# Use of Cold In-Place Recycling on Low-Volume Roads

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In the last several years (since 1984) Oregon has used cold in-place recycling (CIR) techniques as one alternative to conventional practices for the rehabilitation of asphalt concrete (AC) pavements. All CIR efforts have consisted of partial-depth (AC-surface) recycling on low-volume roads—generally less than 2,000 average daily traffic—with good success on most projects. Projects have also been completed on county roads and U.S. Forest Service roads using this technique. In most cases, the recycled mat is treated with a sand seal or a chip seal. Construction costs for this operation are on the order of $1.70 to $2.10 per square yard compared with $2.75 to $4.00 per square yard for a conventional 2-in. AC overlay. Because of the success of the initial projects that were cold recycled in 1984 to 1985, the Oregon State Highway Division (OSHD) and Oregon State University (OSU) have studied cold in-place recycling in detail since 1986. One purpose of the studies by OSHD and OSU has been to develop a better understanding of the performance and economics of the cold in-place recycled pavements. A brief overview of the CIR construction and design process, the performance to date of selected projects, and an economic evaluation of CIR as an alternative to other rehabilitation techniques are provided. Significant findings include (a) the current state-of-the-art in recycling equipment allows for efficient and economic recycling practices; (b) over 75 percent of the CIR projects in Oregon since 1984 were rated fair or better in 1984 to 1989; and (c) CIR can provide significant savings realized through conservation of energy and costly construction materials. On the basis of the results of the joint study to date, it appears that CIR is a viable rehabilitation alternative for low-volume roads. Hence, using the CIR concept on higher-volume roads (including Interstates) is now proposed.

With the national trend away from new construction to preservation of existing pavements, several agencies are turning to cold in-place recycling (CIR) as an approach to rehabilitating distressed pavements. However, many agencies remain skeptical of the use of CIR because of the lack of long-term performance data and adequately documented field engineering studies. Furthermore, because of variability in construction processes with substantially different design concepts and end results (*1–3*), the term CIR is often misunderstood.

Recycling may be defined as the reuse, after processing, of a material that has already served its intended purpose. The different construction processes for cold in-place recycling are defined as follows:

1. Class I. This recycling treatment is performed on a uniform pavement designed and built to specifications. It is expected that a rational CIR mix design can be prepared and produced. The treatment could handle medium-to-heavy traffic volumes, usually as a base on high-volume roads or as a wearing course on low-volume roads. The recycling train method would normally be used; however, depending on the degree of distress, a single-unit train could also produce a Class I treatment. Treatment width is normally 12 ft.
2. Class II. This recycling treatment is performed on a pavement with significant maintenance patches over a uniform pavement or a pavement with minimal design used in the original construction. Either the recycling train or the single-unit train can produce millings of sufficient quality for reasonable mix designs. The finished mix can be used as a base or wearing course as in the case of the Class I process. Treatment width is normally 12 ft.
3. Class III. This treatment is used on low-volume highways where considerable variation in pavement structure exists and it may incorporate additional aggregate. Various milling and pulverizing units can be used to perform this operation. The treatment is normally used as a stabilized base course. Treatment width varies from 4 to 12 ft.

The Oregon State Highway Division is one of the several agencies that has attempted CIR as an approach to rehabilitating distressed asphalt concrete (AC) pavements. Oregon first experimented with partial-depth CIR work in 1984, totaling 14 mi. An additional 68 mi of AC pavement was cold recycled in 1985. Spurred by the initial success of these projects and recognition of the need for a formal mix design procedure, ODOT and OSU, in 1986, undertook a joint study of CIR. The study involved investigating 7 of 13 projects cold-recycled in 1986 to develop an improved understanding of the relationship between mix design and field performance of cold-recycled pavements. The specific objectives of the study were to develop an improved mix design, evaluate the structural contribution and durability, and develop improved construction guidelines and specifications for CIR pavements.

The history of CIR in Oregon from 1984 to 1989, including project information and the construction process used on the projects; the evolution of the design process for CIR; performance information for all projects constructed since 1984; and a life cycle cost analysis comparing CIR and hot mix are described. Also presented are significant conclusions from the work completed to date as well as recommendations for implementation of the findings to date.

## HISTORY OF COLD RECYCLING IN OREGON

Project information associated with the 1984 to 1989 CIR work as well as the process used to construct the projects are described in the following subsections.

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**Project Information**

To date, 500 mi have been cold-recycled in Oregon since 1984. All projects were constructed in Regions 2, 3, 4, and 5. Table 1 presents construction information for all of the Region 4 projects totaling 420 mi constructed between 1984 and 1989. Information for the projects constructed in Regions 2, 3, and 5 was unavailable at the time of writing.

**Construction Process**

Oregon's first efforts (1984) at CIR involved exclusively Class III recycling. The construction process was accomplished with a roto-mill having a 6.5-ft milling head and a motor grader. The surface was milled with the roto-mill, which discharged the millings into a windrow to the side of the cut. Water and CMS-2S emulsion were then applied to the windrow. The

TABLE 1 PROJECTS CONSTRUCTED IN OREGON (1984 to 1988)

| Year | Highway | Project Name | Traffic Volume (ADT) | Length (mi) | Depth of Cut (in.) | Emulsion Type (Content) | Class of Treatment | Surface Treatment |
|---|---|---|---|---|---|---|---|---|
| 1984 | OR 372 | Sand Shed-Mt. Bachelor (Intermittent) | 820 | 4.8 | 1.5 | CMS-2S (1-2%) | Class III, State forces, grader laid | Surface left open winter of 1984, |
| | Misc. | Bend area | Up to 2000 | 9.0 | 1.5 | CMS-2S (1-2%) | Class III, State forces, grader laid | About 50% chip sealed |
| 1985 | US 26 | Sisters-Redmond | 1450-8300 | 18.8 | 1.5 | CMS-2S (1-2%) | Class II | Chip seal placed on about 75% of work |
| | US 395 | Harney Co. Line-Hogback Summit | 220 | 30.7 | 1.5-2 | CMS-2S[1] (1-2%) | Class I | Chip seal |
| | US 140 | Drews Gap-Lakeview | 1000 | 10.3 | 1.5-2 | CMS-2S (1-2%) | Class I | Polymer chip sealed |
| | Misc. | Bend area | Up to 23,000 | 12.0 | 1.5-2 | CMS-2S (1-2%) | Class I | 80% chip sealed |
| 1986 | US 26 | Warm Springs | 2850 | 17.3 | 2-4 | CMS-2S (1%) | Class I | Polymer chip sealed |
| | OR 41 | Powell Butte-Prineville | 3600 | 9.8 | 2 | CMS-2S (1.2%) HFE-150 (1.2%) | Class I | Chip seal |
| | OR 270 | Lake of the Woods | 1750 | 6.4 | 2.5-4 | CMS-2S (1.4%) | Class I | Chip seal |
| | US 20 | Bend-Powell Butte | 4800 | 3.2 | 1.5-2 | CMS-2S (1.5%) | Class I | Chip seal |
| | OR 371 | MP 18.0-Powell Butte | 2200 | 18.0 | 1.5-2 | CMS-2S (1.1-1.3%) | Class II | Chip seal |
| | US 26 | Ochoco Dam-MP 35.0 | 1100 | 10.6 | 1.5-2 | CMS-2S (1.1-1.6%) | Class II | Chip seal |
| | US 26 | MP 73.4-MP 81.6 | 600 | 8.2 | 1.5-2 | CMS-2S (1.8-2.6%) | Class II | 3-in. overlay |
| | OR 41 | MP 89.6-Jct. OR 19 | 600 | 8.7 | 1.5-2 | CMS-2S (1.4-1.5%) | Class I | Chip seal |
| | US 20 | MP 75.0-MP 84.0 | 1000 | 9.0 | 1.5-2 | CMS-2S (1.5-1.6%) | Class I | 3/4-in. oil mat |
| | OR 423 | US 97-OR 39 | 800 | 7.0 | 1.5-2 | CMS-2S (1.5%) | Class I | Chip seal |
| | OR 140 | Dairy-Ritter Rd. | 2000 | 6.0 | 1.5-2 | CMS-2S (1.2-1.9%) | Class II | Chip seal |
| | OR 140 | Sprague River Rd.-Bly | 2700 | 17.8 | 1.5-2 | CMS-2S (1.5%) | Class II | Chip seal |

TABLE 1 (continued on next page)

TABLE 1 *(continued)*

| Year | Highway | Project Name | Traffic Volume (ADT) | Length (mi) | Depth of Cut (in.) | Emulsion Type (Content) | Class of Treatment | Surface Treatment |
|---|---|---|---|---|---|---|---|---|
| 1986 | US 97 | MP 235.3-Spring Creek | 3400 | 6.0 | 1.5-2 | CMS-2S (0.9%) | Class I | Chip seal |
| | OR 7 | W-Horse Ridge-Crooked River Hwy | 900 | 9.2 | 3 | CMS-2S (1.7%) | Class I | Chip seal |
| | OR 372 | Kiwa Springs-Sand Shed | 880 | 5.6 | 2 | CMS-2S (1.0%) | Class I | Chip seal |
| 1987 | OR 41 | Antone-MP 89.6 | 520 | 8.0 | 1.5 | CMS-2S (1.7%) | Class I | Chip seal |
| | OR 293 | Jct. US 97-Tub Springs Rd. | 200 | 9.0 | 2 | CMS-2S (2.8%) | Class I | Chip seal |
| | OR 360 | Jct. US 97-SE Rammes Rd. | 1000 | 9.0 | 2 | CMS-2S (1.6%) | Class I | Chip seal |
| | OR 380 | Conant Basin Rd.-Shotgun Rd. | 180 | 9.1 | 2 | CMS-2S (1.0%) | Class I | Chip seal |
| | OR 4 | Fuego Rd.-Forge Rd. | 3350 | 9.9 | 2 | CMS-2S (1.2%) | Class I | None |
| | OR 427 | Modoc Secondary | 450 | 11.2 | 1 | CMS-2S (1.3%) | Class I | Chip seal |
| 1988 | OR 4 | Shaniko Jct.-Quaale Rd. | 390 | 12.8 | 2 | HFE-150 (0.8-1.2%) | Class I | 3/4 in. cold mix overlay |
| | OR 41 | Prineville-Ochoco Dam | 2200 | 7.0 | 2 | HFE-150 (1.8%) | Class I | † |
| | OR 41 | Ochoco Ranger Sta.-Ruch Creek | 800 | 19.7 | 2 | HFE-150 (0.6%) | Class I | Chip seal |
| | OR 380 | Jct. Ochoco Hwy-Conant Basin Rd. | 3100 | 20.7 | 2 | HFE-150 (2.6%) | Class I | † |
| | OR 50 | Merill Jct.-Hatfield Hwy | 3600 | 2.6 | 2 | CMS-2S (1.2%) | Class I | None |
| | OR 426 | Jct. Klamath Falls-Malin Hwy to Calif. Line | 2350 | 3.0 | 2 | CMS-2S (0.5%) | Class I | None |
| | OR 42 | DeMoss Springs-Moro | 1800 | 5.0 | 2 | HFE-150 (1.0%) | Class I | Chip sealed with HFE |
| | OR 19 | Cogswell Creek-New Pine Creek | 600 | 5.7 | 2.25 | CMS-2S (1.7%) | Class I | Chip sealed with HFE |
| | OR 20[2] | Beatty-Ivory Pine Rd. | 980 | 9.5 | 2.25 | CMS-2S (0.3%) | Class I | None |
| | OR 22 | Fort Klamath-Crooked Creek | 550 | 5.4 | 2 | HFE-150 (1.1%) | Class I | Sand seal |

TABLE 1 *(continued on next page)*

TABLE 1 *(continued)*

| Year | Highway | Project Name | Traffic Volume (ADT) | Length (mi) | Depth of Cut (in.) | Emulsion Type (Content) | Class of Treatment | Surface Treatment |
|---|---|---|---|---|---|---|---|---|
| 1988 | OR 49 | Lake Abert-Valley Falls | 260 | 4.0 | 2 | CMS-2S (1.0%) | Class I | Chip seal |
| | OR 22 | Crater Lake Hwy-Frontage Rd. | 520 | 3.5 | 2 | CMS-2S (1.7%) | Class I | Chip seal |
| 1989 | OR 4 | Gilchrist Section | 3400 | 1.0 | 2 | CMS-2S (0.5%) (w/lime) | Class I | Sand seal |
| | OR 7 | Horse Ridge-Crooked River Jct. | 900 | 7.4 | 2 | HFE-300S | Class I | Cold mix overlay |
| | OR 425 | Umpqua Jct.-US 97 | † | 13.7 | 2 | CMS-2S | Class I | Chip seal |

[1]HFE-150 and HFE-150S were also used, but only for test
[2]One lane only
†Not Available

windrow was then mixed with the motor graders and bladed into the cut.

All subsequent work (1985 to 1989) was accomplished using either the recycling train or a single-unit machine. The work done with the recycling train was contracted out to a construction company that owned the equipment and most of their work would be classified as Class I or Class II treatments. The Oregon DOT maintenance team, on the other hand, relied on the use of a single-unit machine (Class I or Class II treatments). Both construction methods are discussed.

### *Recycling Train*

In the train method, the train was led by a water tanker, and then a CMI 1000 roto-mill having a 12.5-ft milling head. The mill pulled a trailer-mounted screen deck, roll crusher, and pugmill followed by a nurse tanker for the emulsion.

The existing pavements were milled using the CMI 1000 to depths between 1.5 and 2.25 in. The millings were transferred by conveyor belt to the screen deck and screened over 1.5- to 2-in. screens. The oversized millings were crushed such that 100 percent passed the 2-in. screen. Emulsion (CMS–2S or HFE–150) was added and mixed with the millings in the pugmill. This mixture was deposited in a windrow on the roadway. A diluted CMS–2S tack was applied to the milled surface using a spray bar attached to the rear of the train. The train has controls to monitor quantity of emulsion and water.

In order to avoid difficulties in handling of the mixture, the paving machine was operated within 100 to 200 ft of the train. After laydown, a two-stage compaction was specified. The initial compaction was accomplished using a rolling pattern of one pass vibratory and one pass static with an Ingersoll Rand model DA–50 double-drum vibratory roller and one-pass static using a Hyster model 15–7 tandem steel wheel roller. The mat was opened to traffic immediately following initial compaction. The second-stage compaction followed within 3 to 12 days. The variation in days elapsed until second compaction is because of the amount of cure the recycled pavement has undergone, which depends primarily on pavement temperature and moisture content. That is, with high pavement temperatures and low moisture content, second compaction may be appropriate after only 3 days following pavement recycling, whereas up to 12 days may be appropriate for low pavement temperatures and high moisture contents following pavement recycling. The second compaction consisted of at least two passes of a Hyster 8-ton double-drum roller in static mode and at least two passes with a 20-ton pneumatic roller. The second-stage compaction is more effective than the initial compaction. This is because second-stage compaction results in a mat at the same (or nearly the same) density that exists in the wheel tracks that have been compacted under traffic since initial compaction. That is, the second-stage compactive effort merely levels the surface to match the compaction in the wheel tracks caused by traffic.

If humps or rough spots existed in the recycled mat after second compaction, they were removed with a milling machine or corrected with skin patches before sealing. Two weeks or more after recycling, the pavement was covered with a ⅜-in. × #10 single-chip seal [using a CRS–2 or a polymer modified (HFE–150) emulsion] or a fog/sand seal. Through experience, it has been found that a fog/sand seal is best for pavements with a relatively tight surface and having soft asphalt properties. A chip seal, on the other hand, would be appropriate for a cold-recycled mat with an open texture.

### *Single-Unit Train*

The single-unit process involved use of a RAYGO Barco Mill 800. This unit has a 12.5-ft milling head and was serviced by a water and emulsion tanker. A modification was made to the unit to include a spray bar for applying tack immediately ahead of the windrow. Placement was accomplished using a conventional paver. Initial compaction was the same as for the recycling train, but the second-stage compaction was normally done with only a vibratory roller because a 20-ton pneumatic roller was not available.

## PROJECT DESIGN AND IMPLEMENTATION PROCESS

Implementation of CIR is basically a five-step process as follows:

1. Project selection,
2. Evaluation of candidate projects,
3. Mix and structural design,
4. Development of construction guidelines and specifications, and
5. Construction process including quality control.

Figure 1 shows the preconstruction steps in a flowchart and the following sections describe each implementation step in detail.

### Project Selection

The applicability of cold recycling has been a source of some concern. It has been found through experience (*4,5*) that CIR is proving to be an effective treatment under certain pavement, climate, and traffic conditions. Table 2 presents some guidelines to determine whether or not CIR is applicable. Each of these conditions is described in detail in the following paragraphs.

Cold recycling should not be performed in areas that cannot accommodate the traffic volume during construction. That is, CIR is not recommended in areas that would result in excessive traffic control problems. CIR is also not recommended, at this time, for pavements that have exhibited stripping or pavements that have rutted because of an unstable fat mixture. Research is underway to evaluate whether or not CIR is an effective treatment for pavements that have stripped.

CIR work should not be performed in cold and damp conditions because these conditions inhibit the breaking and curing of the emulsion. Furthermore, CIR should not be performed in late fall or early winter, because the recycled pavement requires several days and nights of warm weather for proper curing.

Cold recycling is recommended for rough pavements, cracked and broken pavements, and pavements that have raveled because of age. CIR is effective in improving the ride quality of rough pavements and pavements that have raveled because of age. It is also effective in rehabilitating the structural integrity of cracked and broken pavements. CIR is also recommended for and can provide quality leveling of base courses for overlays. The constraint of ADT 5,000 or less is needed at the higher traffic level for safety and public inconvenience reasons only (i.e., excessive traffic control problems).

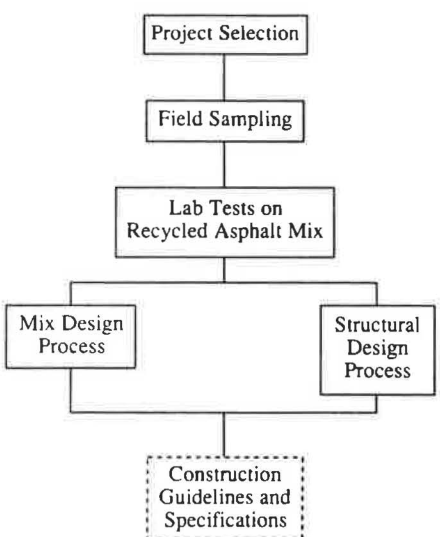


**FIGURE 1 Preconstruction steps for CIR.**

### Evaluation of Candidate Projects

After a project has been identified as a candidate for CIR, a paper search on the history of the highway is performed. Type of asphalt, pavement thickness, and termini of previous jobs are the principal information to be obtained. On the basis of the available records or knowledge (Figure 2), the project is divided into design areas of uniform properties (e.g., pavement thickness and oil content). These are shown as *A*, *B*, and *C* in Figure 2b. Samples from each area should be obtained using a small 16-in. mill with the sample frequency being a minimum of 1 sample plus 1 backup sample per design area. For long sections, it is recommended that as many as three samples plus three backup samples should be obtained (Figure 2c). Samples should weigh 100 lb each to ensure adequate amounts of material are available.

The sample locations should be selected by visual inspection that identifies representative locations within the design area. The depth of milling for samples should correspond to that of the proposed depth of recycling. If the design area contains visible maintenance patches or other intermittent treatments, samples should be obtained from these areas, noting on each sample that it came from a maintenance area. All samples should be kept separate (should not be blended) and submitted to the laboratory for testing.

Tests to be performed by the laboratory on the rap millings obtained from the field sampling should include the following:

1. Penetration at 77°F of Abson-recovered asphalt,
2. Absolute viscosity at 140°F of Abson-recovered asphalt,
3. Gradation of the rap millings (16-in. mill), and
4. Extracted asphalt content.

Values obtained from these tests are to be used to estimate the optimum design emulsion content.

### Mix Design

The mix design procedure consists of estimating the design emulsion content and preparing and testing samples at the

TABLE 2 CONSIDERATIONS FOR PROJECT SELECTION

| a) CIR Not Recommended |
|---|
| • Work area cannot accommodate traffic volume |
| • Asphalt is stripping from aggregate* |
| • Mixes exhibiting rutting due to unstable fat mixture |
| • Cold and damp conditions during and immediately after construction (i.e., a mat temperature of 90°F or greater for at least 2 hr after laydown and in the absence of rain) |
| • Late fall or early winter treatment |
| **b) CIR Recommended** |
| • Cracked and broken pavements |
| • Pavements ravelled due to age |
| • Rough pavements |
| • As leveling and base for overlays |
| • ADT 5000 or less |
| • Where selective rehabilitation is needed (e.g., in truck lane of 4-lane roadway) |

*Emulsions contain effective antistrip agents. While it is not recommended at this time that CIR be used to correct pavements with stripping problems, CIR may prove to be an effective treatment.

estimated design emulsion content and at the estimated design ±0.4 percent. These procedures are described in detail in the following subsections.

### *Estimating Design Emulsion Content*

Estimation of the design emulsion content begins with establishing a base emulsion content and making adjustments on the basis of the results of the laboratory findings. Oregon has found that a base emulsion content of 1.2 percent by dry weight of rap is a good starting point. This figure was determined by trial-and-error techniques; namely, recycling was attempted using emulsion contents of 1, 1.5, 2, 2.5, and 3 percent. It was found that recycled mats having emulsion contents of less than about 1.5 percent tended to ravel, whereas those having emulsion contents of about 2 percent or greater tended to rut. Thus, an emulsion content of 1.5 percent was established as a good starting point. Through substantial use of the estimation procedure described herein, this value was further refined to 1.2 percent in the 1987 construction season. Once established, adjustments are then made to this base content according to softness of extracted asphalt, gradation of the millings (16-in. mill), and the percent of recovered asphalt. The calculations to be made with the adjustments are as follows:

| | |
|---|---|
| Base emulsion content | 1.2 percent |
| Adjustment for softness | 0 to +0.3 percent |
| Adjustment for gradation | ±0.3 percent |
| Adjustment for percent asphalt | 0 to −0.3 percent |
| Estimated design | |
| Lowest design | 0.6 percent |
| Highest design | 1.8 percent |

The estimated design emulsion content can be as low as 0.6 percent and as high as 1.8 percent. This range represents the emulsion contents at which most projects are currently recycled; however, projects can be, and have been, successfully recycled with emulsion contents falling outside this range. The adjustments are discussed in detail as follows:

1. Softness of Asphalt. Penetration and absolute viscosity laboratory test results are used to determine the softness of the extracted asphalt. Figure 3 shows the ranges in these values that have been found in CIR completed to date. By plotting the values obtained from the laboratory on this figure,

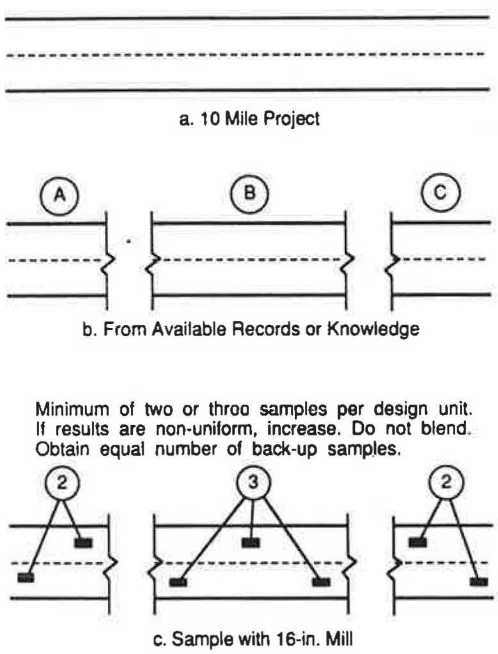


**FIGURE 2 Suggested field sampling.**

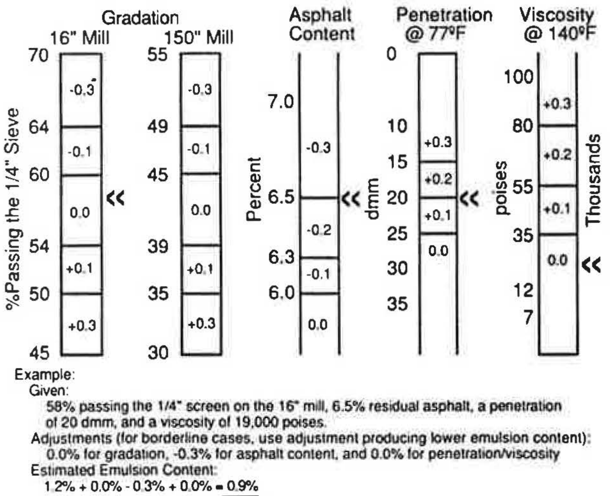


**FIGURE 3 Emulsion content adjustments for gradation, asphalt content, and asphalt softness.**

an adjustment of 0 to +0.3 percent can be selected. Thus, for a hard asphalt the emulsion content adjustment of up to 0.3 percent would be added to the base emulsion content. Conversely, no adjustment would be made to the base emulsion content for a soft asphalt.

2. Gradation Adjustment. By plotting the rap gradations from CIR completed to date, a range of values was obtained for the percent passing the ½-in., ¼-in., and #10 screens. Figure 3 indicates the range of values when the sampling is performed with a 16-in. mill and the expected rap gradation when using a 150-in. mill. By using this graph, a maximum adjustment of ±0.3 percent can be made to the base emulsion content. Rap with a coarse gradation would result in adding an adjustment of up to 0.3 percent to the base emulsion content, whereas up to 0.3 percent would be subtracted for rap with a fine gradation. This will seem intuitively incorrect in that traditional mix design procedures for hot-mix AC would prescribe increasing the asphalt content for fine mixes (relative to coarse mixes) to provide adequate coating of the fine aggregate particles because of the increased surface area of the aggregate. However, because the fines in rap millings appear to be predominately asphalt, and not aggregate particles, increasing the emulsion content tends to activate these fine particles of asphalt, resulting in an unstable mixture. Findings to date indicate that if a rap gradation is on the fine end of the range for the ½-in. screen, it will also be on the fine end for the range for the ¼-in. and #10 screens. The same holds true for a coarse or average gradation (*4,5*).

3. Asphalt Adjustment. The percent of asphalt recovered from the rap was plotted, giving the expected range of asphalt content. Figure 3 shows this range as well as the adjustment range of 0 to −0.3 percent. Rap with a high residual asphalt content would result in subtracting up to 0.3 percent from the base emulsion content, whereas no adjustment would be made for rap with a low residual asphalt content.

The estimated design emulsion content is determined as prescribed earlier. The significance of this procedure may be summarized as follows:

1. The procedure provides a rapid and simple method of determining emulsion content;
2. The laboratory tests used are widely accepted;
3. The procedure eliminates the necessity to fabricate, compact, and cure test briquets in the laboratory at simulated field conditions—one of the more controversial design issues for CIR (*4*);
4. The results generally produce the optimum emulsion content within a fraction of a percent; and
5. For most recycle projects in which preservation and restoration of an existing pavement are the primary objectives, the estimated design emulsion content would be adequate for the final recommended design.

### *Final Design*

The final design emulsion content is determined from tests on samples prepared at the estimated design emulsion content and at the estimated design content ±0.4 percent. Figure 4 shows the steps for selecting a final design emulsion content when the CIR pavement will become part of the structural design to upgrade the surface. The samples should be prepared using either the Hveem or Marshall compaction method. Once compacted and cured as prescribed, the samples are tested for stability, resilient modulus, and index of retained modulus (IRM). The sample preparation procedure is as follows:

1. Split millings into approximately 5500-g batches; this size of sample provides sufficient material for four 6.4-cm (2.5-in.) specimens, with an 1100-g sample for moisture determination.
2. Screen samples on the 2.5-cm (1-in.) sieve. The material retained on the 2.5-cm sieve is reduced in size to 100 percent passing the 2.5-cm sieve using 13.4-N (3-lb) hammer. This is

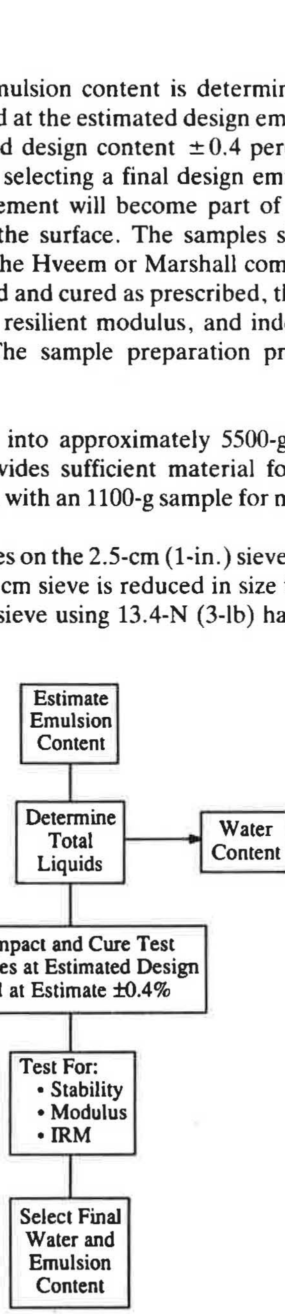


**FIGURE 4 Suggested mix design process—future projects.**

because the retained 2.5 cm is too large for 10.2-cm (4-in.) molds.

3. Batch five 1100-g samples of millings at the average gradation.

4. Determine moisture content of one batch by drying 24 hr at 100°C (230°F).

5. Heat samples to approximately 60°C (140°F) before mixing (1 to 2 hr).

6. Add water to the millings in the appropriate proportion based on the dry weight of the millings: percent water = 4.5 × total liquid − percent of added emulsion. Water is thoroughly mixed into millings by hand.

7. Add water to the premoistened millings after water addition using the recommended content. The added emulsion is based on the dry weight of the millings. The emulsion is preheated to approximately 60°C (140°F) for 1 hr and mixed thoroughly into the batch by hand or using a mechanized mixer.

8. Spread the material into a 30.5- × 41.2-cm (12- × 17-in.) baking pan and allowed to cure for 1 hr at approximately 60°C (140°F) to simulate average time elapsed between paver laydown and initial compaction during actual construction.

9. Mold samples using standard Marshall or Hveem procedures to produce 6.4-cm (2.5-in.) briquets as follows:

(a) Preheat molds to approximately 60°C (140°F).

(b) Compact samples using standard 50-blow compactive effort for Marshall procedure or 150 blows at 3.1 MPa (450 psi) for the Hveem procedure.

(c) Cure overnight at 60°C (140°F) and recompact using 25 blows per side for the Marshall procedure and 75 blows at 3.1 MPa (450 psi) for the Hveem procedure.

(d) Lay the molds on their sides and the briquets are cured for 24 hr at approximately 60°C (140°F) before extrusion.

(e) Extrude briquets with the compression testing machine.

(f) Lay briquets on their side to maximize surface exposure and cure them for 72 hr at approximately room temperature before testing.

10. Specimens are tested for stability, modulus, and fatigue at 25°C (77°F).

### Structural Design

One of the objectives of this study was to develop structural layer coefficients for CIR mixtures. These coefficients would be used to determine the required thickness of the CIR pavement. As a result of the performance studies to date, it appears CIR mixtures may be considered essentially equivalent to conventional hot mix, as discussed in more detail in the next section.

## FIELD PERFORMANCE (1984 to 1989)

Beginning in 1986, the following field and laboratory data were collected to evaluate the field performance of the CIR projects (*4,5*).

1. Pavement condition (visual surveys),
2. Ride (Mays meter), and
3. Mix properties (resilient modulus, fatigue, Marshall stability, and flow).

These data are summarized in the following sections.

### Pavement Condition

Visual condition surveys were conducted on most of the projects in the falls of 1986 and 1987 as well as in the springs of 1988 and 1989. Pavements were rated on a scale of 1 to 5, with 1 being a condition rating of very good as prescribed by the Oregon State Highway Division's (OSHD's) rating procedure (*6*). A summary of the condition of selected projects (as of spring 1989) is presented in Table 3. As indicated, the projects with no mix design (1984) and those with the initial mix design (1985) are generally in fair condition. However, those with the modified mix design (1986) are performing with a fair to very good condition. Conventional mixes placed in the same geographical areas as the recycled pavement deteriorate at the same rate because of the extremely severe weather conditions that prevail in central to eastern Oregon.

### Ride

Ride data were collected on several of the CIR projects using the Mays ride meter. Data were obtained immediately before and after the construction as well as each year after construction. These data are presented in Table 4. The criteria used to rate the smoothness of the pavement are as follows:

| *Mays Reading (in./mi)* | *Rating* |
|---|---|
| 200+ | Very rough |
| 150 to 200 | Rough |
| 100 to 150 | Slightly rough |
| 75 to 100 | Average |
| 0 to 75 | Smooth |

As indicated, ride was improved on the two projects that were rated rough before construction. For the two projects (Warm Springs and Lake of the Woods) that had a smooth rating before construction, the CIR work retained the ride rating.

### Mix Properties

Field cores were extracted from several of the CIR projects beginning in 1986. Tests conducted on these cores were as follows:

1. Bulk specific gravity,
2. Resilient diametral modulus and fatigue [after Scholz (*7*)], and
3. Marshall stability and flow.

These data are presented in Table 5. All values represent the average of tests on three cores. Figure 5 graphically displays the modulus and fatigue results, and Figure 6 graphically displays the Marshall stability and flow results.

The modulus values increased with time for all sections. These increases were expected because of the additional cur-

TABLE 3 SPRING 1989 CONDITION

| Year Built | Section (Note 1) | Hwy No. | M.P. | M.P. | Length (mi.) | Depth of CIR (in.) | Emulsion Used | Original Pavement (Note 2) | Rut Depth (in.) Lt. | Rut Depth (in.) Rt. | Thermal Crack Spacing (ft) | Flushing | Fatigue Cracks | Maint. Work | Rating | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1984 | Fremont Hwy-(N. Lane) | 19 | 8.0 | 8.6 | 0.6 | 1-1/2 | CMS-2S | C | | 1/16 | 20-60 | -- | Minor | Minor | Fair | Delete from study. |
| 1984 | Fremont Hwy-(N. Lane) | 19 | 16.8 | 18.3 | 1.5 | 1-1/2 | CMS-2S | C | 3/16 | 5/16 | 20-60 | Heavy | Minor | Major | Poor | Delete from study. |
| 1984 | Sand Shed-Mt. Bachelor | 372 | 16.6 | 21.6 | 5.0 | 1-1/2 | CMS-2S | C | 1/16 | 3/16 | occasional | Minor | Minor | Minor | Fair | Intermittent CIR between mile points. |
| 1985 | Sisters-Dry Creek | 15 | 93.2 | 99.0 | 5.8 | 2 | CMS-2S | C | 1/8 | 1/16 | 30-50 | Heavy | Minor | -- | Poor-Fair | |
| 1985 | Dry Creek-Warrin Rd. | 15 | 99.0 | 105.0 | 6.0 | 2 | CMS-2S | 0-11 | 1/8 | 3/16 | 30 | -- | Minor | -- | Fair | |
| 1985 | Warrin Rd.-Redmond | 15 | 105.0 | 111.9 | 6.9 | 2 | CMS-2S | B | 1/8 | 1/8 | 15-30 | -- | Minor | -- | Fair-Good | |
| 1985 | Summit Drews Gap-Lakeview | 20 | 81.8 | 92.8 | 11.0 | 1-1/2 | CMS-2S | | 1/16 | 1/8 | 30-100 | Minor | Minor | Minor | Fair-Good | |
| 1985 | Harney Co. Line-Bacon Camp Rd. | 49 | 35.1 | 49.0 | 13.9 | 1 | CMS-2S | variable | 1/8 | 3/16 | 130 | Minor | Minor | Major | Fair | Maintenance due to delamination. |
| 1985 | Bacon Camp Rd.-M.P. 57 | 49 | 49.0 | 57.0 | 8.0 | 1 | CMS-2S | variable | 3/16 | 1/8 | -- | -- | Minor | Major | Fair | |
| 1985 | M.P. 57-Hogback Summit | 49 | 57.0 | 65.8 | 8.8 | 1 | CMS-2S | variable | 3/16 | 3/16 | 100 | -- | Minor | Major | Poor | |
| 1985 | O'Neil-Prineville* | 370 | 9.5 | 17.7 | 8.2 | 1 | CMS-2S | 0-97 | 3/16 | 1/8 | 70-30 | Minor | Minor | Minor | Poor | Grader laid. |
| 1986 | Pilot Butte-Powell Butte Jct. | 7 | 1.1 | 4.3 | 3.2 | 2 | CMS-2S | B | 1/16 | 1/16 | -- | -- | -- | -- | Good | Overlaid w/1-1/2 in. AC. Condition before overlay |
| 1986 | Horse Ridge-Fort Rock Rd. | 7 | 18.1 | 21.0 | 2.9 | 3 | CMS-2S | B | 1/8 | 3/16 | 20 | Minor | Minor | -- | Fair-Good | |
| 1986 | G.I. Ranch-Harney Co. Line | 7 | 75.0 | 84.0 | 9.0 | 1-1/2 | CMS-2S | C | 3/16 | 3/16 | 30-120 | Minor | -- | Minor | Fair-Good | US 20 test section |
| 1986 | Dairy-Wild Horse Cr. | 20 | 19.0 | 25.0 | 6.0 | 1-1/2 | CMS-2S | C | 5/16 | 1/8 | -- | Heavy | -- | Major | Poor | Maintenance due to base failure. Polymer seal. |
| 1986 | Sprague R. Rd.-Sycan Marsh Rd. | 20 | 35.9 | 42.2 | 6.3 | 1-1/2 | CMS-2S | C | 1/8 | 3/16 | 60 | Minor | -- | Minor | Fair | Polymer seal. |
| 1986 | Sycan Marsh-Bly | 20 | 42.2 | 54.0 | 11.8 | 1-1/2 | CMS-2S | C | 1/8 | 3/16 | -- | Minor | -- | Minor | Fair | |
| 1986 | Powell Butte-Houston Lake Rd. | 41 | 6.8 | 16.5 | 9.7 | 1-1/2 | CMS-2S HFE-150 | variable | 3/16 | 1/4 | 100 | -- | Minor | Major | Poor | No seal initially. Pavement flushed when sealed. Overlaid w/OGEM in 1989. |
| 1986 | Ochoco Dam-Ranger Station | 41 | 24.9 | 35.5 | 10.6 | 1-1/4 | CMS-2S | oil mat | 1/16 | 3/16 | -- | Minor | -- | Minor | Fair | Overlaid w/OGEM in 1989. |
| 1986 | Keys Cr. Summit-Whiskey Cr. | 41 | 73.4 | 81.6 | 8.2 | 2 | CMS-2S | C? | 1/16 | 1/16 | -- | -- | -- | -- | Good | Overlaid w/OGEM in 1989. |
| 1986 | M.P. 89.6-Jct. John Day Hwy | 41 | 89.6 | 98.4 | 8.8 | 1-1/2 | CMS-2S | oil mat | 3/16 | 1/16 | -- | Minor | -- | Minor | Good | Chip sealed in 1986. |
| 1986 | M.P. 79.2-Bridge Cr. | 53 | 79.2 | 86.9 | 7.7 | 1-1/2 | CMS-2S | B | 3/16 | 1/8 | occasional | Minor | -- | -- | Fair | Early polymer seal. Recycled w/too much emulsion. |
| 1986 | Bridge Cr.-County Line | 53 | 86.9 | 96.5 | 9.6 | 1-1/2 | CMS-2S | C | 1/8 | 3/16 | 60 | Minor | -- | Minor | Poor | Early polymer seal. Recycled w/too much emulsion. |
| 1986 | Lake Shore Dr.-Gr. Spgs. Hwy | 270 | 62.4 | 68.8 | 6.4 | 1-1/2 | CMS-2S | B | 3/16 | 1/8 | -- | Minor | Minor | -- | Good | |
| 1986 | Tub Springs Rd.-Antelope* | 293 | 9.0 | 13.5 | 4.5 | 1 - 1-1/2 | CMS-2S | oil mat | 1/16 | 1/8 | -- | Minor | -- | -- | Good | |
| 1986 | McKay Cr.-Prineville* | 360 | 23.7 | 26.3 | 2.6 | 1-1/2 | CMS-2S | B-oil mat | 1/8 | 1/4 | -- | Minor | Minor | | Fair-Good | Partially (1 mi.) overlaid in 1986. |
| 1986 | Jct. Ochoco Hwy-Desch. Co. Line | 371 | 0.0 | 7.6 | 7.6 | 3/4 - 1-1/2 | HFE-150 CMS-2S | C & B & oil mat | 1/4 | 3/16 | -- | Heavy | Minor | Minor | Fair-Good | |
| 1986 | Desch. Co. Line-Jct. Cent. Ore. | 371 | 7.6 | 18.0 | 10.4 | 3/4 - 1-1/2 | CMS-2S | oil mat | 1/8 | 3/16 | 30-80 | -- | Minor | Minor | Fair-Good | |
| 1987 | Fort Rock Rd.-Crooked R. Hwy* | 7 | 21.0 | 30.2 | 9.2 | 2 | several | B | N/A | 1/8 | 60-90 | -- | Minor | -- | Poor-Good | East lane only. Overlaid w/OGEM in 1989. |
| 1987 | Whiskey Cr.-M.P. 89.6* | 41 | 81.6 | 89.6 | 8.0 | 1 - 2-1/2 | CMS-2S | variable | 1/8 | 1/8 | -- | Heavy | -- | Minor | Good | |
| 1987 | Jct. Hwy 97-Tub Springs Rd.* | 293 | 0.0 | 9.0 | 9.0 | 1-1/4 - 2 | CMS-2S EB HFE-150 WB | oil mat | 1/16 | 1/8 | -- | Minor | -- | -- | Good | |
| 1987 | Jct. Hwy 97-Rammes Rd.* | 360 | 0.0 | 9.0 | 9.0 | 1-3/4 - 2 | CMS-2S NB HFE-150 SB | oil mat | 3/16 | 1/8 | -- | Minor | Minor | -- | Fair | No base. Recycled w/too much emulsion. |
| 1987 | Kiwa Springs-Sand Shed* | 372 | 11.0 | 16.6 | 5.6 | 2 | HFE 150 | B | 1/6 | 3/16 | 60-100 | -- | Minor | -- | Good | |
| 1987 | Conant Basin Rd.-Shotgun Rd.* | 380 | 20.7 | 29.8 | 9.1 | 1-1/2 - 2 | CMS-2S | variable | 1/8 | 1/8 | -- | Minor | -- | -- | Good | Overlaid w/0-9 in 1987. |

TABLE 3 *(continued on next page)*

TABLE 3 *(continued)*

| Year Built | Section (Note 1) | Hwy No. | M.P. | M.P. | Length (mi.) | Depth of CIR (in.) | Emulsion Used | Original Pavement (Note 2) | Rut Depth (in.) Lt. | Rut Depth (in.) Rt. | Thermal Crack Spacing (ft) | Flushing | Fatigue Cracks | Maint. Work | Rating | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1988 | Shaniko Jct.-Quaale Rd. | 4 | 67.2 | 75.6 | 8.4 | 1-1/2 | HFE-150 | B | 1/8 | 3/16 | -- | -- | -- | -- | Poor-Fair | M.P. 67.2-69.2 (SB) failed due to high asphalt - 2" ruts. |
| 1988 | Shaniko Jct.-Quaale Rd. | 4 | 75.6 | 78.6 | 3.0 | 1-1/2 | HFE-150 | 0-11 | 1/16 | 1/8 | -- | -- | Minor | -- | Good | |
| 1988 | Shaniko Jct.-Quaale Rd. | 4 | 78.6 | 80.0 | 1.4 | 1-1/2 | HFE-150 | 0-11 | 0 | 0 | -- | -- | -- | -- | Good | |
| 1988 | M.P. 152-Cal. Line* | 19 | 152.0 | 157.7 | 5.7 | 2 | CMS-2S | B? | 3/16 | 3/16 | -- | Minor | Minor | Major | Poor | Unstable |
| 1988 | Houston Lake Rd.-Prineville* | 41 | 16.5 | 18.0 | 1.5 | 2 | HFE-150 | B&C | 1/16 | 1/16 | -- | -- | -- | -- | Good | Scheduled to be overlaid w/AC |
| 1988 | Prineville-Ochoco Dam* | 41 | 19.4 | 24.9 | 5.5 | 2 | HFE-150S HFE-150 | B & C & oil mat | 1/16 | 1/8 | -- | Minor | -- | Minor | Fair-Good | Overlaid w/OGEM in 1989 |
| 1988 | Ochoco Ranger St.-Rush Cr.* | 41 | 35.5 | 45.0 | 9.5 | 2 | CMS-2S HFE-150 | variable | 0 | 1/16 | -- | -- | -- | -- | Good | |
| 1988 | Wheeler Co. Line-W. Brand Cr.* | 41 | 50.1 | 60.3 | 10.2 | 2 | HFE-150 | variable | 1/8 | 0 | -- | -- | -- | -- | Good | |
| 1988 | Lake Abert-Valley Falls* | 49 | 87.0 | 89.9 | 2.9 | 1 - 1-1/2 | CMS-2S | oil mat | 3/16 | 1/4 | -- | Minor | Minor | Major | Poor | Fat oil mat. |
| 1988 | Merrill-Jct. Hatfield Hwy* | 50 | 13.7 | 16.3 | 2.6 | 2 | CMS-2S | B | 1/8 | 1/16 | 100-200 | Minor | -- | -- | Good | |
| 1988 | Jct. Ochoco Hwy-Burma Rd.* | 380 | 0.0 | 11.8 | 11.8 | 2 | HFE-150 | C? | 1/8 | 1/16 | -- | | Minor | -- | Fair | No seal - raveled. |
| 1988 | Burma Rd.-Conant Basin Rd.* | 380 | 11.8 | 20.7 | 8.9 | 2 | HFE-150 | C? | 1/16 | 1/16 | -- | | -- | -- | Good | Sealed in 1989. |
| 1988 | Malin HWY-Calif. Line* | 426 | 0.0 | 2.4 | 2.4 | 2 | CMS-2S | Mod-B w/seal | 1/8 | 1/8 | -- | | Minor | -- | Good | Stripped. |
| 1988 | Crater Lake Hwy (Ft. Klamath-Crooked Cr.) | 22 | 90.07 | 95.4 | 5.3 | 2 | HFE-100S | E | | | | | | | Good | |
| 1988 | 12 mi South of Clackamas Ranger Station | FS 46 | - | - | 3.2 | 2 | CMS-2S | B | <1/4 | <1/4 | -- | -- | -- | -- | Very Good | |

**Notes:**

1. Sections with an asterisk (*) were recycled by state forces.
2. B, C, and E denote the class of aggregate gradation as specified in Oregon's standard specifications (reference 6). 0-9 denotes an oil mat having a thickness of 9/100-in. while 0-11 denotes an oil mat with a thickness of 11/100-in.

TABLE 4 BEFORE AND AFTER RIDE DATA FOR SELECTED CIR PROJECTS

| Project | Year Constructed | Average Ride (in./mi) | | Score Rating | |
|---|---|---|---|---|---|
| | | Before | After | Before | After |
| Harney Co. Line-Hogback Summit | 1985 | 175 | 62 | Rough | Smooth |
| Warm Springs | 1986 | 69 | 69 | Smooth | Smooth |
| Powell Butte-Prineville | 1986 | 162 | 112 | Rough | Slightly Rough |
| Lake of the Woods | 1986 | 69 | 61 | Smooth | Smooth |

ing time and densification caused by traffic. (Bulk gravities increase with time as indicated in Table 5.) In all cases in which fatigue was monitored over time, the fatigue lives increased significantly. This increase may also be attributed to the additional cure time and densification caused by traffic. The fatigue lives are comparable to those of conventional mixes (i.e., 10,000 to 50,000 repetitions to failure).

In addition to modulus and fatigue, Marshall stability and flow were monitored over time for the 1986 projects. In all cases, the stabilities increased but the flow values remained slightly high. These results generally reflect, and thus support, the modulus and fatigue test results.

### Life Expectancy

On the basis of present data for low-volume roads, the following life expectancies may be warranted:

1. 2-in. AC—10 to 15 years,
2. CIR (with chip seal)—7 to 8 years, and
3. CIR (with OGEM)—7 to 12 years.

These life expectancies are based on discussions with Oregon Department of Transportation (ODOT) personnel. The CIR (with chip seal) values are based on a study of 32 projects constructed between 1984 and 1988, which are currently serving as wearing courses on low-volume roads (*8*). Fourteen of the projects had experienced no significant patching after an average of 4.5 years. Total service lives of 8 years were predicted for these projects. Eighteen projects had experienced patching after an average of 2 years but were still predicting total service life of 7 years.

## ECONOMICS OF CIR

### Typical Costs

Typical costs for construction and maintenance of CIR versus hot-mix projects are presented in Table 6. Construction and maintenance costs are based on conversations with ODOT personnel and reflect typical values in the state of Oregon.

TABLE 5 SUMMARY OF MIX PROPERTY TEST RESULTS

| Project | Test Period (Months After Construction) | Average Bulk Specific Gravity | Average Resilient Modulus* (ksi) | Average Fatigue Life** | Average Marshall Stability*** (lb) | Average Flow (in./100) |
|---|---|---|---|---|---|---|
| Century Drive | 15 | - | 230 | - | - | - |
| | 17 | 2.203 | 322 | 77800 | - | - |
| | 63 | 2.273 | 713 | 138184 | 2410 | 17 |
| Harney Co. Line - Hogback Summit | 3 | - | 293 | - | - | - |
| | 5 | 1.946 | 403 | 35072 | - | - |
| | 39 | 2.030 | 508 | 108865 | 788 | 33 |
| | 51 | 2.005 | 485 | 175000+ | 1607 | 19 |
| Drews Gap-Lakeview | 3 | 1.940 | 278 | 3424 | - | - |
| | 5 | 2.005 | 323 | 19317 | - | - |
| | 39 | 2.116 | 499 | 61805 | 1196 | 22 |
| | 51 | 2.152 | 531 | 48076 | 2049 | 20 |
| Warm Springs | 3 | 2.160 | 305 | 11030 | 694 | 59 |
| | 12 | 2.333 | 242 | 50010 | 861 | 20 |
| | 24 | 2.273 | 377 | 53965 | 1106 | 21 |
| | 36 | 2.381 | 526 | 150000+ | 1181 | 18 |
| Lake of the Woods | 3 | 2.059 | 513 | 5860 | 605 | 29 |
| | 12 | 2.092 | 504 | 34261 | 614 | 20 |
| | 24 | 2.132 | 530 | 78731 | 1171 | 24 |
| | 36 | 2.141 | 727 | 250000+ | 1597 | 17 |

* ASTM D4123 - Tests run at 23°C, 100 microstrain, and at a load frequency of 1 hertz
** After reference 7
*** ASTM D1559

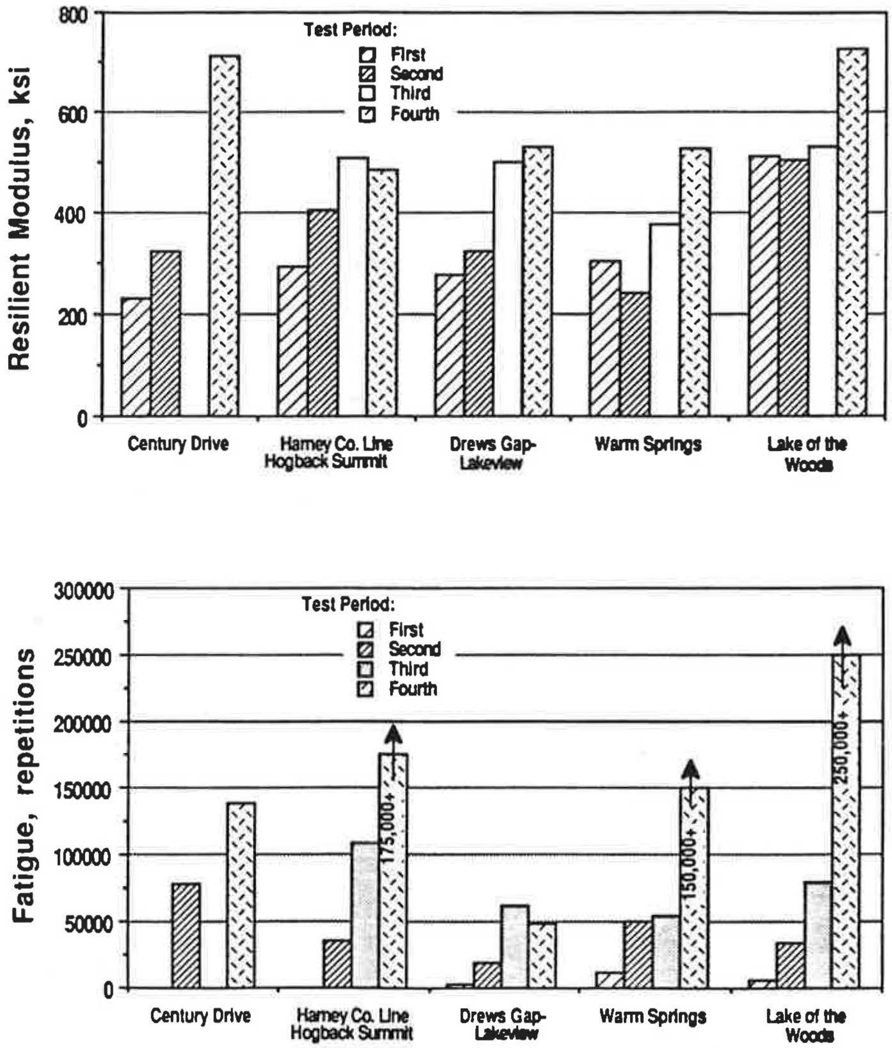


**FIGURE 5 Resilient modulus (*top*) and fatigue (*bottom*) test results.**

## Life Cycle Cost Analysis

Life cycle costs were analyzed for two CIR alternates and a hot-mix overlay alternate. Equivalent annual cost analysis was chosen to simplify the comparison between alternates of differing economic lives. It is assumed that when an alternate's economic life is reached, the same treatment will be repeated, essentially in perpetuity. For example, every 7 or 8 years, the basic CIR alternate is recycled and given a chip seal. Every 10 to 15 years, the 2-in. hot-mix overlay is repeated.

Variables in the life cycle analysis include:

1. Interest rate, 8 percent;
2. Construction costs, see Table 6;
3. Maintenance costs, see Table 6; and
4. Life expectancy (CIR—7 to 8 years, CIR with OGEM—7 to 12 years, and hot mix—10 to 15 years).

The results of the analysis are presented in Table 7. In general, the results indicate the following:

1. Basic CIR represents the lowest first cost of the alternates considered. This means that more miles can be preserved on limited budgets. This, in turn, means it is more likely that more miles of roads can be saved before they deteriorate to the point where expensive reconstruction becomes necessary.
2. Life cycle costs for basic CIR are clearly the lowest of the alternates considered. This means that the easy choice for present budgets will also produce optimum results for future budgets.
3. Best- and worst-case comparisons show CIR with chip seal to have the lowest life cycle costs and the 2-in. hot-mix overlay to have highest life cycle cost, with CIR with OGEM in the middle. Ranges of costs do overlap.
4. CIR's advantages would increase in cases where haul distances are large and hot-mix suppliers are few or not competitive. CIR's advantages would decrease with short haul distance and highly competitive hot-mix suppliers.
5. Analysis does not include user costs. Inclusion of user costs would decrease the advantages of CIR.

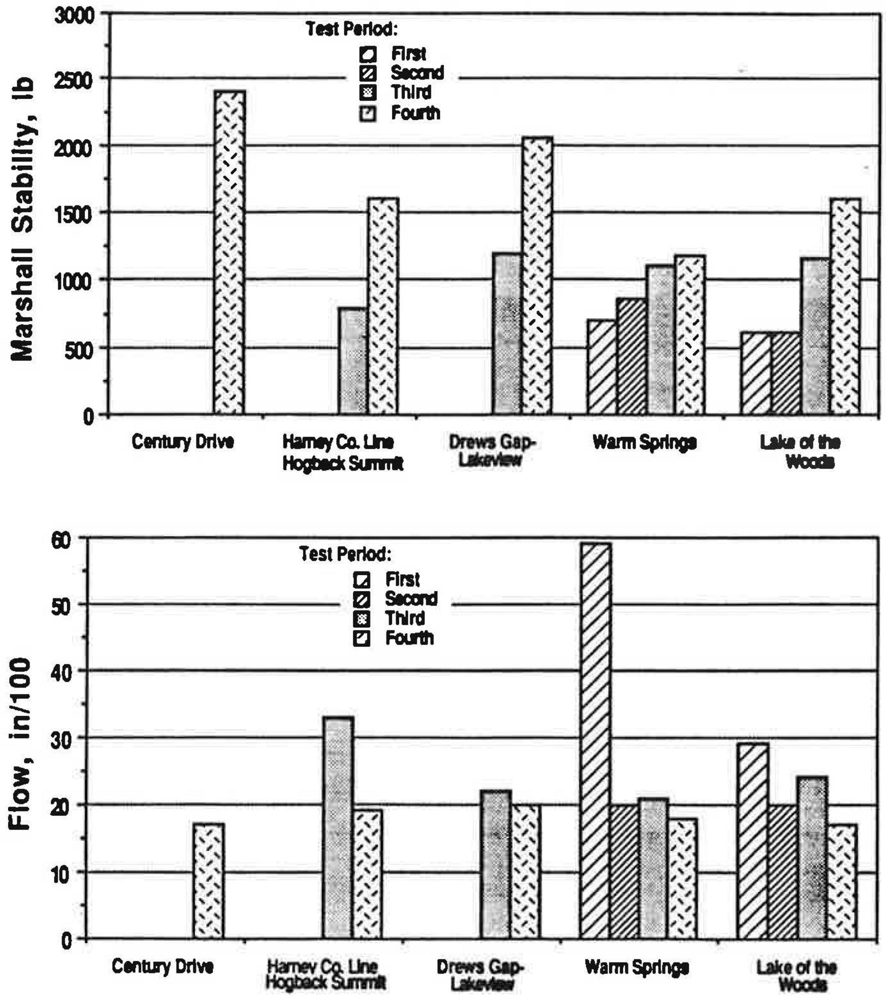


**FIGURE 6 Marshall stability (*top*) and flow (*bottom*) test results.**

TABLE 6 TYPICAL COSTS FOR CIR VERSUS HOT MIX—ODOT

| Item | Construction Cost | Maintenance Cost |
|---|---|---|
| CIR (2-in.) with chip seal | \$1.70 - \$2.10/sq.yd. | Best Case: Maintenance of \$1200/mi/yr beginning in 6th year and increasing 25% each year. Worst Case: Maintenance of \$1200/mi/yr beginning in 3rd year and increasing 25% each year |
| CIR (2-in.) with 1½-in. OGEM | \$2.20 - \$3.00/sq.yd. | \$8,700/mile after 7 years (chip seal) |
| 2-in. Hot Mix Overlay | \$2.75 - \$4.00/sq.yd. | Maintenance of \$1200/mi/yr beginning in 8th year and increasing 25% each year |

TABLE 7 RESULTS OF LIFE CYCLE COST ANALYSIS

| Item | Equivalent Annual Cost Per Mile |
|---|---|
| CIR (2-in.) with chip seal | \$4,500 - \$6,600 |
| CIR (2-in.) with 1½-in. OGEM | \$4,800 - \$8,100 |
| 2-in. Hot Mix Overlay (with maintenance) | \$5,400 - \$8,600 |

6. The fact that the hot-mix overlay alternate has greater structural section (thickness) than the CIR alternates is not reflected in this economic analysis.

## SUMMARY AND CONCLUSIONS

As previously stated, CIR is effective in restoring cracked, broken, raveled, or rough pavements where ADT is 5,000 or less. CIR may also be used for leveling and as a base for overlay. The volume limitation of ADT of 5,000 or less is a result of traffic control problems during construction rather than being related to load. Because of this, CIR is now being considered for higher-volume highways (multilane, including Interstates) where traffic can be effectively controlled. Studies are underway to determine if CIR may be used on pavement with stripping problems. CIR should not be used where pavement has rutted because of a fat mix, or where conditions are too cold and damp to allow adequate curing of the emulsion.

When considering the use of CIR, potential problems must be considered. Implications for traffic control must be thoroughly evaluated. If CIR is to be followed with a chip seal, the usual precautions regarding loose chips must be taken. It is essential that climate conditions allow for the curing of the asphalt emulsion; several warm days and nights are required to allow for adequate curing.

When CIR can be used, it represents a cost-effective method for restoring asphalt pavements of low-volume roads. Ride quality is superior to any type of patching. As has been demonstrated by life cycle cost analysis, CIR is more cost-effective than the application of hot-mix overlays. From a first-cost standpoint, only simple fog seals or chip seals are more economical, and these do nothing to level the pavement.

The preceding discussion leads to the following conclusions:

1. Current state-of-the-art in recycling equipment allows effective cold recycling of asphalt pavements.
2. CIR projects are performing well in the high desert environment of central and eastern Oregon. Performance evaluations in western Oregon are just underway.
3. CIR may be the most cost-effective restoration treatment for low-volume asphalt pavements. Life cycle cost analysis indicates a clear preference for CIR over conventional hot-mix overlays.
4. CIR provides environmental and energy conservation benefits realized through savings in materials and fuel.

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