000; Med 3000<ADT<10,000; Low ADT <3,000

Table 2. Limit Values for Diamond Grinding

	JPCP			JRCP			CRCP		
Traffic Volumes*	**High**	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**
Faulting mm-avg (inches avg)	9.0 (0.35)	12.0 (0.5)	15.0 (0.6)	9.0 (0.35)	12.0 (0.5)	15.0 (0.6)	N.A.		
Skid Resistance	Minimum Local Acceptable Levels								
PSR	3.0	2.5	2.0	3.0	2.5	2.0	3.0	2.5	2.0
IRI m/km (in/mi)	2.5 (160)	3.0 (190)	3.5 (222)	2.5 (160)	3.0 (190)	3.5 (222)	2.5 (160)	3.0 (190)	3.5 (222)

*Volumes: High ADT>10,000; Med 3000<ADT<10,000; Low ADT <3,000

Equipment

Figure 3. Diamond grinding machine.

Diamond grinding equipment uses diamond saw blades that are gang mounted on a cutting head. The three most important aspects of a grinding machine are the weight of the machine, the horsepower available to the grinding head, and the grinding head itself. The front wheels of the equipment will pass over a bump or fault, which is then shaved off by the centrally mounted cutting head. The rear wheels follow in the smooth path left by the grinding head. The cutting head typically has a width ranging from 910 to 970 mm (36 to 38 inches) although newer machines have widths up to 1200 mm (47 inches). The desired corduroy texture is produced using a spacing of 164 to 194 diamond blades per meter (50 to 60 per foot) of shaft.

The three factors that a contractor must consider in selecting saw blades are:

1. Diamond concentration - diamond concentration can overshadow or disguise the effects of either bond hardness or diamond size. More diamonds make a harder grinding head and more efficient cutting.

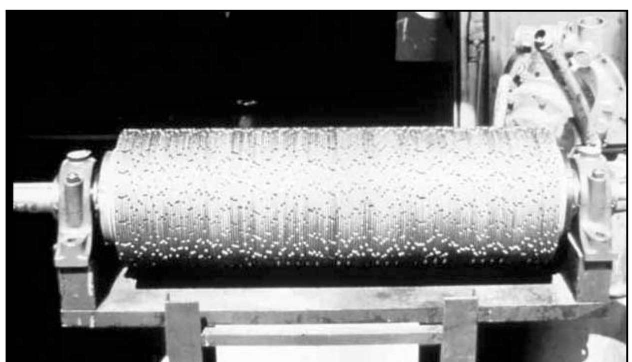


Figure 4. Cutting head of a diamond grinding machine. Note how the circular diamond blades are mounted to a shaft to form the cutting head.

2. Diamond size - diamond size can impact the life, cutting speed, and costs of the grinding head. Larger diamond particles are better for softer aggregate types, while smaller diamonds are better for harder aggregates.

3. Bond hardness - bond hardness refers to the composition of the metal matrix that holds the diamond crystals. It provides supports (bond strength) to each diamond in a cutting segment on the blade edge. However, support to the diamonds must be such that the metal matrix wears at a particular rate. The bond hardness determines the rate that support to the diamond particle is lost, as the diamond becomes dull or worn to the point that it is no longer of value. Therefore, bond hardness has a direct impact on the cutting speed and life of a grinding head. It is important to match the proper bond hardness to the aggregate being ground in order to maintain maximum cutting efficiency.

Figure 5. Final "corduroy" texture produced by diamond grinding.

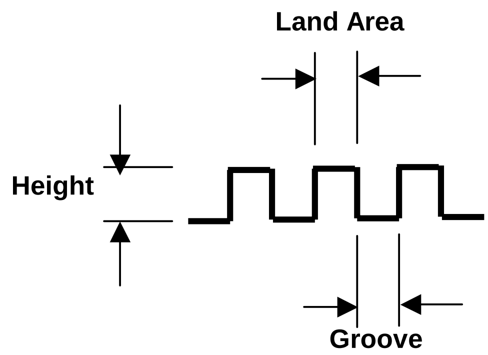
The texture and friction developed by diamond ground surfaces varies with the blade spacing on the grinding head. Proper spacing of the blades may improve the friction and extend the service life of the new surface. In pavement with soft aggregate, the blades can be spaced further apart. A harder aggregate may require tighter spacing. Figure 7 shows the grinding texture and gives recommended dimensions for hard and soft aggregates.

Figure 6. Diamond grinding equipment making multiple passes to grind a full lane width.

CONSTRUCTION

Traffic Control

Diamond grinding operations do not require shutting down adjacent traffic lanes. Traffic can be maintained on adjacent lanes with no detrimental effects. A contractor can sequence grinding and CPR work to enable the pavement to be fully opened for rush hour traffic. However, an approved traffic control plan is essential for the maximum protection of the traveling public and the construction crew. Several machines working together allow a lane to be completed in one pass. This improves productivity for large projects. On small projects, contractors normally use only one machine and several passes are made to complete a lane grinding. The maximum overlap between passes should be 50 mm (2 inches).



	Range of Values mm (in)	Hard Aggregate mm (in)	Soft Aggregate mm (in)
Grooves	2.0 – 4.0 (0.08-0.16)	2.5 – 4.0 (0.1-0.16)	2.5 – 4.0 (0.1-0.16)
Land Area	1.5 – 3.5 (0.06-0.14)	2.0 (0.08)	2.5 (0.1)
Height	1.5 (0.06)	1.5 (0.06)	1.5 (0.06)
No. Grooves per meter	164 – 194 (50-60)	174 – 194 (53-60)	164 – 177 (50-54)

Figure 7. Typical grinding texture for different aggregates.

Field Operations

The diamond grinding operation should begin after all repairs, including slab stabilization, patching, and joint and drainage repairs have been completed. Grinding should be performed continuously along a traffic lane for best results. Diamond grinding should begin and end at lines normal to the pavement centerline. Grinding is always longitudinal (parallel to lanes). The best direction for performing the grinding depends on sequencing operations and work zone limitations. The contractor must select the grinding direction in conjunction with the State engineer. The direction of diamond grinding will not influence the smoothness of the resulting profile, the resulting texture or effect on joints. Grinding should be performed across the entire lane surface to achieve the highest degree of ride quality, uniform skid resistance, and uniform appearance. Spot grinding is not recommended.

Grinding specifications may allow for some isolated low areas that were built into the concrete pavement during construction. Isolated low spots that measured less than 0.2 m^2 (2.4 sy) need not be textured.

The grinding equipment uses water to cool the cutting head. The slurry or residue resulting form the grinding operations should be continuously removed from the pavement. All modern diamond grinding equipment contain on-board wet vacuums to perform the removal function. The slurry should not be allowed to flow across lanes occupied by the traffic or to flow into gutters or other drainage facilities. However, in rural areas, the slurry, a non-hazardous material as defined by the Environmental Protection Agency, may be deposited directly onto adjacent slopes.

Figure 8. Diamond grinding convoy including grinder, vacuum to pick-up slurry residue and water tank for cooling the blades.

Figure 9. Slurry residue of diamond grinding being discharged to the embankment in a rural area.

After the pavement surface has been diamond ground, the only construction operation remaining is resealing the joints and sealing cracks as directed in the project specifications. A set of generic construction specifications for diamond grinding are included in the Appendix.

PERFORMANCE AND COST

Performance of Diamond Ground Pavements

A recent study of diamond grinding has shown excellent performance of diamond ground surfaces (Rao, Yu, Darter). Survival analysis conducted to quantify the effectiveness of diamond grinding in extending the service life of concrete pavement showed that the probability that diamond-ground pavements will have to be overlaid or reconstructed before the pavement reaches 30 years of age is less than 15 percent. One possible explanation for the extension in service life of a diamond ground pavement is the reduction in dynamic or impact loads on the pavement, as well as other CPR techniques being applied at the proper time. Dynamic loading is created when trucks travel across bumps and dips and bounce vertically on their suspension system. Dynamic loads are greater than the static load from the weight of the vehicle. This increases stresses in the pavement materials and consequently may decrease the pavement life. By providing a smooth surface, diamond grinding limits the dynamic loading, therefore extending the useful pavement life. However, as mentioned above, a complete CPR strategy that addresses structural and fuctional defects (including diamond grinding) is the best approach to extending the service life of a pavement cost-effectively.

The same study shows that the probability of a diamond ground surface will last at least 8 years before requiring another rehabilitation is 98 percent. Therefore, based on the study, a diamond ground surface may be expected to last at least 8 to 10 years.

After the initial performance period, a diamond ground surface may be reground to re-achieve acceptable levels of ride and surface texture. Fatigue analysis results show that a typical concrete pavement may be ground up to three times without compromising its fatigue life.

Diamond grinding results in a significant increase in surface macrotexture and corresponding improvement in friction. The improvements in skid resistance immediately after grinding may be dramatic. However, the improvement may be temporary, particularly if the pavement contains aggregate that is succeptible to polishing. An initial decrease in skid resistance during the first few years after grinding is normally leveled out at adequate macrotexture levels that are maintained for many years. Climate and age may be the most significant factors in the rate of reduction of macrotexture on a diamond-ground surface. Wet-freeze areas exhibit larger decreases in macrotexture than dry-non-freeze areas. The sand patch test should be used to determine the macrotexture characteristics of a diamond ground concrete surface.

Cost of Diamond Grinding

Diamond Grinding is a cost-effective treatment, wheter used alone or as part of an overall CPR program. Diamond grinding costs on average between \$2.00 and \$8.00 per square meter (\$1.70 and \$6.70 per sy). However, the cost may be higher (up to \$12/m^2 or \$10/sy) when concrete contains very hard river gravel. The cost depends on many factors including aggregate and PCC mix properties, average depth of removal, and smoothness requirements. The cost of diamond grinding has dropped in the last few years. Increased competition and better diamond blade performance may help lower prices even more the future. State DOT’s have found that the cost of diamond grinding is generally lower than the cost of an asphalt concrete overlay. Much of the cost savings can be attributed to the fact that diamond grinding can be applied only to lanes that need the corrective treatment.

Cost-effectiveness makes diamond grinding an important and appealing alternative for many concrete rehabilitation projects. Diamond grinding should also be part of any preventive maintenance program for concrete pavements.

ACKNOWLEDGEMENT

This document would not have been possible without the assistance and cooperation of the FHWA's Office of Pavement Technology and the Southern Resource Center. Part of the information used in preparing this document was collected as part of the FHWA's Special Project 205, Quality Concrete Pavement Rehabilitation.

Special thanks to Roger Larson, Keith Herbold, Gregg Schiess, and Phil Arena from FHWA for their review and comments. Wouter Gulden and John Roberts from the American Concrete Pavement Association also provided helpful information and comments on this document.

The contents of this document reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented.

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APPENDIX

Generic Guide Specifications

DIAMOND GRINDING

Description

This specification covers diamond grinding of Portland cement concrete pavement to eliminate joint faulting, and restore proper drainage and ride quality. This work shall be accomplished in accordance with these specifications, the details shown on the plans, and as directed by the engineer.

Equipment

The grinding equipment shall use diamond tipped saw blades mounted on a power driven, self-propelled machine that is specifically designed to smooth and texture PCC pavement. The equipment shall grind the pavement to the specified texture and smoothness tolerances. The equipment shall not damage the underlying surface of the pavement, cause excessive ravels, aggregate fractures, spalls, or otherwise disturb the transverse or longitudinal joint

Construction

The plans will designate areas of pavement surfaces to be ground. Grinding of roadway shoulders and bridge decks will not be required unless indicated on the plans, or is directed by the engineer. Grinding shall be performed in a longitudinal direction and shall begin and end at lines normal to the pavement centerline in any ground section. However, this is not required at the end of each work shift.

The grinding shall produce a uniform finished surface, eliminate joint or crack faults, and provide positive lateral surface drainage. Auxiliary or ramp lane grinding shall transition as required from the mainline edge to maintain or provide positive lateral drainage and an acceptable riding surface.

Grinding will provide a positive lateral drainage by maintaining a constant cross slope across each lane. The entire area designated on the plans shall be textured and surfaces on both sides of the transverse joints or cracks shall be in essentially the same plan, in accordance with smoothness specifications. A 1 by 30-meter (3-foot x 100-foot) test area shall require 95% coverage. However, extra depth grinding to eliminate minor depressions is not required.

The slurry or residue resulting from the grinding operations shall be continuously removed from the pavement. The slurry shall not be allowed to flow across lanes occupied by traffic or to flow into gutters or other drainage facilities. However, in rural areas it may be deposited directly onto adjacent slopes.

Final Surface Finish

The ground pavement surface shall be uniform in appearance with longitudinal corduroy type texture. The grooves shall be between 2 and 4 mm (0.10 and 0.15 inches) wide. The land area between the grooves shall be between 1.5 and 3.5 mm (0.065 and 0.125 inches). The peak of the ridges shall be approximately 1.5 mm (1/16 inch) higher than the bottom of the grooves. Adjusting the blade spacing may be necessary to achieve the specified texture.

The ground pavement shall meet a surface tolerance at least as stringent as the specifying agency's surface tolerance for new pavement. The pavement surface shall be measured for riding quality using a multiple wheel profilograph or a profiler. If a profilograph is used, the pavement is to be evaluated in 1.6 km (0.1 mile) sections. When using a profilograph, the profile index shall not exceed 40 inches per mile for a **0.0** blanking band. A unit price adjustment may be used for a profile index of 40 to 50 inches per mile in lieu of re-grinding to meet the 40 inches per mile criterion. No payment will be made for a profile index in excess of 50 inches per mile. The profiler tolerance will be the same as the agency's surface tolerance for new pavement.

A straight-edge requirement may be used to control bumps and/or rides in the pavement surface. Grinding along the inside edge of existing pavement shall conform to the highway agency's straight-edge requirement. Straight-edge requirements do not apply across longitudinal joints or outside the ground areas. The transverse slope of the pavement shall be uniform to a degree that there shall be no depressions or misalignment of slope greater than 1/8 inch between passes of the cutting head when tested by stringline or straight-edge placed perpendicular to the centerline. Transverse joints and random cracks shall be visually inspected to insure that adjacent surfaces are in the same plane. Misalignment of the planes of these surfaces shall not exceed 1.5 mm per meter (1/16 inch in 3 feet).

Traffic Control

The contractor shall provide all traffic control devices necessary for maximum protection of the traveling public and construction work area with only a minimum of interference. Unless otherwise specified, the contractor shall prepare and submit in advance, a written traffic control plan in accordance with Part VI of the Manual of Uniform Traffic Control Devices current edition, for review and approval by the engineer.(10)

Measurement

Pavement grinding shall be measured by the square meter (square yard), ground to any depth. The quantity of work is determined by multiplying the width by the length of ground areas.

Payment

Pavement grinding will be paid for at the contract price per square yard. Payment is full compensation for furnishing all labor, materials, supplies, tools, equipment, any incidental work, and for doing all work involved in grinding and texturing the pavement and shoulders and cleaning the pavement.

Traffic control will be paid for under the separate pay items for the project. Traffic control will include all devices and requirements as stated in the traffic control section.