Case Histories of Cold In-Place Recycled Asphalt Pavements in Central Oregon

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Region 4 of the Oregon Department of Transportation (ODOT) began the use of cold in-place recycling (CIR) for rehabilitation of asphalt pavements in 1984. The process has proven successful and today is an important part of ODOT's surface preservation strategies. ODOT, with assistance from Oregon State University, has actively monitored selected CIR projects constructed between 1984 and 1988. Detailed data are presented for 10 projects with regard to visual inspection, deflection data before and after recycling, diametral resilient modulus and fatigue, and Marshall stability and flow. A tabulation of service life estimates for 47 CIR projects and the life cycle cost implications thereof are also presented. Most of the CIR projects have only been chip sealed. In several cases cold, open-graded overlays have been applied. Significant findings include the following: (*a*) deflections before and after CIR are about the same, and no structural improvement should be expected; (*b*) generally, for CIR projects over time, diametral modulus and fatigue life and Marshall stability increase while Marshall flow decreases; and (*c*) with the exception of two significant failures, life cycle costs for CIR projects ranged from 37 to 82 percent of the cost of a 2-in. hot mix overlay.

Case history and performance data for cold in-place recycling (CIR) projects constructed and maintained by the Oregon Department of Transportation (ODOT) are presented. The first project was constructed in 1984. Performance data are presented through 1990.

After a presentation of background information and a statement of purpose, a brief description of the two construction processes used is provided. Mix property data derived from field cores and deflection data are presented. Estimated service lives are presented, followed by a life cycle cost analysis. Finally, conclusions are drawn.

BACKGROUND

ODOT constructed its first CIR project in 1984 in an attempt to more effectively use the limited maintenance and preservation funds available. Innovative procedures were desired to halt the decline in pavement condition ratings. It was hoped that use of CIR would allow restoration of ride quality and drainage crown for more miles of highway than conventional procedures, thus preventing further deterioration and "buying time" before overlays could be accomplished.

Region 4 of ODOT has led Oregon's CIR efforts. Region 4 is characterized by a high-desert environment with large temperature extremes and frequent freeze-thaw cycles, low population density, and consequently considerable mileage of low-volume roads. It is an area where thermal cracking and oxidation of asphalt pavements are serious problems. CIR showed potential as a low-cost method for quickly restoring the distressed asphalt pavements. Results from the initial CIR project in 1984 were so successful that more projects were constructed in 1985. Since that time, use of CIR has grown steadily in Region 4, and CIR has been used in other regions of ODOT. More than 500 centerline miles of two-lane asphalt roads has been restored.

To speed the development of CIR and to gather data to assess the performance and cost-effectiveness of CIR, ODOT contracted with Oregon State University (OSU) for two research projects running concurrently from 1986 through 1990. The projects provided data on deflections, mix properties, and pavement condition, as well as service life expectations and life cycle costs. Information from these research projects is presented elsewhere (*1–4*).

This paper is presented as a means to share the performance, service life, and life cycle cost information gained through the research described. This information should be useful to those who must make decisions about maintenance and rehabilitation of asphalt pavements.

DESCRIPTION OF PROJECTS

Construction

Oregon's CIR projects have been constructed using two different methods. Contracted projects have used a complete recycling train, including milling machine, screening deck, crusher, pugmill, and paving machine. Other projects have been completed using state maintenance forces and a single-unit train approach. The single-unit train, operated by ODOT, is a milling machine capable of metering recycling agent and mix water into the milling chamber and depositing the material in a windrow. The windrow is picked up and placed using a conventional asphalt paving machine.

Except for test sections, ODOT's CIR projects have used two types of emulsified asphalts: CMS-2S (now designated CMS-2RA) and high-float emulsions (HFE), primarily HFE-150. High-floats have been both conventional and polymer modified. The CMS-2S is a cationic medium set emulsion with up to 12 percent naphtha.

Performance

Ten projects were chosen for intensive study and are given in Table 1, which also includes construction information (i.e.,

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TABLE 1 CIR PROJECTS (1984–1988) CHOSEN FOR IN-DEPTH EVALUATION

Year	Highway	Project Name	Length (mi.)	Recycle Depth (in.)	Emulsion Type (Content)	Surface Treatment
1984	OR 372	Sand Shed-Mt. Bachelor	5.0	1.5	CMS-2S (1-2%)	Surface left open winter of 1984, chip sealed in 1985
1985	OR 20	Drews Gap-Lakeview	11.0	1.5-2	CMS-2S (1-2%)	Polymer chip seal
	OR 49	Harney Co. Line-Hogback Summit	30.7	1.5-2	CMS-2S (1-2%)	Chip seal
1986	OR 53	MP 79.2-Wasco Co. Line	17.3	2-4	CMS-2S (1%)	Polymer chip seal
	OR 41	MP 89.6-Jct. OR 19	8.7	1.5-2	CMS-2S (1.4-1.5%)	Chip seal
	OR 270	Lakeshore Dr.-Greensprings Jct.	6.4	2.5-4	CMS-2S (1.4%)	Chip seal
	OR 372	Lava Springs-Sand Shed	5.7	2	CMS-2S (1%)	Chip seal
1988	OR 426	Jct. Klamath Falls-Malin Hwy-CA Line	2.8	2	CMS-2S (0.5%)	None
	OR 42	MP 13.27-Moro	4.8	2	HFE-150 (1.0%)	Polymer chip seal
	OR 22	Fort Klamath-Crooked Creek	5.7	2	HFE-150 (1.1%)	Sand seal

project length, class of recycle, type of emulsion used, etc.). Table 2 presents a summary of performance data obtained for the 10 projects. Summary discussions of these projects follow.

OR-372, Sand Shed–Mt. Bachelor (1984)

Visual inspection indicated that this project had a fair overall condition rating in both 1989 and 1990. The project has had signs of some fatigue (alligator) cracking and potholes, minor rutting and flushing, and has had some patching. It is expected to have a service life of 9 years without significant patching. This project has little truck traffic but heavy recreational traffic during the winter ski season. Figure 1 gives an indication of the surface condition of this project in 1990.

This section was fairly typical of CIR treatments in that deflections increase 7 percent after CIR. Five years after construction, cores indicated air voids of 7.7 percent and some of the highest modulus, fatigue, and Marshall stability values of the projects tested. Since experience indicates strengthening of CIR treatments with age and the curing of the emulsion, and since this is ODOT's oldest project, this is not surprising. This has been a very successful project.

OR-20, Drews Gap–Lakeview (1985)

In 1989, this project had a fair to good condition rating with minor distress, mainly thermal cracking, and some flushing in the wheel tracks. The 1990 rating was still fair. The project is expected to have a service life of 8 years, although chip sealing was required on the project after only 2 years. Initial CIR depth was 1½ in. Although ride quality after CIR was good, about ⅜ in. of the recycled pavement was milled as part of the CIR project to improve ride. The milling did not prove worthwhile.

Figure 2 shows both the 1990 surface condition at the location of cores and an example of a full-width transverse crack on this project. Similar transverse cracks 1 year after a hot mix overlay would not be uncommon in this climatic region. ODOT engineering and maintenance personnel believe that recycling to a depth one-half to two-thirds of the pavement section is required to prevent reflective cracking. This project only recycled 1½ in. of an existing 4- to 5-in. AC pavement.

Changes in deflection with the CIR treatment were highly variable, increasing in some cases and decreasing in others. Air voids were the lowest of any of the projects studied. All mechanical test results were considered favorable 4 and 5 years after construction. This has been a successful project.

OR-49, Harney Co. Line–Hogback Summit (1985)

This project is divided into three sections for discussion purposes as follows: Harney Co. Line–Bacon Camp Rd. (14 mi), Bacon Camp Rd.–MP 57 (8 mi), and MP 57–Hogback Summit (9 mi).

The first section had a fair condition rating in 1989 with minor distress (minor rutting, flushing, and fatigue cracking). However, between Mileposts 39 and 41, sections of the pavement had raveled badly, with some areas showing bare gravel whereas others were fat with asphalt. Between Mileposts 44 and 47 the pavement looked fine with no potholes but had slight bleeding problems.

The second section had a fair condition rating in 1989 but looked dry in asphalt, with some of the pavement falling apart in large potholes. Consequently, maintenance work had been required on this section.

TABLE 2 SUMMARY DATA FOR 10 SELECTED PROJECTS

Project	Year Constr.	Change in Defl. Bef/Aft CIR	Air Voids (%)		Average Modulus		Fatigue Life (1000 cycles)		Marshall Stability (lb)		Marshall Flow (in./100)		Life as Wearing Course		Total* Expected Life as Wearing Course	Condition Rating		Research Team's Evaluation of Project
			1988	1989	1988	1989	1988	1989	1988	1989	1988	1989	Before Sig. Patching	After Sig. Patching		1989	1990	
Sand Shed-Mt. Bachelor	1984	7%		7.7		713		138		2410		17			9	fair	fair	very successful
Drews Gap-Lakeview	1985	-16% to 34%	5.8	5.2	499	531	62	98	1196	2049	22	20	2	6	8	fair-good	fair	successful
Harney Co. Line-Hogback Summit	1985	-1% to 5%	8.8	10.1	508	485	109	176+	788	1607	33	19	2	5	7	fair-poor	good	satisfactory
M.P. 79.2-Wasco Co. Line	1986	-2% to 18%	10.8	7.4	377	526	54	150+	1106	1181	21	18	1	2	3	fair-poor	fair	unsuccessful
M.P. 89.6-Jct. OR 19	1986	-26% to -17%	9.8	6.6	607	479	47	58	928	1372	22	17			8	good	fair	successful
Lakeshore Dr.-Greensprings Jct.	1986	-5% to 6%	12.9	13.0	530	727	79	250+	1171	1597	24	17	3	6	9	good	fair	successful
Lava Springs-Sand Shed	1986		11.3	13.3	451	487	59	119	1392	1625	29	18			6	good	fair	successful
Jct. Klamath Falls-Malin Hwy-CA Line	1988		10.1	9.1	603	780	28	41	1028	1816	21	19			7	good	fair	successful
M.P. 13.27-Moro	1988	23% to 51%	12.4	11.7	253	445	18	26	683	1566	26	17					good	successful
Fort Klamath-Crooked Creek	1988		14.5	12.9	490	501	11	24	595	1023	24	17			8	good	fair	successful

*Based on most pessimistic of estimates by Region Engineer and District Maintenance Supervisor.

FIGURE 1 Sand Shed–Mt. Bachelor typical surface condition, May 1990.

The third section had a poor condition rating in 1989 with more pronounced rutting and thermal cracking relative to the other two sections. Although the pavement looked acceptable, the surface had a rough texture. The rough texture was the result of milling the surface after CIR. It was thought at the time that milling would improve the ride. It did not, and this extra procedure is no longer used.

The condition ratings made in 1988 and 1990 gave overall ratings to this total project of good, compared with a poor rating in 1989. The differences in surface ratings are understandable. This is a difficult project to rate. The research team inspected this project in May 1990. Clearly there were areas where localized failures had required maintenance. Many of these were related to base failures. Still, the condition of most of the project was good.

In 6 years (1985 to 1991) this long section (> 30 mi) has required minimal maintenance on a highway that was, before CIR, severely broken and, in the opinion of ODOT personnel, 1 to 2 years away from total failure. Had this low-volume road (ADT 220) failed, protests from taxpayers and users would have been so great that ODOT would have had to design and construct a structural overlay at costs up to $300,000/mi. The only source for funding would have been a diversion of funds from a high-volume road such as US-97 (3,000 to 10,0000 ADT and 800 to 1400 trucks per day). In this case, CIR did more than buy time—it kept agency costs on the low-volume highway low and allowed the preservation of funds needed for high-volume roads. Thus, in spite of some ongoing maintenance and local base failures, for this low-volume highway CIR presented the best outcome considering known alternatives and budget restraints.

This project, in excess of 30 centerline mi, is expected to have a total service life of 7 years. Significant patching began in localized areas after only 2 years. Deflections for this project changed very little with the CIR treatment. Mechanical properties of cores tested are good. Fatigue lives are high. This project has had satisfactory performance, considering base conditions and possible alternative maintenance strategies.

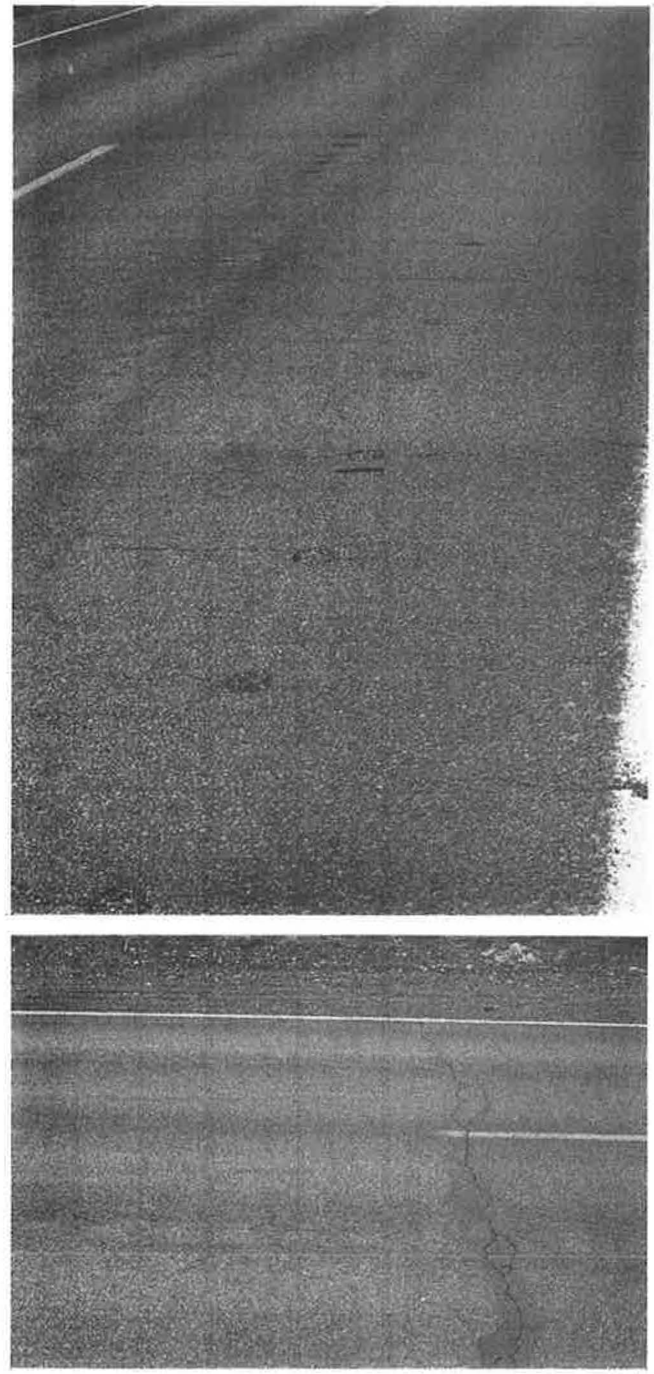

FIGURE 2 Drew's Gap–Lakeview surface condition, May 1990: *top*, at location of cores; *bottom*, typical transverse crack.

OR-53, MP 79.2–Wasco Co. Line (1986)

This project was divided into two sections for inspection purposes with both sections showing distress. In 1989, one section had a fair condition rating, whereas the other had a poor rating. Both projects received fair ratings in 1990. Significant maintenance work has been required to maintain these ratings. Because of the failure of this project, it has been intensively studied. It was determined that the pavement was recycled with too high an emulsion content and that a polymer chip seal was placed too soon, trapping moisture and solvent in the pavement.

This project was visited in August 1990 when a section was being re-recycled, this time with a target addition of 3 percent lime. Stripping had been a problem. It was hoped that recycling with lime could stabilize this problem. Initial indications are that re-recycling with lime is working. Inspection in December 1991 showed no signs of distress.

Also during the August 1990 visit, the entire length of the 1986 recycle project was examined. The conclusion was that only about 30 percent of the original project was still serving as a wearing course, and most of that was heavily patched. Large sections had been inlaid.

The deflections and mechanical properties measured for this project give no indication that the majority of the project was a failure, except perhaps the 1989 Marshall stabilities, which are relatively low for 3-year-old CIR pavements. Most of the project had a service life of only 3 years, with maintenance beginning the first year. This project was considered to be unsuccessful.

OR-41, MP 89.6–Jct. OR-19 (1986)

In 1989 this project had a good condition rating. Only minor distress (some rutting and flushing) was apparent, and the pavement had experienced only minor maintenance work. The surface condition had fallen to fair in the 1990 rating.

Deflection readings for this project were unusual in that both readings decreased after CIR treatment. This was also only one of two projects showing a decrease in modulus between 1988 and 1989 cores.

Service life is predicted to be 8 years, with no significant patching experienced to date. This has been a successful project.

OR-270, Lakeshore Dr.–Greensprings Jct. (1986)

In 1989, this project had a good condition rating with only minor distress. Some fat spots were apparent, and cracks in the shoulders were beginning to spread into the recycled pavement. Also, some signs of raveling had appeared in the eastbound lane. In 1990, the surface condition rating had dropped to fair, but there were still no signs of serious distress.

The air voids for this project are the highest of the 1986 projects cored, but mechanical properties still look good. Service life is predicted to be 9 years with only minor patching experienced after 3 years. This has been a successful project.

OR-372, Lava Springs–Sand Shed (1986)

This project was rated good in 1989 and fair in 1990. It has experienced no significant patching to date and is expected to have a service life of 6 years. Figure 3 shows the contrast between the recycled travel land and the nonrecycled shoulder area.

FIGURE 3 Lava Springs–Sand Shed, May 1990. Nonrecycled shoulder on left and recycled travel lane on right.

No unusual results are apparent from mechanical testing. This has been a successful project.

OR-426, Jct. Klamath Falls–Malin Hwy–CA Line (1988)

In 1989 this project had a good condition rating after having been in service through one winter. No maintenance work had been performed, and only minor distress was apparent. The original pavement was stripped. The surface condition rating had fallen to fair in 1990, but service life is still expected to be 7 years, and no significant patching has been experienced to date. Air voids were relatively low, and modulus and 1989 Marshall stability were relatively high, given the age of the pavement. This is a successful project.

OR-42, MP 13.27–Moro (1988)

The pavement had a consistent gradation and asphalt content throughout the project in 1989. However, areas in the wheelpaths had started to show signs of flushing of chip seal and had a somewhat smooth appearance. ODOT's 1990 rating for this section was good. No forecast of service life was available. This project was unusual in that deflection increases after CIR were substantial. In spite of the apparent increase in deflection, this project has withstood 500 heavy trucks per day quite well. This is a successful project.

OR-22, Fort Klamath–Crooked Creek (1988)

In 1989 this project had a good condition rating. However, the pavement had some segregation problems as well as some raveling, bleeding, and cracking. The 1990 rating was fair. Expected service life is 8 years. This project had the highest air voids (the RAP was an open-graded mix) and lowest fatigue life and stability of the 1988 projects that were cored. This is a successful project.

Deflection

Deflection data have been obtained over time on 9 of the 10 projects selected for more intensive study. In all cases the deflections are the average of 11 readings obtained using the ODOT Dynaflect. The deflections are those recorded for geophone Number 1 adjusted to a standard pavement temperature of 70°F.

The changes in deflection from the last available deflection before CIR treatment and the first measurement after CIR were summarized in the third column of Table 2. In the best case, deflections measured after CIR were 26 percent less than before. In the worst case, deflection measured after CIR increased 51 percent. When all of the deflection data are examined, in most cases, the change in deflection resulting from CIR treatment is less than 10 percent. When all of the change values are averaged, the mean change in deflection for CIR treatments is an increase in deflection of 9 percent.

Examination of the deflection data leads to the conclusion that CIR cannot be expected to increase the stiffness of the pavement section. Although on the average CIR resulted in slightly increased deflections, the increase was small, essentially maintaining the stiffness of the existing pavement.

Figure 4 shows results of deflection measurements over time for the oldest CIR project, Sand Shed–Mt. Bachelor. Deflections have increased only slightly in the 5 years since construction. Deflection over time plots for other projects show similar curves.

Mix Properties

To aid in the evaluation of cold recycled pavement performance, mix properties have been investigated over time. Mix property tests have been conducted on cores taken in fall 1988 and fall 1989 from the 10 projects being intensively evaluated for life expectancy of recycled pavements. Tables 3 and 4 summarize the test results. The tests performed on these cores included

1. Bulk and theoretical maximum specific gravities (ASTM D2726 and ASTM D2041),
2. Asphalt coating,
3. Diametral modulus and fatigue (ASTM D4123), and
4. Marshall stability and flow (ASTM D1559).

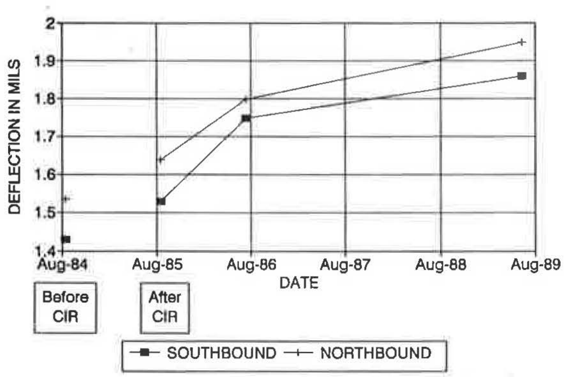

FIGURE 4 Deflection over time, Sand Shed–Mt. Bachelor MP 17.5.

The air voids and asphalt coating results (see Table 3) generally indicate the following:

1. Voids are between about 5 and 15 percent with several of the older (pre-1987) projects showing void contents of 10 percent or less.
2. Asphalt coating (on broken surfaces) ranges between 30 and 100 percent (from dry or uncoated to sufficiently coated). Five of the 10 projects were reported with asphalt coating of 50 percent or less when 1989 cores were examined. This is a dramatic change from examination of 1988 cores, which showed the minimum coating observed to be 80 percent. Nothing in the field performance of these projects indicates that such a change has taken place. The most likely explanation is that it is difficult to interpret asphalt coating for recycled asphalt pavements.

The diametral modulus and fatigue test results for the field cores are summarized in Table 4. All modulus tests were conducted in accordance with ASTM D4123 (*5*). The tests were conducted at 23°C, at a pulse load frequency of 1 Hz, with a pulse load duration of 0.1 sec, and at a pulse load magnitude to induce a tensile strain of 100 microstrain ($\mu\varepsilon$). The fatigue tests were conducted in the diametral mode under the same loading conditions and temperatures as that of the modulus tests. The results of these tests generally indicate that

1. Moduli of 1988 cores range between about 250 and 600 ksi;
2. Moduli of 1989 cores range between about 450 and 800 ksi;
3. Little change in modulus for four projects, dramatic increase in modulus for four projects, and about a 20 percent decrease in modulus for one project;
4. Fatigue lives of 1988 cores range between about 10,000 and 110,000 cycles to failure;
5. Fatigue lives of 1989 cores range between about 24,000 and lives in excess of 150,000 cycles to failure; and
6. Fatigue lives for 1989 cores increased compared with 1988 cores in all cases, and dramatically in most cases.

Table 5 summarizes the Marshall stability and flow values from tests of the field cores. These tests were conducted in accordance with ASTM D1559 (*5*) at 60°C. The results generally indicate the following:

1. Stabilities for the 1988 cores range between about 600 and 1,400 lb.
2. Stabilities for the 1989 cores range between about 1,000 and 2,400 lb.
3. All projects but one show significant increases in stabilities from 1988 to 1989 cores. The other project shows only a slight increase.
4. Flow values for the 1988 cores range between 21 and 33 in./100.
5. Flow values for the 1989 cores range between 17 and 20 in./100.
6. All projects show decreases in flow from 1988 to 1989 cores, and in most cases the decrease is substantial.

TABLE 3 CORE LOCATIONS AND PROPERTIES

Project	Highway	Year Constructed	Test Period	M.P. & Location	Bulk Gravity	Rice Gravity	% Voids	Asphalt Coating*	
								%	Notes
Sand Shed- Mt. Bachelor	OR 372	1984	Fall 88	not cored					
			Fall 89	22.00, 7'L	2.273	2.462	7.7	100	Sufficient
Drews Gap- Lakeview	OR 20	1985	Fall 88	87.40, 9'L	2.116	2.247	5.8	95	
			Fall 89	87.40, 9'L	2.152	2.270	5.2	90	Sufficient
Harney Co. Line- Hogback Summit	OR 49	1985	Fall 88	64.50, 8'R	2.030	2.226	8.8	85-90	
			Fall 89	64.20, 9.5'R	2.005	2.230	10.1	30-45	Dry
M.P. 79.2- Wasco Co. Line	OR 53	1986	Fall 88	89.90, 7'L	2.273	2.549	10.8	85-90	
			Fall 89	89.90, 8'L	2.381	2.571	7.4	50	Dry
M.P. 89.6- Jct OR 19	OR 41	1986	Fall 88	96.40, 8.5'L	2.241	2.484	9.8	85-90	
			Fall 89	96.40, 7'L	2.338	2.502	6.6	30-45	Dry
Lakeshore Dr- Greensprings Jct	OR 270	1986	Fall 88	63.36, 9'R	2.132	2.448	12.9	85	
			Fall 89	63.36, 9'R	2.141	2.461	13.0	75-80	Dry-sufficient
Lava Springs- Sand Shed	OR 372	1986	Fall 88	14.60, 8.5'L	2.134	2.405	11.3	90-95	
			Fall 89	14.60, 7'L	2.088	2.409	13.3	65-70	Dry-sufficient
Jct Klamath Falls- Malin Hwy-CA Line	OR 426	1988	Fall 88	1.00, 10'R	2.159	2.402	10.1	80	
			Fall 89	1.00, 10'R	2.190	2.410	9.1	40	1.4-in.+ uncoated
MP 13.27-Moro	OR 42	1988	Fall 88	16.00, 9.5'R	2.235	2.551	12.4	85-90	
			Fall 89	16.00, 9'R	2.283	2.585	11.7	95-100	Sufficient
Fort Klamath- Crooked Creek	OR 22	1988	Fall 88	94.00, 9'R	2.002	2.342	14.5	85-90	
			Fall 89	94.00, 8'R	2.034	2.335	12.9	40	Dull

*Visual inspection of broken cores

TABLE 4 MODULUS AND FATIGUE RESULTS

Project	1988		1989		1988		1989	
	Resilient Modulus (ksi)	Average Modulus (ksi)	Resilient Modulus (ksi)	Average Modulus (ksi)	Fatige Life (reps)	Average Fatigue (reps)	Fatigue Life (reps)	Average Fatigue (reps)
Sand Shed- Mt. Bachelor	Not cored in fall 1988		757 501 882	713	Not cored in fall 1988		**** 138184 85983*	138184
Drews Gap- Lakeview	467 535 494	499	550 562 481	531	51046 72798 61571	61805	** 73860 122291	98076
Harney Co. Line- Hogback Summit	453 558 514	508	395 530 529	485	111276 108712 106608	108865	192473* 159821 ***	176147+
M.P. 79.2- Wasco Co. Line	371 351 410	377	518 527 535	526	45929 68725 47240	53965	150100* ** **	150000+
M.P. 89.6- Jct OR 19	588 586 646	607	399 492 546	479	31536 69347 40360	47081	73030 61343 39355	57909
Lakeshore Dr- Greensprings Jct	545 513 533	530	749 771 661	727	69519 94655 72018	78731	46034 542379* 160561	250000+
Lava Springs Sand Shed	433 467 452	451	520 506 436	487	72099 67633 38015	59249	151231 94114 111563	118969
Jct Klamath Falls- Malin Hwy-CA Line	628 563 617	603	815 821 704	780	30885 24767 28909	28187	38444 24209 58803	40485
M.P. 13.27-Moro	187 246 326	253	462 466 409	445	23416 22523 8499	18146	41553 14600 22344	26166
Fort Klamath- Crooked Creek	495 520 456	490	475 522 506	501	14110 8096 10267	10824	28026 22800 20219	23682

*Test intentionally terminated due to excessive fatigue life, **test equipment failure, ***purposely did not test due to excessive fatigue life of other cores, ****localized failure near the loading strip.

TABLE 5 MARSHALL STABILITIES AND FLOWS—FIELD CORES

Project	1988		1989		1988		1989	
	Marshall Stability	Average Stability	Marshall Stability	Average Stability	Flow (in/100)	Average Flow (in/100)	Flow (in/100)	Average Flow (in/100)
Sand Shed-Mt. Bachelor	Not cored in fall 1988		2454 2365 2412	2410	Not cored in fall 1988		17 17 16	17
Drews Gap-Lakeview	1251 1142 *	1196	2274 1693 2180	2049	22 23 *	22	18 21 19	20
Harney Co. Line-Hogback Summit	774 859 731	788	1542 1771 1508	1607	30 37 31	33	20 20 16	19
M.P. 79.2-Wasco Co. Line	1127 1107 1084	1106	1240 1102 1202	1181	22 19 21	21	19 18 15	18
M.P. 89.6-Jct OR 19	1007 934 844	928	1214 1429 1473	1372	20 23 22	22	16 18 17	17
Lakeshore Dr-Greensprings Jct	1167 1131 1216	1171	1722 1456 1614	1597	21 28 22	24	16 18 16	17
Lava Springs Sand Shed	1762 1219 1194	1392	1396 1714 1764	1625	34 23 31	29	18 20 17	18
Jct Klamath Falls-Malin Hwy-CA Line	897 1104 1084	1028	1553 2079	1816	22 23 18	21	21 17	19
M.P. 13.27-Moro	663 760 625	683	1467 1641 1589	1566	25 35 18	26	17 18 16	17
Fort Klamath-Crooked Creek	563 602 620	595	1085 1062 921	1023	24 25 24	24	18 17 17	17

The increases in modulus, fatigue life, and Marshall stability over time are probably due to the continued curing of the emulsion and the hardening of the original asphalt in the RAP material, as well as in some cases decrease in air voids due to compaction under traffic. The two oldest of the nine projects for which both 1988 and 1989 cores were available, Drew's Gap–Lakeview and Harney Co. Line–Hogback Summit, still showed significant increases in fatigue life and stability between the third and fourth years after construction.

Estimated Service Lives

At the end of summer 1990, the district maintenance supervisors (DMSs) and Region 4 engineer were asked to make their best estimate of the service lives for 47 CIR projects constructed from 1984 to 1988. Thus, in most cases, two estimates of service lives were obtained. When the estimates did not agree, the more pessimistic of the estimates was used. Table 6 summarizes the estimates.

TABLE 6 ESTIMATED SERVICE LIVES OF CIR PROJECTS

Category	Total Number of Projects	Number of HFE Projects	Life as Wearing Course Before Sig. Patching (yrs)	Life as Wearing Course After Sig. Patching (yrs)	Total Life as Wearing Course (yrs)	Years Without Maint. So Far (yrs)	Life as Base Course After Overlay and Before Next Overlay (yrs)
Projects Currently Serving as Wearing Course							
Without Significant Maintenance	14	3			7.9	4.5	
With Significant Maintenance	18	2	1.9	4.7	6.6		
Projects Which Have Been Overlaid							
Immediate Overlay	5	3					6.6
Served as Wearing Course Prior to Overlay							
Without Significant Maintenance	4	2			1.8		8.5
With Significant Maintenance	4		1.5	2.0	3.5		7.0
Projects Which Have Been Inlaid	2		2.0	1.0	3.0		
	47	10					

The projects for which service life estimates were obtained were divided into six categories, depending on whether the CIR treatment has been overlaid or inlaid or is serving as a wearing course, and whether the CIR treatment has experienced "significant" patching. Of the 47 projects, 13 have been overlaid, 2 have been inlaid, and 32 are serving as wearing courses. Only the two projects requiring inlays are considered failures. Of the 32 projects serving as wearing courses, 14 (44 percent) have not had significant patching so far (average age of 4.5 years) and are projected to have total average service lives of 7.9 years. The projects currently serving as wearing courses and having experienced significant patching first required maintenance after an average of 1.9 years and expect total service lives of 6.6 years. Weak areas or areas of poor CIR become apparent in the first 2 years.

The data are inconclusive regarding the relative merits of CMS-2S and HFE-150. The early projects were all done with CMS-2S. Of the CIR treatments currently serving as wearing courses, the average service life expectancy is 7.2 years, which is exactly the average life expectancy of the five HFE projects included among these 32 sections. Again for the sections serving as wearing courses, the HFE projects are slightly overrepresented in the "without patching" group (3 of 14) and slightly underrepresented in the "with" patching group (2 of 18). The difference is inconclusive, however.

LIFE CYCLE COST ANALYSIS

Life cycle costs were analyzed for all of the cases covered in Table 6 and compared with the alternative of a hot mix overlay. Equivalent annual cost analysis was chosen to simplify the comparison between alternatives of differing economic lives. It is assumed that when an alternative's economic life is reached, the same cycle will be repeated, essentially in perpetuity.

Table 7 summarizes the inputs and outputs from the life cycle cost analysis. The construction costs are based on analysis of costs for "surface preservation" jobs by Region 4 of ODOT. Construction costs represent total project costs divided by area of surface "preserved" in 1989–1990 dollars. The maintenance costs shown are the best estimates based on information from the Surfacing Design Unit of ODOT and from conversations with district maintenance personnel. The timing of expenditures is based on the summaries presented in Table 6. The equivalent annual costs of the different types of CIR experience in Oregon are presented in the last column of Table 7. An interest rate of 8 percent was used.

Table 7 indicates that all of the CIR experiences, except the two inlaid projects, have a clear cost advantage over the alternative of 2 in. of hot mix overlay. Costs of successful CIR projects vary from 37 to 82 percent of costs for the hot mix alternative. Only the two failed (inlaid) CIR projects resulted in higher costs than the hot mix alternative. These costs do not consider user costs—only costs to ODOT are considered. No credit is given to the increased structural section of the overlay options.

The cost-effectiveness of CIR compared with the hot mix overlay was not sensitive to changes in interest rate. The successful CIR alternatives were always preferred when interest rates were varied between 0 and 20 percent. Increasing

TABLE 7 LIFE CYCLE COST ANALYSIS

	Category	Expenditures	For	Timing	Life Cycle (yrs)	Equivalent Annual Cost ($/mi)
Projects Currently Serving as Wearing Course	Without Significant Maintenance					
	a) optimistic assumptions	$2.10/sy	CIR with chip seal	Initial	8	$5100
	b) pessimistic assumptions	$2.10/sy $4000/mi/yr	CIR with chip seal Maintenance	Initial Annually after 5th year	8	$6500
	With Significant Maintenance	$2.10/sy $1200-$4000/mi/yr	CIR with chip seal Maintenance	Initial Annually after 2nd year	7	$6300-7900
Projects Which Have Been Overlaid	Immediate Overlay	$3.06/sy	CIR with 2" OGEM	Initial	7	$11,000
Served as Wearing Course Prior to Overlay	Without Significant Maintenance	$2.10/sy $2.88/sy	CIR with chip seal 2" OGEM with chip seal	Initial After 2nd year	10	$10,800
	With Significant Maintenance	$2.10/sy $1200-$4000/mi/yr $2.88/sy	CIR with chip seal Maintenance 2" OGEM with chip seal	Initial End of years 2 through 3 End of 4th year	11	$9700-10,600
Projects Which Have Been Inlaid		$2.10/sy $1100-$4000/mi/yr	CIR with chip seal Maintenance	Initial After 1st year	3	$17,600-20,300
2" Hot Mix Overlay Alternate		$5.25/sy $1250-$4000/mi/yr	2" hot mix overlay Maintenance	 After 10th year	12	$13,200-13,600

Notes:

Interest rate = 8%
Costs are for 1989-90
OGEM = Open-Graded Emulsion Mix

interest rates favor the CIR alternatives. Maintenance costs would have to rise to $17,500/mi/year (from the estimated $1,200 to $4,000/mi/year) before the CIR alternatives with maintenance early in their life cycles would lose their attractiveness compared with the hot mix overlay alternative.

CIR has energy conservation advantages. Consequently, as petroleum and energy costs increase, CIR becomes more cost-effective compared with hot mix because of savings in hauling costs, aggregate processing costs, and heating costs. CIR typically uses about 1 percent emulsion addition (0.6 percent asphalt), which is significantly less than the 5 to 7 percent of asphalt typically added to hot mix. Since asphalt is a petroleum derivative, this also improves the cost-effectiveness of CIR in periods of rising petroleum costs.

RISK

There is risk associated with CIR treatments. Not all of ODOT's experiences with CIR have been favorable. For the 47 projects given in Table 6, the worst experience resulted in portions of the project being inlaid after 3 years because of stripping problems with the aggregate. In hindsight, it would have been better to inlay the pavement at the time of the CIR treatment instead of performing the CIR. However, even though this was a bad experience, knowledge was gained and progress was made at a relatively low cost.

Experience in ODOT's Region 2 during the 1989 construction season has indicated that the greatest risk associated with CIR is improper project selection. During 1989, projects were chosen for recycling that were not good candidates for CIR. Sections had inadequate or no base and were experiencing base failures. Sections had AC pavement thickness of less than 2 in. Attempts were made to widen paving surfaces either by thinning out the pavement or incorporating unbound shoulder rock into the pavement. Existing pavement material had high moisture content. Areas of "eternal shade" were extensive on the projects chosen, causing curing problems. Failures resulted and the pavements required blade patching through the winter and were overlaid during the summer of 1990. Even with these "failures," the CIR eliminated any need for a leveling course.

CONCLUSIONS

Significant findings include the following:

1. Generally, deflections before and after CIR are about the same. The average change was an increase in deflection of 9 percent. No structural improvement should be expected with CIR.
2. Generally, for CIR projects over time, diametral modulus increases, diametral fatigue life increases, Marshall stability increases, and Marshall flow decreases.
3. ODOT engineering and maintenance managers believe the CIR to be "excellent" in stopping reflective thermal cracking when recycle depth is at least two-thirds the depth of the AC pavement.
4. Only 2 of 47 Region 4 projects for which service life data were available were clear failures. These two failures were 1986 projects, only 2 years after ODOT's first CIR attempts.
5. Life cycle cost analysis indicated that with the exception of the 2 failures noted above, life cycle costs for CIR surface preservation projects ranged from 37 to 82 percent of the 2-in. hot mix overlay alternative. The economics of increased structural section resulting from hot mix overlay were not considered.
6. Not all pavements may be effectively recycled. Proper project selection is important. For example, recycling of very nonuniform pavements or pavements less than 2 in. thick is not recommended. Recycling in cool, damp, sunless conditions presents curing problems. A list of types of conditions where CIR is not recommended is given elsewhere (*4*).

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REFERENCES

1. T. V. Scholz, R. G. Hicks, D. F. Rogge, and D. Allen. Use of Cold In-Place Recycling on Low-Volume Roads. In *Transportation Research Record 1291*, Vol. 2, TRB, National Research Council, Washington, D.C., 1991, pp. 239–252.
2. R. G. Hicks et al. *Development of Improved Mix Design and Construction Procedures for Cold In-Place Recycled Pavements*. OR/RD-87-06, Vols. 1 and 2. Oregon Department of Transportation, 1987.
3. T. V. Scholz, R. G. Hicks, and D. Allen. *Development of Improved Mix Design and Construction Procedures for Cold In-Place Recycled Pavements*. OR/RD-89-01, Vols. 3 and 4. Oregon Department of Transportation, 1988.
4. D. F. Rogge, T. V. Scholz, and R. G. Hicks. *In-Depth Study of Cold In-Place Recycled Pavement Performance, Vols. 1 and 2—Final Report*. FHWA-OR-RD-91-02 A&B, 1990.
5. *Annual Book of ASTM Standards*. Road and Paving Materials. Vol. 04.03, 1989.

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