FLEXIBLE PAVEMENT REHABILITATION USING PULVERIZATION

California Department of Transportation
Division of Maintenance Pavement Program
Office of Concrete Pavement and Foundations

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DISCLAIMER

This manual presents an overview of flexible pavement rehabilitation using pulverization. This manual is intended as guidance and is not a substitute for good engineering judgment. **This manual is intended for the use of Caltrans personnel. Engineers and agencies outside of Caltrans may use this manual at their own discretion. Caltrans is not responsible for any work performed by non-Caltrans personnel using this manual.**

GLOSSARY

Alligator Cracking — Also referred to as fatigue cracking. Load related distress caused by inadequate structural support. Rated as 'A', 'B', or 'C'. Alligator 'A' cracking is a single longitudinal crack in a wheel path. Alligator 'B' cracking is a series of interconnecting or interlaced cracks forming small polygons in a wheel path. Alligator 'C' cracking is a pattern of interconnected or interlaced cracks outside the wheel paths.[6]

Dynaflect — Trailer mounted pavement deflection measuring device. Uses a 1,000 pound oscillating load application. Not in widespread use within Caltrans.

Dynamic Cone Penetrometer (DCP) — The standard DCP is a hand-held device featuring a 17.6 pound hammer which is raised and dropped from a height of 22.6 inches along a steel rod. The impact of the hammer drives a 60° conical tip into a layer of granular or fine-grained material. The associated depth of penetration is plotted against the number of blows, indicating the layer thickness and shear strength of the material.

Falling Weight Deflectometer (FWD) — Pavement deflection measuring device. Applies a specified impulse load (Caltrans typically uses 9,000 pounds) to the pavement surface. May be mounted on a trailer or truck.

Gravel Equivalent (GE) — The thickness of gravel (or aggregate subbase) required to prevent deformation in the underlying layer from a traffic load.

Gravel Factor (G_f) — The relative strength of a material compared to gravel.

Hot Mix Asphalt (HMA) — Formerly known as "asphalt concrete" or "AC." A material used for flexible pavement consisting of dense-graded aggregate mixed with asphalt binder.

Pavement Structure — Formerly known as "structural section." Consists of the layers above the subgrade that support traffic loads.

Pulverization — Mechanized process that transforms the existing flexible pavement surface layer and a portion of the underlying granular base material layer into a uniform granular material suitable for use as a base layer.

Open-Graded Friction Course (OGFC) — Formerly known as open-graded asphalt concrete (OGAC). OGFC is a free draining HMA mixture with few fine-sized aggregate particles. Typically placed as a thin surface wearing course. For design purposes, OGFC is not considered to make a structural contribution to the pavement structure.

Resistance Value (R-value) — A measure of resistance to deformation under loading of saturated soil.

Rubberized Hot Mix Asphalt (RHMA) — Formerly known as rubberized asphalt concrete (RAC). Material produced for hot mix applications by mixing asphalt rubber binder (a combination of asphalt binder and crumb rubber modifier) with graded aggregate. The most commonly used gradations are gap-graded (RHMA-G) and open-graded (RHMA-O). For added durability, rubberized open-graded with a higher binder content (RHMA-O-HB) can be used.

Stress Absorbing Membrane Interlayer (SAMI) — The two types used by Caltrans are geosynthetic fabric (SAMI-F) and rubberized (SAMI-R), which is an application of asphalt rubber binder and coated aggregate screenings. SAMI-F is also currently referred to as geosynthetic pavement interlayer (GPI) and was formerly known as pavement reinforcing fabric (PRF).

GLOSSARY

Traffic Index (TI) — The Traffic Index (TI) is a measure of the number of 18 kip Equivalent Single Axle Loads (ESALs) expected in the traffic lane over the pavement design life of the facility. The TI does not vary linearly with ESALs and is determined to the nearest 0.5.

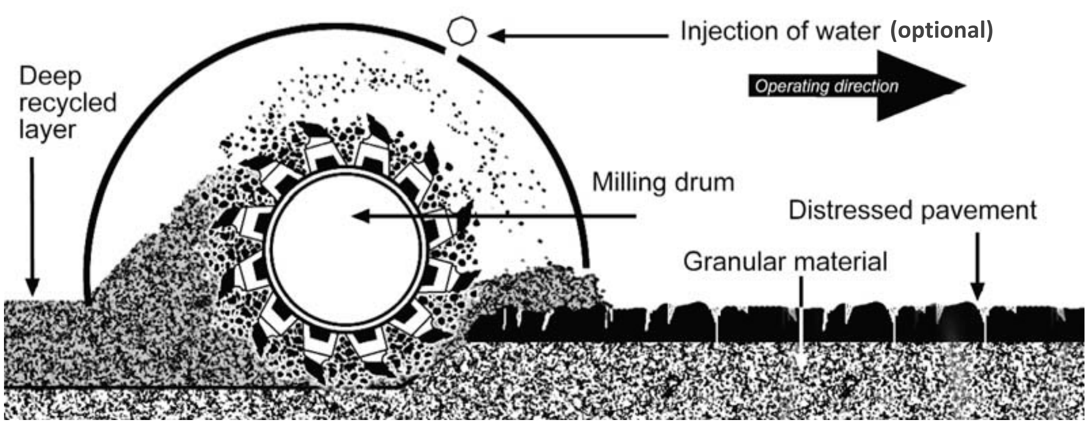
1.0 DESCRIPTION

Pulverization is a roadway rehabilitation strategy that involves in-place recycling of the entire existing flexible pavement layer and some of the existing underlying granular base material (Figure 1). The pulverization process transforms an existing distressed flexible pavement into base for a new flexible pavement structure. Pavement pulverization provides an alternative to conventional rehabilitation methods and can be an economical method of conserving and reusing existing pavement materials.

In its simplest application, the flexible pavement layer is pulverized and mixed with at least 1 inch of underlying granular base material and water in one operation to produce a uniformly blended, well-graded granular base material. The physical properties of the pulverized base material (PAB) are comparable to those of new Class 2 aggregate base (AB). Designers can take advantage of PAB's flexibility to reshape cross slopes and profiles, or simply "match existing" configurations (although grade control for construction is preferable). The finished PAB surface can be used by traffic during construction, supplementary aggregate can be added to increase the volume, and low percentages of cement can be mixed in to provide additional strength.

Pulverization equipment can mix a depth in excess of 12 inches in one pass although achieving compaction and homogeneous mixtures can become an issue at these depths. Depending on a variety of factors, the pulverization equipment may need multiple passes to be effective. The specifications will not determine the methods for the Contractor's operations; however, a test strip is required to prove the Contractor's methods can construct PAB in compliance with the specifications. If depths in excess of 12 inches are designed, Construction should be alerted to pay particular attention to the test strip to ensure homogeneity and compaction can be achieved.

When PAB is used by traffic before paving, a coat of diluted asphaltic emulsion and sand cover are applied after the PAB is shaped and compacted. This protects the surface from raveling and, if cement is used, acts as a curing treatment. The surface is then swept with a power broom and prepared for traffic. Finished PAB surfaces should be covered with at least a 0.15-foot surface course layer (HMA) within an appropriate number of days depending on the length of the project and traffic conditions, ideally not more than 3 days. Before placing the HMA, the surface must be prepared by repairing any uneven or unstable areas, sweeping with a power broom, and applying additional asphaltic emulsion.



Note: depending on the in-situ moisture content, water may be injected in the mixing drum during pulverization.

Figure 1. Inside the Pulverizer

In general, the pulverized roadbed process consists of:

1) Pulverization of the roadway (Figure 2).
2) Shaping the roadbed, if a change is required
3) Addition and mixing of aggregate or cement, if needed.
4) Initial or breakdown compaction (using a vibratory steel drum roller and sheepsfoot roller with a blade for thicknesses greater than 6 inches, Figure 3).
5) Initial grading.
6) Intermediate compaction (using vibratory steel drum roller, Figure 3).
7) Final grading.
8) Final compaction (using a pneumatic-tired or static steel drum roller).
9) Application of asphaltic emulsion and sand cover to the compacted pulverized surface.
10) Repairing and sweeping the surface to remove loose material.
11) Placement of a new flexible pavement surface layer.

The sequence depends on project variables, and the Contractor will choose the exact process. These variables include thick sections, supplementary aggregate or cement additives, profile and cross section corrections, and use by traffic before paving. As mentioned above, the specifications require a test strip to prove the Contractor's methods can produce PAB in compliance with the specifications.

Figure 2. Pulverizer

Figure 3. Steel Drum Roller and Sheepsfoot Roller (no blade)

2.0 PROJECT EVALUATION

2.1 Field Review and Pavement Investigation

Appropriate application of pulverization requires a comprehensive field review prior to design to evaluate the type, severity, and extent of the pavement distress. In-place materials may vary widely in composition, uniformity, and quality. Review and assessment of the project surroundings, pavement conditions, structural capacity, material properties, geometrics, traffic issues, constructability, and cost effectiveness should be conducted as part of the project evaluation process. The District Materials and Maintenance Engineers should be consulted during the initial project assessment. Other resources include as-built plans, the photo surveys, the Pavement Condition Survey Pavement Evaluation Manual, the biannual Pavement Condition Report (generated by the Division of Maintenance), and associated mapping available from Geographic Information Services.

Since the pulverization process involves surface grading and placement of a new flexible pavement layer, it allows for changes to existing grades. During the field review and evaluation, note any drainage problems, utility locations or conflicts, and recommendations to change profiles and cross slopes. Also, identify potential staging areas and consider potential access problems for the pulverizer with respect to any confined or miscellaneous paved areas adjacent to the traveled way (such as turnouts, maintenance pullouts, vista points, etc).

2.2 Appropriate Applications

Pulverization can treat a variety of project conditions, but is most cost effective on surfaces requiring digouts of 20% or more by paving area. Appropriate applications include:

- Structurally inadequate pavement sections, which would otherwise require a thick overlay, as indicated by:
    - Advanced pavement distress such as severe cracking (wider than ¼ inch, continuous deep reflective cracking, or Alligator 'C'—see Figure 4) or plastic deformation (shoving or rutting greater than ¾ inch, see Figure 5).
    - Significant cracking and a deflection study with 80^{th} percentile deflections greater than 0.015 inch (see Section 3.2.2).
- Rough surfaces that require smoothing of bumps and dips to improve ride quality.
- Needed longitudinal or transverse corrections to grade, cross-slope, or superelevation.
- Base deterioration due to fatigue, moisture intrusion, pumping, or other causes.

For pavement sections with rutting or cracking distress caused by localized subgrade or base failures and drainage problems, subsurface repairs should be performed prior to pulverization and must be completed before placing HMA (see Highway Design Manual Index 625.1).

Figure 4. Structurally Inadequate Pavement (severe alligator cracking and rutting distress) Suitable for Pulverization.

2.3 General Limitations

The following conditions are not suitable for pulverization:

- Pavement structures with concrete, treated base, or a geosynthetic pavement interlayer (or fabric stress absorbing membrane). Older treated bases (especially LCB and CTB) are suitable for pulverization if they can be penetrated with a dynamic cone penetrometer (DCP, see section 3.2.2).
- Roadways with material under the existing AC that contains large rocks greater than 4 inches. Large rocks damage the pulverizing equipment's grinding teeth.
- Roadways with traffic volumes sufficient to produce delays exceeding 30 minutes under one-way traffic control (typically > 20,000 ADT) and high truck traffic (> 1,000 ADT). Since pulverized surfaces are unbound, high traffic volumes prior to paving can also cause raveling. This may not be a limitation if construction occurs under a closure or detour.
- Roadways with numerous shallow utilities or drainage facilities within 6 inches of the proposed pulverization depth. Ground penetrating radar (GPR) can assist in locating underground utilities.
- Roadways with good quality base, grades, and cross slopes despite a moderately cracked pavement surface with less than 1/2-inch crack widths (only an overlay is needed).
- Urban areas where noise created by the pulverizing machine may be problematic.

If any of these conditions or various combinations exist, careful consideration should be made before selecting a pavement strategy. Mitigation may be feasible but will increase costs and could reduce the effectiveness of pulverization or other rehabilitation strategies such as overlay, mill and fill, or remove and replace. Consult with the District Materials Engineer or Division of Maintenance Pavement Program for available pavement strategy alternatives.

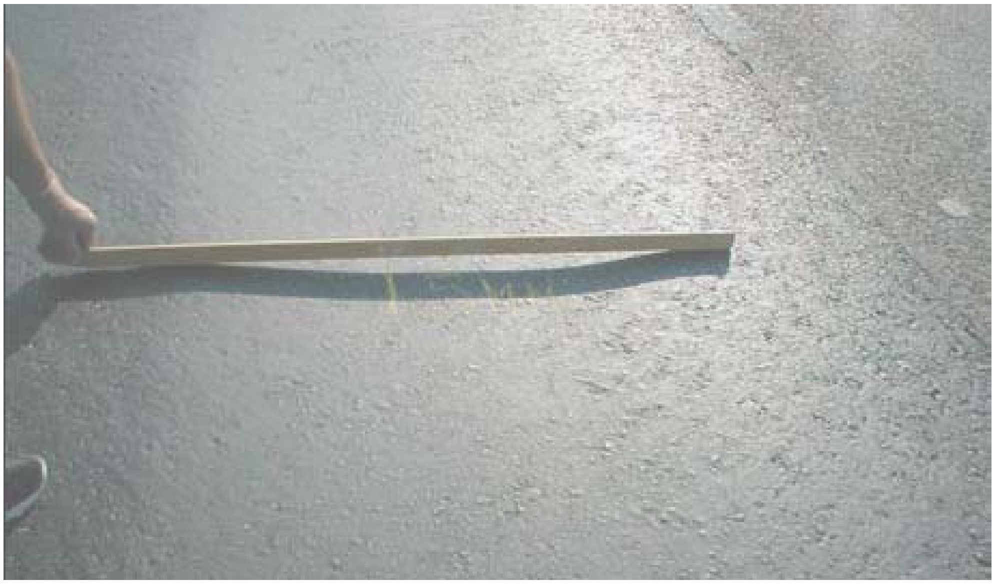


Figure 5. Pavement Surface Rutting (over ¾ inch) Suitable for Pulverization.

3.0 FIELD AND LABORATORY TESTING

3.1 Field Sampling

During the field review and pavement investigation, representative samples of existing pavement surface, base, and subgrade material are extracted from the pavement structure to assess the material properties, composition, layer thicknesses, and condition. Typically, approximately 110 pounds total of homogeneous, crushed flexible pavement and underlying granular material are required for laboratory testing. If material is variable throughout the project limits, enough material should be obtained from each representative section to provide homogeneous samples for desired testing (see Section 3.3).

The material samples can be extracted from the existing pavement by means of coring (Figure 6a) or digging test pits (Figure 7a) throughout the project limits. Depending on the length of the project and variability of existing materials, the sampling frequency will vary between 1000 to 1700 feet. Shorter projects or pavement structures with variable conditions will have more frequent sampling than longer projects or uniform pavement structures. Cores are expedient when many samples are needed, but are limited because underlying granular material cannot be readily extracted, as with test pits.

Table 1: Sampling

Project Length	Pavement Structure[1]	Core Sampling Frequency	Test Pit Sampling Frequency	Minimum Project Sampling Requirements
< 3 miles	Variable[2] or Uniform	1000 ft (5 per mile)	1 for each variable pavement structure or unexpected site conditions or 2 minimum	110 lbs homogeneous material for each variable pavement structure
> 3 miles	Variable[2]	1000 ft (5 per mile) or as needed to define variable area	1 for each variable pavement structure or unexpected site conditions or 2 minimum	110 lbs homogeneous material for each variable pavement structure
	Uniform	1700 ft (3 per mile)		

[1]Pavement structure criteria include distress, layer materials, and layer thickness.
[2]Variable pavement structures exhibit changes in distress severity, layer materials, or layer thickness (30% or more).

3.1.1 Coring

Core samples are typically 4 inches in diameter (Figure 6b). The entire depth of a core sample should be examined in order to analyze different pavement layers, interlayers (SAMI-F or SAMI-R), or specialty mixes (OGFC, RHMA, etc.). After analysis of the core samples is complete, they are crushed to produce a sample laboratory gradation similar to the actual gradation of the pulverized material that will be produced in the field during construction. Where granular base or subgrade material is needed, or in areas of severe cracking or rutting distress, core borings may be clustered together to facilitate sampling of granular material (Figure 6c).

Figure 6a. Coring Operation

Figure 6b. Core (4 Inch Diameter)

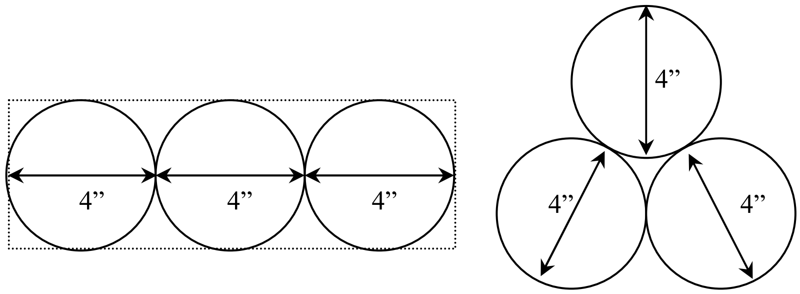


Figure 6c. Examples of Clustered Coring Patterns

3.1.2 Test Pits

A test pit is dug by cutting at least 1 ft^2 of existing pavement and excavating the underlying material. The excavation should be at least as deep as the anticipated pulverization depth (see Section 4.3) and may go deeper if the underlying material is inconsistent or subgrade samples are needed. Larger and more representative sample materials can be obtained from pits relative to cores since all layers of the pavement structure can be examined (Figure 7a) and extracted, but are potentially more disruptive to traffic as they take longer to complete and are more destructive to the existing roadway than cores. Each project should have at least two representative pits. Additionally, test pit samples should be obtained wherever pavement structure materials change unexpectedly from information shown in as-built plans or other records.

Figure 7a. Test Pit

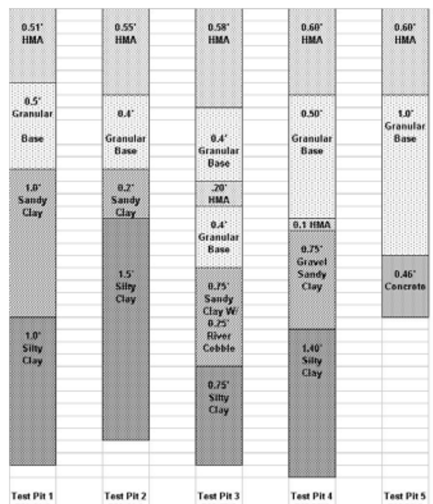


Figure 7b. Example Test Pit Profile

3.2 Field Testing

In conjunction with the field review, pavement investigation, and sampling needs for pulverization, several field test options are available to characterize the existing pavement structure.

3.2.1 Pavement Structure Layer Identification

Ground Penetrating Radar (GPR), used in conjunction with coring and test pits, is a non-destructive alternative to identify existing pavement structure layer thicknesses. The radar system uses reflected pulses of electromagnetic waves to identify changes in material properties and provide a profile of each pavement structure layer.

Although coring is still required to correlate GPR data, the number of cores for medium length and longer projects can be significantly reduced. GPR is also applicable to projects with limited, outdated, or poor historical as-built data, or projects with highly variable pavement structures. To use GPR on a Caltrans project, contact the Office of Roadway Materials Testing in the Division of Materials Engineering and Testing Services (METS).

3.2.2 Pavement Structure Capacity

Two useful methods in assessing the structural capacity of layers within the existing pavement structure are deflection measurement and dynamic cone penetrometer testing.

Falling Weight Deflectometer (FWD)

California Test 356 is used to determine overlay requirements from pavement deflection measurements. To obtain deflection measurements for subgrade analysis during pulverization site investigation, follow CT 356, Method A with the following modifications:

- Testing should ideally be carried out at the end of the rainy season, when subgrade moisture is likely to be highest.
- The lane with the worst existing pavement condition should be tested unless each lane is designed separately, in which case both lanes should be tested.
- Use core thicknesses to determine the pavement structure profile and conduct DCP analysis (see below).
- Use a calibrated FWD unit capable of applying impact loads of 9,000 lb on a standard 12 inch diameter plate and measuring pavement deflection at a distance of 24 ± 1.0 inch from the plate center.
- Conduct tests between the wheelpaths to minimize the effects of severe wheelpath cracking on the seating of the FWD load and sensors.
- Use a test interval of approximately 200 ft to obtain 21 deflection measurements per lane-mi. Testing productivity will be approximately 2.0 lane-mi/hr. Longer test intervals can be adopted if there are constraints such as traffic or limited closure schedules; however, this increases the risk of missing weaker sections. Areas of interest identified during the pavement evaluation should be tested in addition to measurements at the regular interval.
- Analyze FWD test results according to the procedures in Appendix D. Assess all areas with FWD determined subgrade stiffness less than 6500 psi or R-value < 20. Likely reasons for low strength should be identified (e.g., drainage problems, subgrade materials, etc.).

Dynamic Cone Penetrometer (DCP)

Use a standard DCP with 60° cone and a 1,500 ft test interval for DCP measurements. DCP testing should coincide with the removal of cores, discussed in Section 3.1.1. In areas of suspected high variability in underlying materials, such as cut and fill transitions, changes in moisture condition, soil or vegetation type, or failed or repaired areas, more frequent measurements (every 300 to 500 ft) should be taken to better understand the pavement structure and layer thicknesses. DCP measurements can be taken inside the core hole, although care must be taken when interpreting the results as water used to cool the core bit will soften the upper layer of material under the surfacing, giving an unrealistically low shear strength for the upper layer. Measure the penetration after every five blows up to a depth of 800 mm (31.5 in.). Analyze DCP results according to the procedures in Appendix E.[2]

3.3 Laboratory Testing

After field samples of existing flexible pavement are crushed to simulate pulverization and proportionally combined with base material, laboratory tests need to be performed to characterize the pulverized material to determine the viability of pulverization as a project strategy. The laboratory tests determine the gradation, R-value, moisture-density relationship, and the type and amount of additives (if necessary) of the material sampled in the field. The laboratory tests are only a preliminary assessment of pulverized material characteristics for pavement structure design since project field conditions are variable. Field adjustments will be necessary during construction as indicated by changes to site conditions or quality control (QC) and quality assurance (QA) test results.

3.3.1 Sieve Analysis (CT 202) and Plasticity Index (CT 204)

Mechanical sieving needs to be conducted according to CT 202 to determine the gradation of material sampled in the field and prepare samples for CT 216 and CT 301. The anticipated design pulverization depth is crucial to establishing a reasonable laboratory approximation of the constructed pulverized pavement material gradation. The ratio of reclaimed asphalt pavement (RAP) to base is an indicator of pulverized material properties and should be above 60:40 (see Section 4.3). The gradation, together with the plasticity index (CT 204), is also used to indicate the need for additives (see Section 3.3.3). If the existing pavement structure has a base layer, subgrade plasticity is less critical than for non-engineered sections where native material is underlying the existing AC surface layer and will be blended into the pulverized material. For more information on pulverized material gradation, refer to Section 5.3.

3.3.2 California R-Value (CT 301)

California Test 301 can be conducted to indicate the structural quality of the material sampled in the field. The R-value is a measure of the deformation resistance of a material as a function of the ratio of transmitted lateral pressure to applied vertical pressure. With quality subgrade, proper design, and good gradation, pulverized material generally meets the minimum R-value of 78 for Class 2 AB and R-value testing during construction is not necessary. R-value testing of existing base and subgrade material may be necessary during preliminary design depending on the design of the pulverized pavement structure, the availability of as-built information, and the quality of the subgrade.

If historical subgrade R-value information based on actual test data does not exist for the project, samples of subgrade material should be obtained from test pits and tested. Sampling should take into account potential variability of native material R-values based on geologic, geographic, topographic, and hydrologic changes throughout the project limits. Deflection studies can also indicate subsurface variation through unusually high or low deflection values. For projects with uniform conditions, one R-value test per mile is generally adequate for material characterization. R-value changes of 20 or more are considered significant and should be accounted for in pulverized pavement structure design. For weak subgrade or in areas where subsurface moisture is a concern, cement should be added to the pulverized mixture to increase strength (see Section 3.3.3).

If a granular base layer is present in the existing pavement structure, samples of base must be tested for R-value to determine strengths for the new pulverized pavement structure design (see Figure 10). For more information on R-value, refer to HDM Index 614.3.

3.3.3 Additives

Cement

To improve strength and quality, cement can be added at a rate from 1 to 2.0% by dry weight of pulverized material. However, consideration should be given to the following:

1. Cost. Currently, strength gained from the application of cement at most raises the gravel factor by 0.1 for the pulverized roadbed layer, so there may not be direct savings from the cement. Also, even if traffic will not use the PAB before paving, an application of asphaltic emulsion will be necessary for curing.
2. Time constraints. If cement is used as an additive, mixing must occur within 30 minutes of application and all grading and compaction must be completed within 4 hours. Consideration should be given for the specified 24 hours curing time without equipment or traffic loading.
3. Repair. Untreated pulverized roadbed can be more easily repaired for deficiencies such as raveling, segregation, elevation, or smoothness. With cement, repair work will detrimentally affect the cementitious bond.
4. Quality control. Close monitoring of the pulverized material's moisture content must occur to ensure proper hydration of the cement.

While some laboratory research has indicated this relatively small amount of cement will improve pulverized material strength properties,[3] using higher amounts can cause brittleness and shrinkage cracking. This guide does not recommend adding more than 1 to 2% cement by dry weight.

Lime and Other Additives

The above notwithstanding, lime or other additives may be effective if strength is weak, or subsurface moisture is a concern. There are numerous methods for determining the need and type of additives based on pulverized material characteristics such as gradation, plasticity, and soil classification. If an additive other than cement is contemplated, consult with the Office of Rigid Pavements and Pavement Foundations.

If the material characterization indicates a poorly graded or plastic material, supplementary aggregate or a fine material such as crusher dust may be added to improve the pulverized material characteristics. More commonly, supplementary aggregate may be needed to provide additional material for shoulder widening or profile or cross slope corrections. Supplementary aggregate should comply with the aggregate quality of Cl 2 AB, but a specific gradation may not be necessary.

3.3.4 Relative Compaction (CT 231 and 216)

During construction, the relative compaction of the pulverized material layer will be determined according to CT 231 and CT 216. In order to obtain the wet test maximum density and establish the optimum moisture content, compaction tests are first conducted during the laboratory testing to determine the moisture-density relationship of the pulverized material. A minimum of 45 pounds of homogeneous material is needed for CT 216.

4.0 DESIGN OF PULVERIZED PAVEMENT STRUCTURES

The design of the flexible pavement structure follows pavement investigation, field-testing, and laboratory testing. Although pulverization is a process for rehabilitation of an existing road, the design process is similar to that for a new pavement since the pavement structure is being reconstructed from the base up, with the pulverized materials forming a new base for the new flexible pavement layer. For design purposes, material below the pulverization depth can be considered subgrade, aggregate subbase, or aggregate base depending on test R-values (see Figure 10). Topic 633 of the HDM describes the engineering procedures for new design of flexible pavement structures based on gravel equivalent (GE) and gravel factor (G_f), and Appendix 'B' provides an example pulverized pavement structure design.

4.1 Design Life

The expected design life of the pavement structure is related to the pulverization depth and the type and thickness of the new flexible surface layer. Pulverization projects should be designed with a minimum pavement design life of 20 years, unless a life cycle cost analysis indicates a 40-year pavement design life is more cost effective. See Highway Design Manual, Index 612.5.

4.2 Traffic Index (TI)

Pavement design requires knowledge of anticipated traffic volumes and loading, which dictate the pavement structure requirements. Gather available traffic information and see HDM Topic 613 for procedures to determine the traffic index for the design life or contact the district traffic forecasting office.

4.3 Pulverization Depth and Gravel Factor (G_f)

Depth and material consistency can be achieved when pulverization takes place in a continuous manner. The pulverization depth should be at least 1 inch more than the thickness of the existing flexible surface layer. The pulverizer milling teeth (Figure 8) must extend into the existing base to prevent excessive wear and maintain productivity. Pulverization depth may be increased further into the existing base to provide additional GE, resulting in a thinner flexible pavement layer and reduced material costs. The pulverizer should be able to process a minimum depth of 12 inches. If the pulverization depth or the grade correction exceeds 12 inches, the pulverized material should be collected, placed on the side of the roadway in a windrow, and spread and compacted in two lifts due to the difficulty of compacting deep layers.

Any profile or cross slope corrections to the base layer need to account for the minimum design depth of the pulverized layer. If the pulverizer is set at even depth to match the existing cross slope of the roadway surface, the processed pulverization depth must exceed the minimum design pulverization depth (see Figure 9). Depending on the project parameters, it may be necessary to cold plane the pavement surface prior to pulverization to attain the minimum pulverization depth, although lowering the RAP ratio can weaken the pulverized material.

Research conducted by the University of California Pavement Research Center indicates that pulverized material with a high percentage of RAP has similar characteristics (shear strength, stiffness, and rutting resistance) to Class 2 AB.[6] The pulverized material (PAB) is stronger if it consists primarily of RAP as opposed to underlying granular material, but the pulverized layer must be designed thick enough to provide the required GE and form a stable base for the new flexible pavement layer.

The pulverization depth is critical to determining the G_f of the pulverized material. If the design pulverization depth results in pulverized material with at least 60% RAP or the material is treated with cement additive, use a G_f of 1.2. If the pulverization depth extends deeper into the existing granular base, PAB is assumed to be equivalent to Class 2 AB (G_f = 1.1). Table 2 provides the range of pulverized material GE's, based on design pulverization depths (with G_f = 1.2, except as noted):

Table 2: Pulverized Material (PAB) Layer Design

Base Portion (ft)	0.10		0.15		0.20		0.25		0.30		0.35		0.40	
RAP Portion: Exist AC Thick (ft)	Min. Design Pulv Depth (ft)	GE_{PAB} (ft)	Design Pulv Depth (ft)	GE_{PAB} (ft)	Design Pulv Depth (ft)	GE_{PAB} (ft)	Design Pulv Depth (ft)	GE_{PAB} (ft)	Design Pulv Depth (ft)	GE_{PAB} (ft)	Design Pulv Depth (ft)	GE_{PAB} (ft)	Design Pulv Depth (ft)	GE_{PAB} (ft)
0.30	0.40	0.48	0.45	0.54	0.50	0.60	0.55	0.66[b]	0.60	0.66[b]	0.65	0.72[b]	0.70	0.77[b]
0.35	0.45	0.54	0.50	0.60	0.55	0.66	0.60	0.72[b]	0.65	0.72[b]	0.70	0.77[b]	0.75	0.83[b]
0.40	0.50	0.60	0.55	0.66	0.60	0.72	0.65	0.78	0.70	0.77[b]	0.75	0.83[b]	0.80	0.88[b]
0.45	0.55	0.66	0.60	0.72	0.65	0.78	0.70	0.84	0.75	0.90	0.80	0.88[b]	0.85	0.94[b]
0.50	0.60	0.72	0.65	0.78	0.70	0.84	0.75	0.90	0.80	0.96	0.85	0.94[b]	----	----
0.55	0.65	0.78	0.70	0.84	0.75	0.90	0.80	0.96	0.85	1.02	----	----	----	----
0.60	0.70	0.84	0.75	0.90	0.80	0.96	0.85	1.02	----	----	----	----	----	----
0.65	0.75	0.90	0.80	0.96	0.85	1.02	----	----	----	----	----	----	----	----
0.70	0.80	0.96	0.85	1.02	----	----	----	----	----	----	----	----	----	----
0.75	0.85	1.02	----	----	----	----	----	----	----	----	----	----	----	----

[a]$G_{f\ PAB}$ = 1.2 for PAB with RAP $\geq$ 60%
[b]$G_{f\ PAB}$ = 1.1 for PAB with RAP < 60%

Figure 8. Pulverizer Milling Teeth

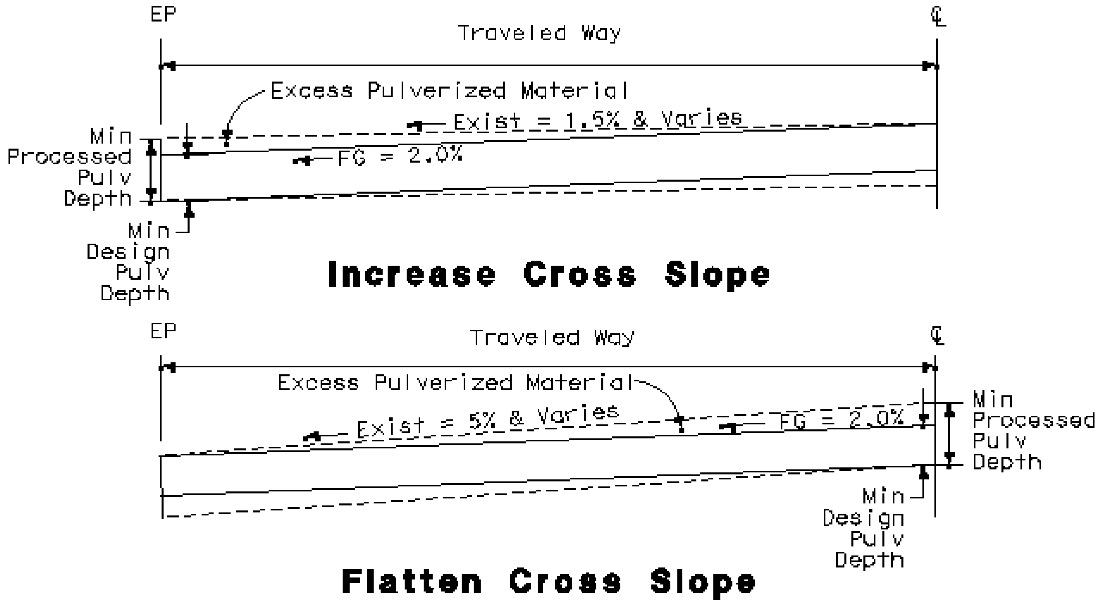


Figure 9. Slope Corrections and Minimum Design Pulverization Depth

As an alternative, minor profile or cross slope corrections can be made during placement of the flexible pavement layer, although this process may be less cost effective due to increased HMA quantities.

Figure 10 shows the pulverized pavement structure design process:

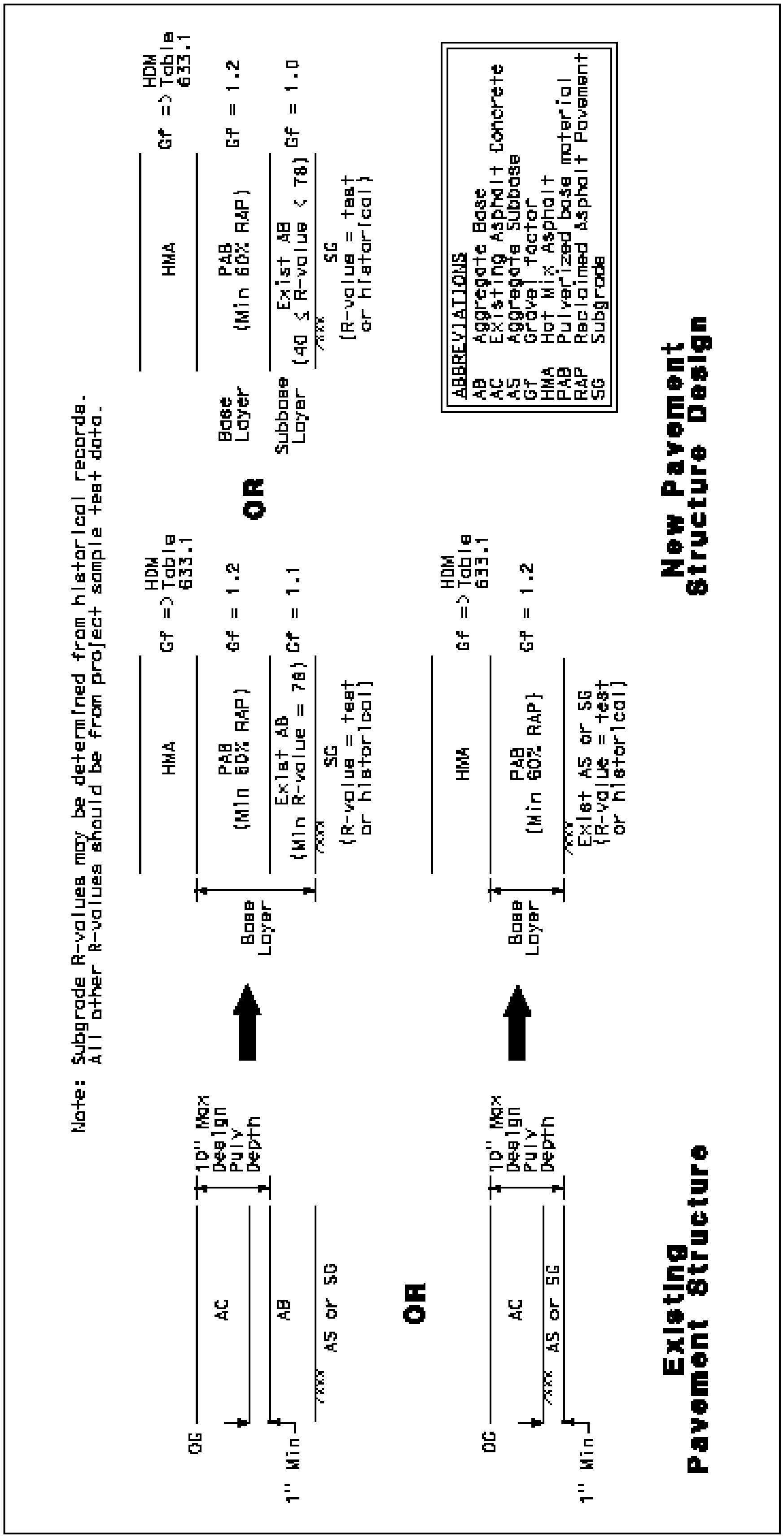


Figure 10. Pulverized Pavement Structure Design

5.0 SPECIAL CONSIDERATIONS

5.1 Volumetric Change

The pulverization process alters gradation and lowers the density of existing roadway material as it is transformed into compacted pulverized material. Even without adding new material, compacted pulverized material typically swells from 5 to 10% relative to the original material. Excess pulverized material may be used for a thicker base layer, corrections to profile and cross slope, widening sections, or shoulder backing; but excess pulverized material must be accounted for in the project design. If more material is required for the design, supplemental aggregate can be added.

5.2 Pulverization Area

The width and crown of the roadway to be pulverized dictates the number of passes to cover the full width. Pulverizer milling drums are typically 8 feet wide but can vary in width from 6 to 12 feet. Several passes will normally be required to pulverize the roadway width. If the roadway is crowned, the pulverizer should not pass over the crown to ensure uniform treatment depth and consistency in the pulverized material. If the pulverizer does pass over the crown, the processing depth must be increased accordingly so the minimum design depth for the pulverized layer is obtained. Be advised that the strength of the pulverized material is potentially decreased as the ratio of RAP to granular base decreases with deeper pulverization.

Pulverization should proceed from the outside of the roadway towards the centerline to maintain a reference to the profile elevation. The first pass uses the full width of the pulverizer. In subsequent pulverization passes, the treatment width will be reduced by a minimum overlap of 4 inches. If the treatment depth is more than 12 inches or the pulverized material is coarse, the overlap width should be increased.

Other factors to consider are adjacent obstructions such as curb and gutter, concrete barrier, or retaining walls. In the case of curb and gutter, the pulverizer should be able to treat the roadway up to the edge of the gutter. For taller obstructions, the adjacent roadway will have to be removed using another method. The pulverization area should include the entire cross section of the pavement structure from edge of pavement to edge of pavement.

5.3 Pulverized Material Gradation

Gradation is controlled by the forward working speed of the pulverizer, milling drum speed, gradation control beam position, mixing chamber front and rear door position, and size of the existing material.(1) When the existing pavement has extensive alligator cracking, the milling drum tends to flip up or lift the flexible layer in large chunks rather than pulverizing the material. If adjustments such as reducing forward speed, increasing milling drum rotational speed, and lowering the rear door are not made, oversized materials can cause problems in the grading and compaction process. The maximum size of the pulverized material will be larger than the maximum size of the original aggregate due to clumping of the RAP.

The gradation of the pulverized material should be tested during construction to ensure it corresponds to the gradation required in the special provisions. As shown below in Table 3, the particle distribution should be 100% smaller than 2 inches and 90 to 100% passing the 1½ inch sieve:

Table 3: Grading Requirements

Sieve Sizes	Percentage Passing
2”	100
1½”	90-100

If the underlying base material contains coarse rock or is poorly graded, the gradation can be adjusted by adding a specifically graded material to the surface of the existing flexible layer prior to pulverization (see Section 3.3.3).

5.4 Underlying Unsuitable Material

The potential for unsuitable material below the pulverized depth should be considered during the initial project investigation. Areas exhibiting drainage problems, pumping, rutting, severe cracking, or moisture intrusion may indicate deteriorated base or subgrade. Analysis of abnormally high deflections or DCP penetration rates generally indicate weak underlying layers. Often, unsuitable material cannot be identified until commencement of construction operations when removal of the pavement surface and repeated loading from heavy equipment induces pumping action, causing rutting and cracking. Localized areas of unsuitable material should be removed, disposed, and replaced with excess pulverized base or new Class 2 AB according to Section 19-1.03B of the Standard Specifications. Often, unsuitable material cannot be identified until commencement of construction operations when removal of the pavement surface and repeated loading from heavy equipment and compaction induces pumping action, causing rutting and cracking in the PAB layer.

If weak material is widespread throughout the project limits, the pavement structure design should be strengthened and any moisture or drainage issues addressed. Alternatives include increasing the reclamation depth, importing Class 2 AB, using an additive, or subgrade stabilization. Pulverized material requires support from underlying layers to achieve compaction and design strength. If mitigation cannot be attained, alternative rehabilitation or reconstruction strategies should be considered.

5.5 Test Strip

The test strip determines the efficacy of the QC Plan's pulverizing and paving plan, which outlines the sequence of work for PAB operations. The pulverized roadbed SSP is by and large an "end-result" specification, in which the Contractor will determine the sequence of operations to achieve the desired results. For example, the addition of water can occur during pulverization or afterward (subject to remixing), as long as the specifications for a homogeneous and uniform mixture and compaction are met. When cement is added, it can be spread on the unpulverized AC surface and mixed during pulverization; or, cement can be spread after shaping the pulverized material to the grades specified, and mixed under a separate operation. Either way, the moisture content must be correct during mixing and compaction must be completed within 4 hours. The test strip is crucial to ensuring the Contractor's operations produce quality pulverized roadbed.

5.6 Compaction

Compaction should proceed according to the pattern established during construction of the initial test strip using vibratory rollers with a static weight of at least 15 tons. Initial compaction is done with a sheepsfoot roller equipped with a blade. During compaction, the construction inspector must ensure the blade is dropped when reversing direction to back drag pulverized material and fill in the sheepsfoot imprints, which should prevent differential compaction in the wheel tracks. Compaction should continue until refusal density is obtained and the sheepsfoot roller walks out of the compacted layer leaving minimal imprints.

If cement is added to the pulverized material, mixing must occur within 30 minutes of application and all mixing, grading, and compaction must be completed within 4 hours.

5.7 Constructability

Pulverized pavement structure designs should account for significant variations in controlling parameters such as subgrade R-values or existing pavement structure layers and thicknesses in a consistent manner. For ease of construction, design parameters such as material additives, pulverization depth, pulverization area, and overlay thickness should not vary more frequently than ½-mile to 1-mile long segments. Transverse variations in the design cross section should take into account equipment width (see Section 5.2) and other requirements.

As with all full depth reclamation operations, control over material uniformity is largely dependent on site conditions. Field adjustments will be necessary during construction as indicated by changes to in-situ conditions or QC/QA test results.

Conflicting utilities, including valves and access points, must be referenced and lowered 6 inches below the pulverization depth. If utility depths have not been confirmed by field inspection or potholing, the design pulverization depth should be at least 12 inches above the approximate utility depth.

5.8 Traffic Handling

Pulverization is best suited for moderate to low volume roadways. Since pulverized surfaces are frequently exposed to traffic during construction, high traffic volumes prior to paving can cause raveling. Accordingly, pulverization operations require 24-hour traffic control. For two-lane conventional highways, a pilot car should be used to escort vehicles through the work zone.

If cement is used as an additive, no public traffic or heavy contractor equipment should be allowed on the finished pulverized surface until all construction activities in the work zone are complete to allow the layer to cure. On routes with high truck traffic volumes > 1800 ADTT, a curing period of 4 hours from completion of mixing should be provided.

6.0 PLANS, SPECIFICATIONS, AND ESTIMATING

6.1 Plans

The plans for a pulverization project are analogous to a project using standard roadway rehabilitation strategies. The typical cross sections should clearly show the cross slope, width, and depth of the existing pavement layers, new pulverized base layer, and new flexible pavement layers. The layout plans should show the existing roadway and the limits of pulverization (width and length). Surveyed slope stake information may not be necessary if existing grades are maintained. Any design changes to profile, cross slope, and superelevation should be indicated in the plans so the contractor can account for any additional grading. Areas with and without additives should also be designated.

The construction details should include conforming transverse tapers where the pulverized pavement structure ties into existing or new roadway. Quantity sheets should include the stationing and corresponding pulverization areas and additive amounts in the roadway items table. Appendix 'C' contains example plan sheets for a pulverization project.

6.2 Specifications

A nonstandard special provision for pulverization (nSSP) has been used in the North Region, and a standard special provision (SSP) is currently being developed. The specification addresses material and equipment requirements, construction methods, inspection, quality control and quality assurance (QC/QA), acceptance requirements, measurement, and payment. Until the SSP is finalized, prior approval from the Chief of the Office of Flexible Pavement Materials in the Division of Materials Engineering and Testing Services (METS) is required to use pulverization on Caltrans projects.

6.3 Estimating

The estimation process for pulverization cost must take into account several project specific features: project location, length, schedule, geometrics, and traffic handling, as well as pulverization depth and area. Typical project mobilization costs for pulverization equipment run under $10,000, keeping the process cost effective for smaller projects and areas. Historical cost data for District 2 pulverization projects is available on the intranet from the North Region Unit Cost Database (see Appendix C). Among other considerations, analysis of historical costs must consider that past pulverization projects were located in a single district and used an nSSP that quantified unit cost by station.

6.3.1 Measurement and Payment

The item "Pulverize Roadbed" is measured and paid for by the square yard based on the pulverization area and includes all labor, materials, tools, equipment, and testing related to the pulverization operation and preparation of the existing roadway. The roadbed dimensions to be pulverized should be shown on the typical sections, layout plans, and quantity sheets to clearly indicate the limits of the pulverized roadbed (See Appendix C).

Additional additives such as supplementary aggregate and cement are measured and paid for per ton. The item includes all labor, materials, tools, equipment, and incidentals for placing and mixing the additive with the pulverized roadbed. No cost adjustment is made for increases or decreases in additive quantities during construction operations unless the pulverization dimensions are changed. Section 4-1.03B, "Increased or Decreased Quantities," of the Standard Specifications does not apply.

6.3.2 Supplemental Work

Due to the difficulty in identifying underlying unsuitable material (see Section 5.4), a Supplemental Work item for roadway excavation to remove and dispose of the material should be included in the estimate if unsuitable material has been identified, is difficult to accurately quantify, or is otherwise likely to be present on a project. Any unsuitable material that has already been identified and located should be quantified and estimated as a roadway item and not included in Supplemental Work.

6.3.3 Working Days

Due to the wide array of equipment available and varying roadway distress addressed using pulverization, it is difficult to suggest a single expected production rate. Daily production rates may vary on average from 4,750 yd^2 to 9,500 yd^2 based on the interaction of variables such as existing pavement structure, distress, pulverization depth, gradation, and grading.[1] The experience level of the contractor with the pulverization process is also a factor. If the contractor uses multiple pulverizers, production will be increased, but grading and compacting are the typical constraints on construction productivity. Based on experience with rural, 2-lane conventional highways in District 2, a single pulverizer can typically cover 1 mile in three passes during an 8-hour shift, but grading and compacting takes an additional half a shift. Daily paving operations typically consist of two lifts over half a mile. Table 4 provides a general guide for estimating pulverization production rates:

Table 4: Daily Pulverization Production

Daily Production Rate (yd^2)		Existing AC Thickness (in.)	Pulverization Depth[1] (in.)	Alligator Cracking (frequency)	PAB Gradation	Profile/Cross Slope Corrections
Range	4700	Thick (7-9 inches)	Deep (8-10 inches)	Continuous (85-100%)	Coarse	Numerous
	7100	Medium (5-7 inches)	Medium (6-8 inches)	Nearly continuous (50-85%)	Medium	Some
	9500	Thin (3-5 inches)	Shallow (4-6 inches)	None to intermittent (0-50%)	Fine	Minor

7.0 REFERENCES:

1. Asphalt Recycling and Reclaiming Association, "Basic Asphalt Recycling Manual" – 2001.

2. David Jones and John Harvey – "Relationship between DCP, Stiffness, Shear Strength, and R-value" – July 2005.

3. Manuel Bejarano and Bruce Steven – "Effects of Different Compaction Efforts on Virgin and Recycled Granular Materials for Roads" – September 2006.

4. Manuel Bejarano – "Evaluation of Recycled Asphalt Concrete Materials as Aggregate Base" – November 2001.

5. Joint Departments of the Army and Air Force, USA, TM 5-822-14/AFMAN 32-8010, "Soil Stabilization for Pavements" – 25 October 1994.

6. Bruce Steven, Eungjin Jeon, and John T. Harvey – "Initial Recommendation of a Gravel Factor for Pulverized Asphalt Concrete Used as an Unbound Base" – April 2007.

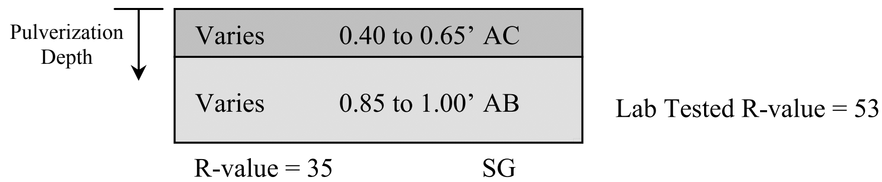
7. Wirtgen GmbH – "Wirtgen Cold Recycling Manual" – 2nd Ed., 2004.

APPENDIX A – DESIGN EXAMPLE
PULVERIZED PAVEMENT STRUCTURE

GIVEN PROJECT:

Description	2-lane, rural conventional highway
Traffic Index	$TI_{20} = 10.5$
Length	4.3 miles
Width (EP to EP)	28 ft

Existing Pavement Structure:



DETERMINE: Pulverized Pavement Structure Design:

- Minimum design pulverization depth
- Estimated excess pulverized material quantity
- PAB layer thickness
- HMA overlay thickness

SOLUTION: 1 Calculate the minimum pulverization depth

For a single depth pavement structure design throughout the project, the **maximum existing AC thickness governs the minimum design pulverization depth**:

From Table 2: *With max existing AC thickness = 0.65 ft → G_f = 1.2;* GE = 0.90

Min. design pulverization depth = 0.75 ft

2 Estimate the excess pulverized material

From Section 5.1: *Compacted pulverized material swells by 5-10%*

Assume swell factor = 7%

Pulverized material volume = (4.3 miles)(5280ft/mi)(28ft)(0.75ft)

= 476,784 ft^3

Excess pulverized material = 7%(476,784 ft^3)

Est. excess pulverized material = 33,375 ft^3 = 1,236 yd^3

Optional: This quantity can be considered roadway excavation or used to increase the actual thickness of the PAB layer, correct profile or cross slope, level existing surface undulations, or widen the roadway. PAB material can also be used as embankment.
Do not include estimates of excess material in pavement structure design calculations.

depth)

= 7%(0.75 ft) + 0.75 ft

PAB layer actual thickness = 0.80 ft

3 Calculate the total required gravel equivalent

$GE_{Total} = GE_{HMA} + GE_{PAB} + GE_{AB}$

For a 20-year design:

$GE_{Total} = 0.0032(TI_{20})(100 – R_{SG})$

$GE_{Total} = 0.0032(10.5)(100 – 35)$

$GE_{Total} = 2.18$ ft

From HDM Index 633.1: Apply safety factor (treat as full depth design)

→ SF = 0.10 ft

$G_{req'd} = GE_{Total} + SF$

= 2.18 + 0.10

$G_{req'd} = 2.28$ ft

4 Calculate GE of each pavement structure layer

$$Thickness = \frac{GE}{Gf}$$

$GE_{PAB} = (\text{thickness})(G_f) = (0.75)(1.2)$

→ $GE_{PAB} = 0.90$

To determine the GE of the remaining AB, use the average existing pavement structure thicknesses:

$$Average\ Existing\ \ AC\ Thickness\ = \frac{0.40+0.65}{2} = 0.525\ ft$$

$$Average\ Existing\ \ AB\ Thickness\ = \frac{0.85+1.00}{2} = 0.925\ ft$$

$$Pulverization\ Depth = 0.75\ \text{ft}$$

$$Average\ Remaining\ AB\ Thickness = 0.525 + 0.925 - 0.75 = 0.70\ \text{ft}$$

From Figure 8: With existing pavement structure & R-value$_{AB}$ = 53, G_f = 1.0

$GE_{AB} = 0.70 \times 1.0$

→ $GE_{AB} = 0.70$

The GE required for the HMA layer is:

$GE_{HMA} = GE_{Total} - GE_{PAB} - GE_{AB}$

$GE_{HMA} = 2.28 - 0.90 - 0.70$

$\rightarrow GE_{HMA} = 0.68$

5 Determine the HMA overlay thickness

From HDM Table 633.1:

With $TI_{20} = 10.5 \rightarrow G_{f\,(HMA)} = 1.71$

$$Thickness = \frac{GE}{Gf} = \frac{0.68}{1.71}$$

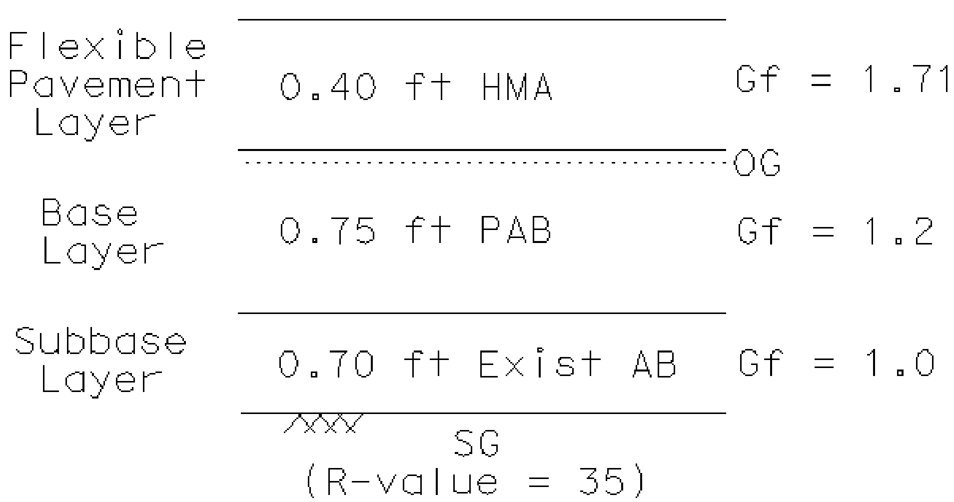
$= 0.398$ ft

From HDM Index 633.1(1)(d):

Round up to the nearest 0.05 ft increment

Design HMA Thickness = 0.40 ft

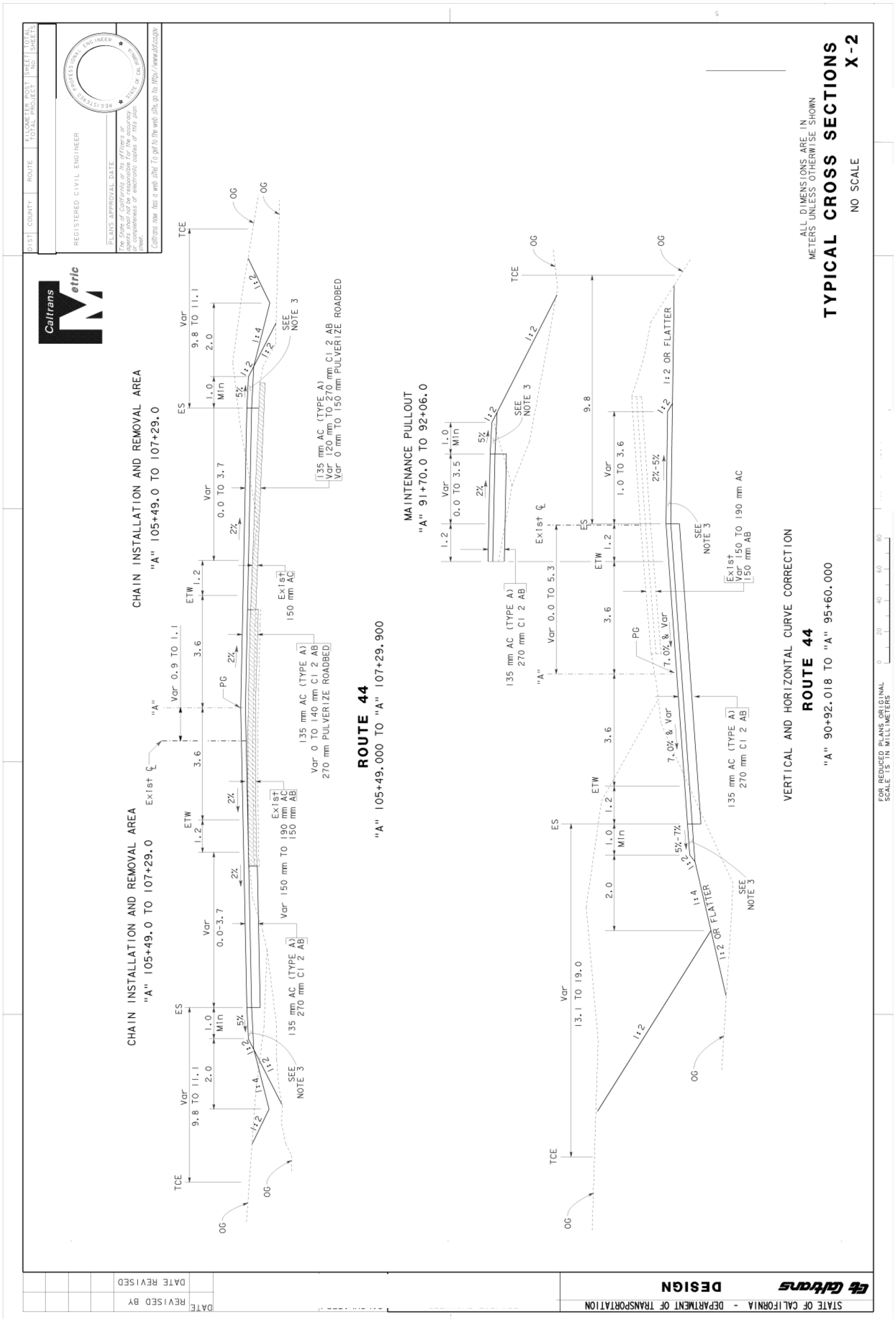
PULVERIZED PAVEMENT STRUCTURE DESIGN



NOTE:
For pavement structures with existing AC thicknesses less than 0.75 ft, increasing pulverization depth can offer potential cost savings by minimizing demand for new material. Increasing the PAB layer thickness reduces the required thickness of the new HMA layer, which must be at least 0.15 ft according to HDM Index 633.1. However, for PAB material with RAP < 60%, $G_f = 1.1$ (see Section 4.3).

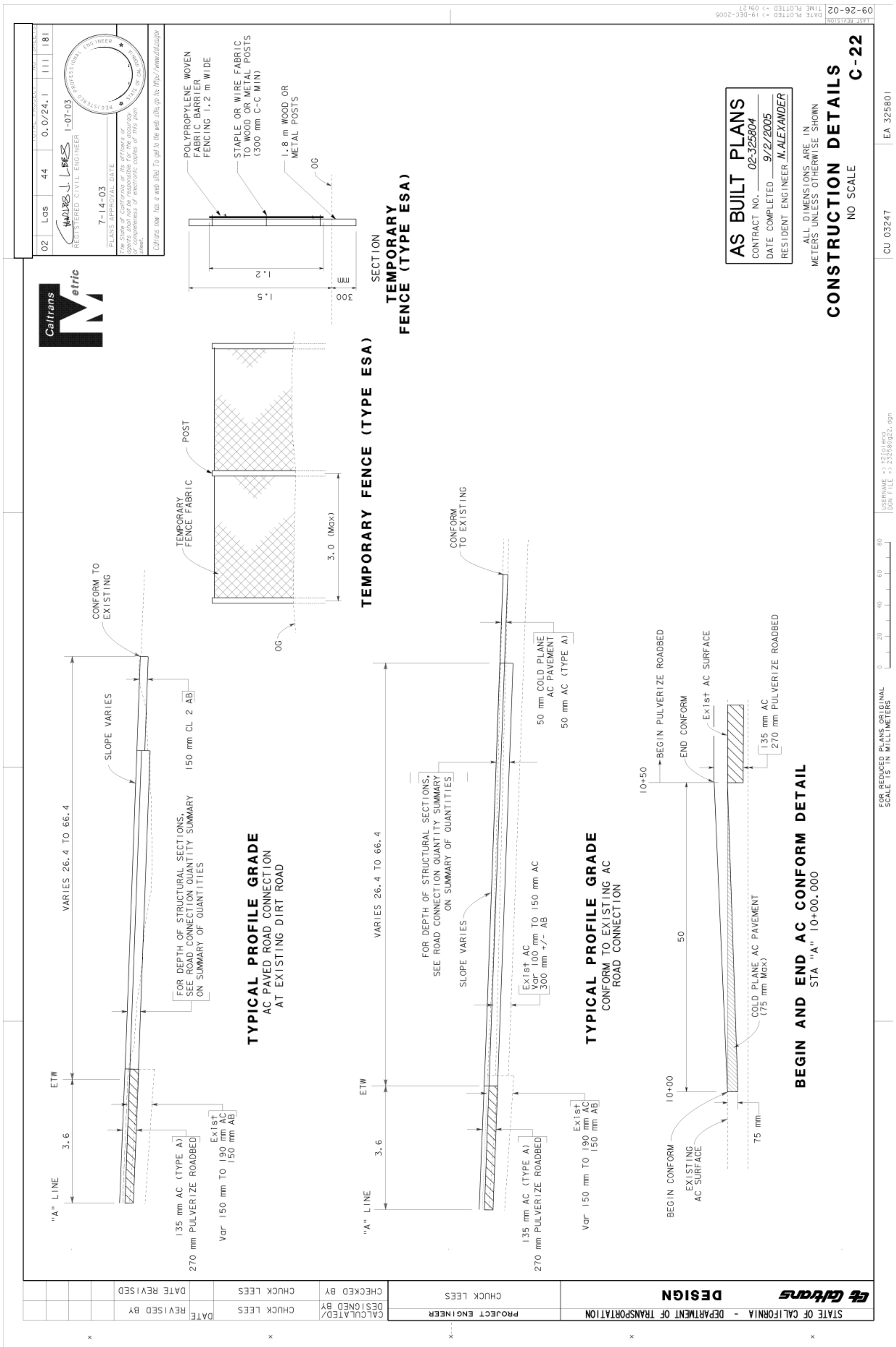
APPENDIX B

Example Pulverization Project Plans



APPENDIX B

Example Pulverization Project Plans



APPENDIX B

Example Pulverization Project Plans

DIST	COUNTY	ROUTE	KILOMETER POST TOTAL PROJECT	SHEET No.	TOTAL SHEETS

Caltrans Metric

REGISTERED CIVIL ENGINEER

PLANS APPROVAL DATE

REGISTERED PROFESSIONAL ENGINEER

STATE OF CALIFORNIA

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ROAD CONNECTION QUANTITIES

STATION	Lt	Rt	ROADWAY EXCAVATION	(N) EMBANKMENT	OBLITERATE SURFACING	ASPHALT CONCRETE (SEE NOTE 1)	CL 2 AB	IMPORTED MATERIAL (SHOULDER BACKING)	REMARKS	STRUCTURAL SECTION THICKNESS (N) AC	AB
			m3	m3	m2	TONNES	TONNES	TONNES		mm	mm
20+18.184 "A"		X	78	27		28	146	16	RC1	75	200
23+94.253 "A"		X	110	171		111	303	37	RC2	135	270
43+95.823 "A"		X	53	43		56	163	16	RC4	75	200
43+98.082 "A"	X		58	6		52	130	16	RC3	75	200
47+90.322 "A"	X		82	123		247	482	37	RC5	135	270
47+90.322 "A"		X	39	211		249	462	37	RC6	135	270
49+89.954 "A"	X		45	180	101.2	116	192	36	RC7	135	270
67+75.330 "A"	X		307	78		201	419	37	RC8	135	270
74+44.396 "A"		X	467	2		252	394	37	RC9	135	270
94+24.304 "A"		X	92	21		25	176	16	RC10	75	200
101+85.817 "A"		X	69	61		30	201	16	RC11	75	200
111+24.293 "A"	X		133	105		180	411	36	RC12	135	270
143+93.953 "A"		X	49	189		68	196	16	RC13	75	200
151+09.370 "A"	X		85	99		225	374	37	RC14	135	270
157+62.475 "A"		X	280	4		182	359	36	RC15	135	270
211+00.000 "A"	X		18	207		265	437	37	RC16	135	270
211+13.160 "A"		X	384	33		243	622	37	RC17	135	270
243+63.450 "A"	X		50	7		99	191	36	RC18	135	270
243+64.499 "A"		X	192	55		245	490	37	RC19	135	270
245+85.065 "A"	X		254	19		153	378	36	RC20	135	270
246+77.620 "A"		X	78	255		204	386	37	RC21	135	270
ROAD CONNECTION TOTAL			2923	1896	101.2	3231	6912	646			

NOTES: 1. SEE ROADWAY QUANTITY SUMMARY TABLE FOR COMPLETE SUMMARY OF ITEMS
(N) NOT A SEPARATE PAY ITEM, FOR INFORMATION ONLY.

ROADWAY QUANTITY SUMMARY

STATION	ROADWAY EXCAVATION	(N) EMBANKMENT	IMPORTED BORROW (SEE NOTE 1)	IMPORTED MATERIAL (SHOULDER BACKING)	ASPHALT CONCRETE (TYPE A)	CL 2 AB	OBLITERATE SURFACING	PULVERIZE ROADBED
	m3	m3	m3	TONNE	TONNE	TONNE	0	STA
"A"10+00 - 45+00	2377	7966	5589	2512	11333	8483	0	35
"A"45+00 - 80+00	4159	5648	1489	2324	11278	9043	0	35
"A"80+00 - 115+00	12627	4658	-7969	2795	11809	10348	0	35
"A"115+00 - 150+00	2076	9071	6995	3573	11454	9446	0	35
"A"150+00 - 180+00	2262	4991	2729	2106	10633	8905	0	30
"A"180+00 - 220+00	918	7490	6572	3067	12951	10570	0	40
"A"220+00 - 250+65	2667	14558	11891	2173	11811	11622	0	30.65
ROADWAY TOTAL	27086	54382	27296	18550	81269	68417	0	240.65
ROAD CONNECTION TOTAL	2923	1896	0	646	3231	6912	101.2	0
GRAND TOTAL	30009	56278	27296	19196	84500	75329	101.2	240.65

NOTES: 1. ASPHALT CONCRETE QUANTITY INCLUDES ALL PLACE ASPHALT CONCRETE (MISC AREA) QUANTITY
(N) NOT A SEPARATE PAY ITEM, FOR INFORMATION ONLY.

STATE OF CALIFORNIA - DEPARTMENT OF TRANSPORTATION

Caltrans DESIGN

SUMMARY OF QUANTITIES

Q-3

FOR REDUCED PLANS ORIGINAL SCALE IS IN MILLIMETERS

0 20 40 60 80

APPENDIX C -- ADDITIONAL RESOURCES

Information	Internet Address
Highway Design Manual (HDM)	http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
Life Cycle Cost Analysis	http://www.dot.ca.gov/hq/esc/Translab/ope/LCCA.html
Office of Roadway Materials Testing (ORMT-METS)	http://www.dot.ca.gov/hq/esc/Translab/ofpm/index.htm
Pavement Management Program	http://www.dot.ca.gov/hq/esc/Translab/ope/OPE.html
Pulverization	http://www.dot.ca.gov/hq/esc/Translab/ope/Pulverization.html
Standard Specifications (May 2006)	http://www.dot.ca.gov/hq/esc/oe/specifications/std_specs/ 2006_StdSpecs/

Information	Intranet Address (Caltrans Only)
(North Region Unit) Cost Database	http://sv03fmp13.dot.ca.gov/fmi/iwp/cgi?-db=Cost%20Data%209&-loadframes
Document Retrieval System	http://drs.dot.ca.gov
Geographic Information Services (GIS)	http://onramp.dot.ca.gov/hq/gis/
Pavement Condition Report (PCR 4.0)	http://onramp.dot.ca.gov/hq/maint/roadway_rehab/index.htm#pcr
Pavement Evaluation Manual	http://onramp.dot.ca.gov/hq/maint/roadway/pcs/pdf/PCS2000.pdf
Photolog	http://onramp.dot.ca.gov/photolog/

APPENDIX D – FWD ANALYSIS

The following analysis procedures are intended for use with deflection measurements obtained using a falling weight deflectometer (FWD) under CT 356 modified by Section 3.3.2 to evaluate the stiffness of underlying layers and identify areas of weak subgrade.

Site evaluation often involves testing pavements with severe alligator cracking, which violates the continuity assumption for modulus backcalculation based on FWD data. Pavement layer modulus backcalculation is not appropriate in these instances but valuable information about the subgrade properties can be obtained by approximating the modulus from the measured deflection using the following Boussinesq's equation (Equation D.1):

$$\mathrm{E}_r = \frac{(1-v^2)\times P}{\pi \times r \times d} \tag{D.1}$$

where:
- E_r = deflection modulus at distance r (psi)
- P = the applied load (lbs)
- v = Poisson's ratio, generally using 0.35
- r = the distance from the load center to the measured deflection (inches)
- d = measured deflection at distance r (inches)

For a layered pavement structure the calculated deflection modulus (E_r) is a function of the distance from the load center (r) at which the deflection is measured. Typically, the deflection modulus at r = 24 ± 1.0 in. (distance to the fifth FWD sensor) is approximately equivalent to the subgrade modulus ($E_{24} \approx E_{SG}$). Consider:

- To calculate E_r, use the measured distance between the sensor and the load center.
- No temperature correction is necessary since the calculated deflection modulus E_{24} is not significantly affected by the surface layer condition,

Results of the analysis should be plotted against postmile or station on a graph (Figure D.1). The graph can be used to identify problem subgrade or drainage areas. The following criteria (Table D.1) should be used to interpret the deflection data from the 24 in. sensor with the load normalized to 9,000 lb:

Table D.1: Deflection Criteria for Assessing Subgrade

$d_{(24)}$*	E_r*	Subgrade Zone (Figure D.1)[1]	Conclusion	Potential Corrective Actions
< 15 mils	>6,500 psi	A	SG sufficient	None
15 – 49 mils	3,600 – 6,500 psi	B	May need to improve SG prior to PAB	None, soil stabilization, geosynthetic reinforcement, remove and replace, raise profile, address drainage, thicker pavement structure
> 49 mils	< 3,600 psi	C	Improve SG prior to PAB or other strategy	Conduct more detailed survey and consider corrective actions or other rehab/ reconstruction strategies
*Values are only an approximate guide				

APPENDIX D
FWD Analysis

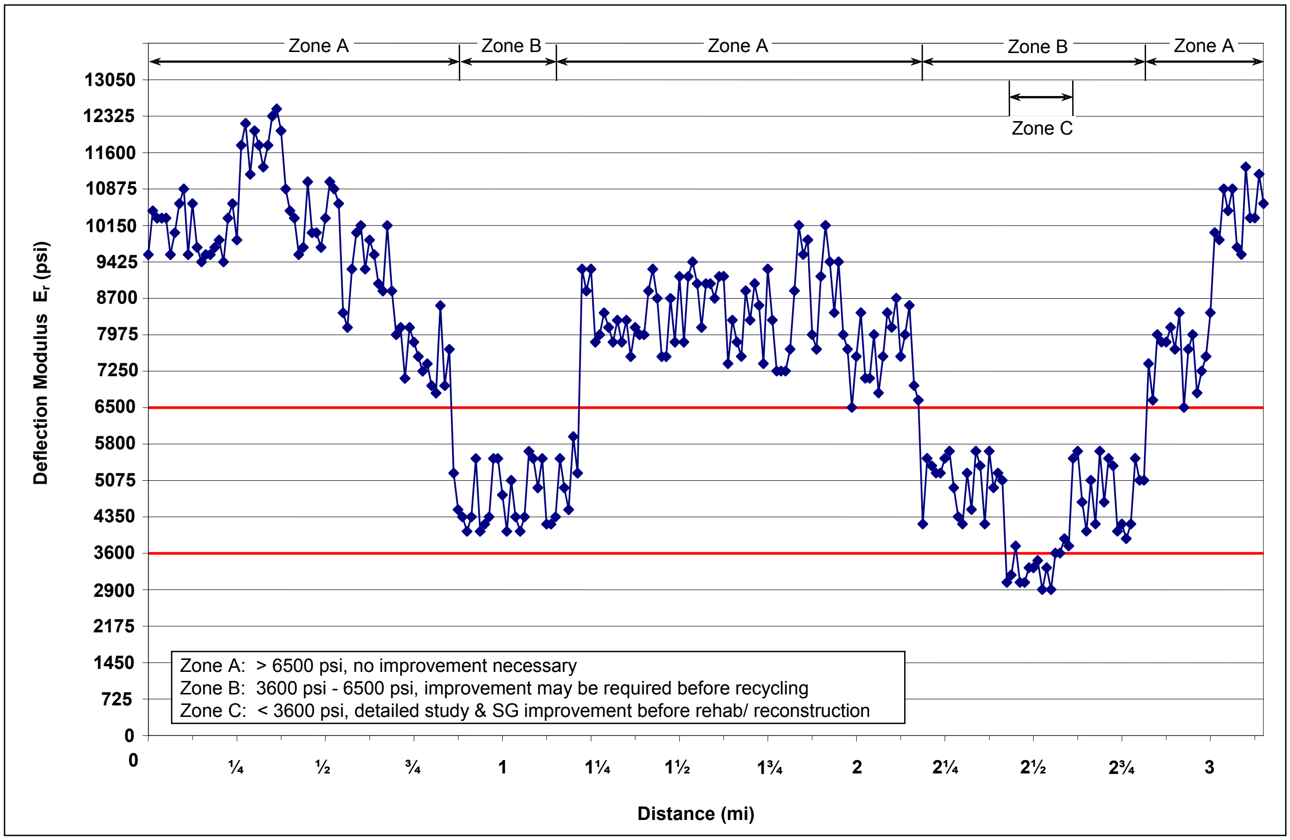

Figure D.1: Example FWD analysis.

Ideally, Zone B + Zone C < 10% total project length.

If Zone B + Zone C > 10% total project length, PAB can still be considered as a rehabilitation strategy. As with other alternatives, the service life may be reduced and additional design features should be included to mitigate poor subgrade material (see Section 3.3).

APPENDIX E – DCP ANALYSIS

Dynamic cone penetrometer (DCP) results are typically analyzed in terms of the DCP Number (DN) to provide a relative indication of layer shear strength and thickness. AC layers are excluded from the evaluation. The DCP layer Structure Number (DSN) and the DCP Pavement Structure Number (DSN_{800}) can also be used to assess pavement structures but are not covered in this guidance.

1. Calculate the DCP Number (DN) as the DCP rate of penetration in millimeters (mm) per hammer blow (mm/blow). This provides an indication of the relative shear strength of the material at the depth where it was calculated. Shear strength will typically reduce with increasing depth. If the DN is plotted against depth, distinct jumps are often apparent. The points of each jump can be used to indicate changes in material type, properties, or moisture conditions and to estimate underlying layer thicknesses.

   No comprehensive studies have been documented to relate DN to R-value, but empirical relationships have been developed to relate the penetration rate to the effective layer stiffness and California Bearing Ratio (CBR*)*. These relationships provide useful indicators that can be combined with FWD measurements and visual assessments to identify and evaluate potential problem areas, but resulting stiffness and CBR values should be considered **approximate estimates** only.

2. Calculate the effective elastic modulus. An example relationship between stiffness and penetration rate developed in South Africa is given below (Equation C.1) and a summary of DN ranges, corresponding stiffnesses, and subgrade zone is provided in Table C.1.

$$E_{eff} = 145.04 \text{ x } 10^{3.05-1.066(Log(DN))} \qquad \textbf{(E.1)}$$

where: E_{eff} is the effective elastic modulus (psi)

Table E.1: Approximate Relationship between DN, CBR & E_{eff}

DN Range (mm/blow)	CBR Range[1] (%)	E_{eff} [1] (psi)	R-value[1,2]	Subgrade Zone (Figure C.1)[1]	Subgrade Description
< 4	>70	>37400	>80	A	Relatively strong
4 – 5	50 – 70	29600 – 37400	75 – 80		
5 – 8	30 – 50	18000 – 29600	65 – 75		
8 – 14	30 – 15	9900 – 18000	50 – 65		
14 – 19	10 – 15	6500 – 9900	42 – 50		
19 – 25	7 – 10	5400 – 6500	35 – 42	B	Marginal strength
25 – 30	3 – 7	4350 – 5400	18 – 35		
30 – 35	1 – 3	3600 – 4350	1 – 18		
> 35	< 1	< 3600	< 1	C	Weak, potentially wet

[1]Values are only an approximate guide. Use with caution as there is no published correlation between DN and R-value.
[2]From Huang 1993 based on CBR comparison to R-value through laboratory testing. Not developed from DCP and R-value analysis. Not verified for use in California. R-value < 50 appears to be too high for rate of DCP penetration.

3. Plot DN over the project length and calculate the average and standard deviation to help identify uniform sections and potential problem areas (Figure E.1):

APPENDIX E

DCP Analysis

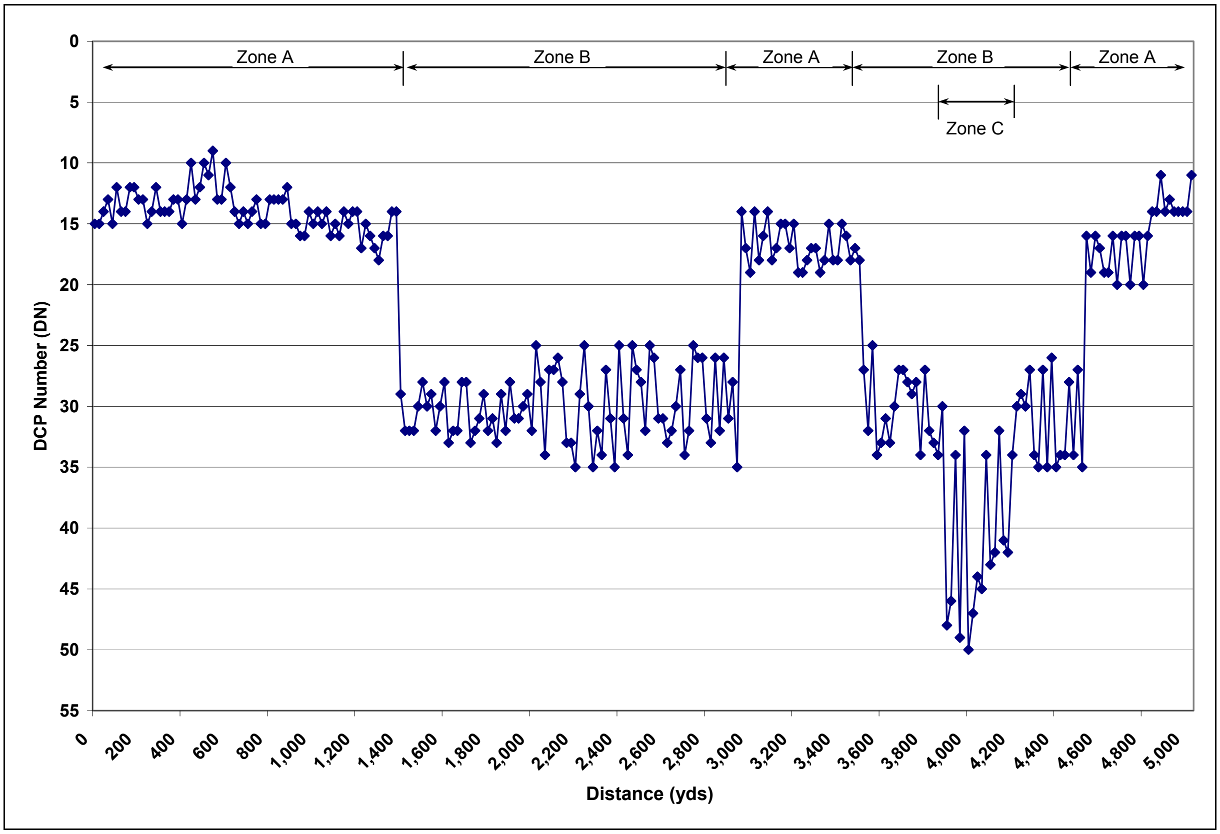

Figure E.1: Example DCP Number analysis.

4. Categorize the data relative to a subgrade zone. For the example in Figure C.1, eight uniform sections can be identified and divided into three different zones: A, B, and C.

   Zone A can be considered reasonably strong for subgrade material. Zone B has marginal strength, and Zone C is very weak, indicating potentially wet, clay soils

   As with FWD analysis, ideally Zone B + Zone C < 10% total project length.

   If Zone B + Zone C > 10% total project length, FDR-FA can still be considered as a rehabilitation strategy. As with other alternatives, the service life may be reduced and additional design features should be included to mitigate poor subgrade material (see Section 3.3)