Use of Asphalt Emulsions for In-Place Recycling: Oregon Experience

D. F. ROGGE, R. G. HICKS, T. V. SCHOLZ, AND DALE ALLEN

An overview of the use of emulsified asphalts for cold in-place recycling (CIR) of asphalt pavements by the Oregon Department of Transportation (ODOT) is presented. Project selection, design, construction, and inspection considerations are presented. ODOT has successfully used both CMS-2S (now called CMS-2RA) and high-float emulsions for recycling. Typical projects have been recycled to depths of 2 to 4 in. followed by either a chip seal or an open-graded emulsion mix. A brief overview of the CIR process is followed by a discussion of project selection—where to use and where not to use CIR. Procedures for estimating required water and emulsion additions to recycled asphalt pavement are presented. Procedures for field adjustments of emulsion and water content and for proper compaction of CIR pavements are presented. Finally, a discussion of problems experienced and appropriate preventive and remedial measures is presented. Significant findings include the following: (*a*) careful project selection is important to CIR project success; (*b*) the maintenance of proper proportions of emulsion and mix water is the biggest challenge in the field (the estimation procedure presented provides a good starting point and the discussion of construction control provides criteria for adjustments to meet changing field conditions); and (*c*) excess moisture from construction must be allowed to leave the mat before sealing, which should take place before winter conditions.

The national trend away from new construction to preservation of the highway system is requiring highway agencies to seek alternative approaches to rehabilitating distressed pavements. One promising and cost-effective approach is cold in-place recycling (CIR). Although CIR of asphalt pavements has been used in the United States in some form since the 1920s, several methods have evolved since 1980. During this period, spurred by the development of milling and reclaiming equipment, CIR has evolved into one of the fastest-growing pavement rehabilitation techniques.

BACKGROUND

Region 4 of the Oregon Department of Transportation (ODOT) constructed its first CIR project in 1984. Spurred by the initial success of the project, use of CIR in Region 4 has continued to grow, and other ODOT regions have investigated and constructed projects implementing CIR techniques. Figure 1 shows the growth of the use of CIR in ODOT Region 4. The sharp decrease from 1986 to 1987 was due to budgetary constraints. Although exact figures are not available for 1989 to 1991, it is known that CIR construction has continued to grow beyond the 1988 levels shown.

The term cold recycling is frequently misunderstood because it has been used to describe different processes used with substantially different design concepts and results. These processes include in-place recycling of bound asphalt concrete (AC) material only, as well as full-depth reclamation where unbound granular base material is incorporated with the addition of emulsified asphalt. ODOT has used recycling of AC material only. Consequently, CIR is discussed in this paper as the cold in-place recycling of AC materials only. Full-depth reclamation is not addressed.

When CIR is performed on a uniform pavement designed and built to specifications, it is expected that the recycled pavement can handle low to medium traffic as a wearing course (with chip seal) and medium traffic volumes as a base course. When CIR is performed on a pavement with significant maintenance patches over a uniform pavement or a pavement with minimal design used in the original construction, it is likely that the recycled pavement can be used as a wearing course only for low-volume roads.

CIR treatments produce significant cost savings (see Table 1) compared with conventional hot mix overlays (*1*). In addition, there are savings in energy, a conservation of materials, a reduced impact on the environment, and production rates as high as 6-lane mi per shift. Another significant advantage of CIR is the ability to limit the correction to the distressed lane.

ODOT has used the resources of Oregon State University (OSU) for developing CIR procedures and gathering and analyzing performance data. These research efforts are documented in detail elsewhere (*1–4*) and summarized by Scholz et al. (*5*). This paper is drawn primarily from Rogge et al. (*2*).

OBJECTIVES

The overall objective of this paper is to provide the user/contractor with a better understanding of the project selection, design, construction, and quality control consideration required to ensure a successful cold in-place recycled project. Specifically, the objectives are to provide the following:

1. Guidelines for project selection, sampling, and mix design;
2. Information on equipment, procedures, and specification for CIR;

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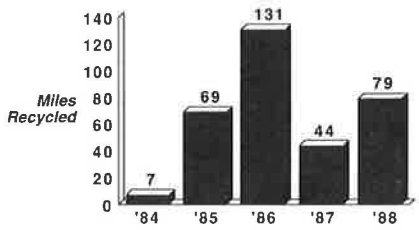

FIGURE 1 Growth in the use of CIR in ODOT Region 4.

3. Quality assurance guidelines for the engineer, contractor, and inspector; and
4. Guidelines for postconstruction evaluation.

This paper is based on CIR design and construction as practiced by the Oregon Department of Transportation (ODOT) in 1990 using CMS-2S or HFE-150 asphalt emulsion and milling to depths of 2 to 4 in. with the majority of projects milling to 2 in. It is not intended for use on projects involving full-depth reclamation.

CIR THEORIES

Two theories have been proposed when designing cold recycled asphalt pavement (*3*). Briefly, the theories are as follows:

1. Treat the millings as a black aggregate with some hardened asphalt coating, and design an asphalt content to coat the milled particles. The assumption is that the millings will act as an aggregate.
2. Evaluate the physical (and possibly the chemical) characteristics of the asphalt in the old pavement and add a rejuvenating or softening agent that will restore the asphalt to its original condition. The assumption is that 100 percent softening occurs and a "new asphalt" is created.

In recent years, California, Oregon, Nevada, and New Mexico have concluded that a combination of the two theories most likely occurs. This "effective asphalt theory" is shown in Figure 2.

On the basis of this theory, a percentage of the old asphalt softens and combines with the added emulsion to produce an asphalt content in the mixture known as the effective asphalt. The percentage of asphalt that is softened is directly related to the softness of the old asphalt, the recycled asphalt pavement (RAP) gradation, and the percentage of asphalt in the old mix. Because these values can be readily measured, they have been incorporated into a procedure to estimate an initial emulsion content, which is described later in this paper.

TABLE 1 COST COMPARISON OF CIR VERSUS 2-in. HOT-MIX OVERLAY BASED ON ODOT REGION 4 DATA AND 1990 COSTS

	First Cost	Life Cycle Cost (Equivalent Annual Cost)
2 Inch Hot-Mix Overlay	$5.25/sy	$13,000-$14,000/mi
2 Inch CIR with Chip Seal	$2.10/sy	$5,000-$8,000/mi

Effective Asphalt = % Emulsion + % of Softened Asphalt

Where:

1) % emulsion is the amount of emulsion added; and
2) % of softened asphalt is directly related to:
   - Viscosity and/or penetration of old asphalt
   - Gradation of RAP
   - Percent asphalt in old pavement

FIGURE 2 Design theory for CIR pavements.

PRECONSTRUCTION STEPS

Project Selection and Testing Plan

Project selection is an important factor in determining the success of a CIR project. Not all projects are appropriate for CIR. Improper project selection can result in project failure. Figure 3 shows types of projects for which CIR is and is not recommended. Once it has been determined that CIR is feasible, preconstruction activities include field sampling, laboratory testing, and mix design.

Field Sampling

After a project has been identified as a recycle candidate, the first step in the preliminary engineering phase is to perform a paper search on the history of that highway. The information to be collected is the type of asphalt used in the pavement, thickness of the pavement, and termini of previous jobs (Figure 4). The project is then divided into preliminary mix design areas (e.g., shown in A, B, and C). Within each area, milling samples should be obtained using a small 16-in. mill. The sample frequency in each design area would be a minimum of three samples plus three backup samples on each section. The sample locations would be selected visually by identifying representative locations within the design area. Milling depth should correspond to the proposed recycle depth. Samples should be collected with the mill in forward motion. If visible maintenance patches or other intermittent treatments occur within the section, a sample would be taken from that section noting on the sample that it came from a patched area. Samples are kept separate and submitted to the laboratory for testing.

Laboratory Tests on RAP

Consistent with the previously described effective asphalt theory, the following tests should be performed on the RAP obtained from the field sampling:

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

These values are then used to estimate the optimum emulsion content, described in the next section.

a) CIR Not Recommended
Pavements with obvious subgrade problems
Work area cannot accommodate traffic volume
Asphalt is stripping from aggregate*
Mixes exhibiting rutting due to unstable, fat mixtures
Cold and damp conditions, including heavily shaded areas
Late fall or early winter treatment
Asphalt pavement is less than 1.5 inch thick
Intent is to widen roadway by reducing thickness and incorporating unbound shoulder rock
b) CIR Recommended
Cracked and broken pavements
Pavements raveled due to age
Rough pavements
As leveling and base for overlays
ADT 5000 or less unless multilane
Where selective rehabilitation is needed (e.g., in truck lane of 4-lane roadway)
Native aggregate poor or in short supply

*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. Use of lime in CIR is also being evaluated.

FIGURE 3 Considerations for project selection.

Mix Design Considerations

Several procedures are available to determine the optimum emulsion and water content for CIR mixtures. The one described is based on the work performed in Oregon.

Estimation of Emulsion Content

The procedure to select the amount of emulsion to be added to a recycled mixture is essentially an estimation process. It begins with a base emulsion content to which adjustments are made on the basis of the results of laboratory tests conducted on a sample taken, using a 16-in. mill, from the pavement to be recycled. It has been found through experience with the CMS-2S and HFE-150 emulsions that a base emulsion content of 1.2 percent is a good starting point (*5*). Adjustments are then made to the base content according to the softness of the extracted asphalt, gradation of millings as produced by the 16-in. mill, and the percentage of asphalt recovered from the sample.

The penetration (ASTM D5) or the absolute viscosity (ASTM D2171) laboratory test results are used to determine the softness of the extracted asphalt, and the RAP gradation is determined for only three screens—½ in., ¼ in., and #10. The percentage of recovered asphalt is determined by the Abson method (ASTM D1856). From the laboratory test results, the added emulsion content (based on dry weight of millings) can be determined through the use of Figure 5 and the following equation:

$$EC_{EST} = 1.2 + A_G + A_{A/C} + A_{P/V}$$

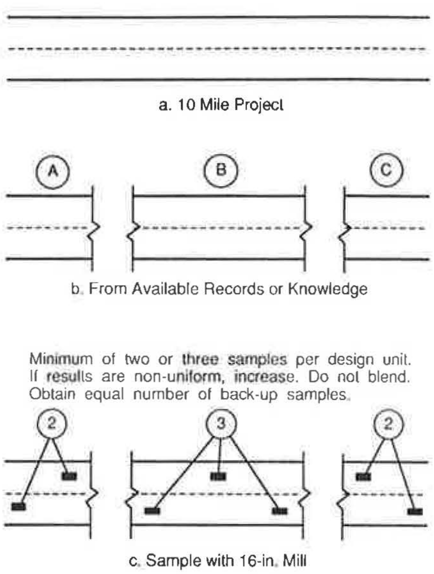

FIGURE 4 Suggested field sampling.

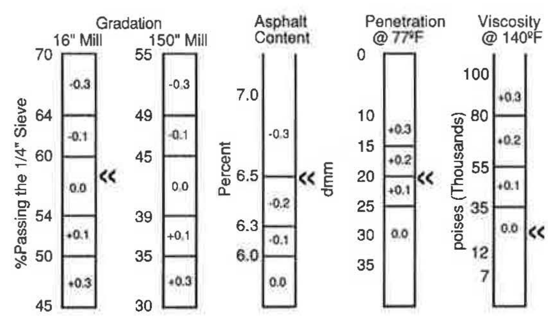

FIGURE 5 Emulsion content adjustments for gradation, asphalt content, and asphalt softness.

where

EC_{EST} = estimated emulsion content (percent),
1.2 = base emulsion content (percent),
A_G = adjustment for gradation (percent),
$A_{A/C}$ = adjustment for residual asphalt content (percent), and
$A_{P/V}$ = adjustment for penetration or viscosity (percent).

For borderline cases (those that fall on a boundary) in Figure 5, the adjustment resulting in a lower estimated emulsion content should be used. Also, where there is a discrepancy between the adjustments for penetration and absolute viscosity, the adjustment resulting in a lower estimated emulsion content should be used. For example, given 58 percent passing the ¼-in. screen on the 16-in. mill, 6.5 percent residual asphalt, a penetration of 20 dmm, and a viscosity of 19,000 poises, the adjustments are as follows (for borderline cases, use adjustment producing lower emulsion content):

1. 0.0 percent for gradation,
2. −0.3 percent for asphalt content, and
3. 0.0 percent for penetration/viscosity.

The estimated emulsion content is 1.2 percent + 0.0 percent − 0.3 percent + 0.0 percent = 0.9 percent.

The advantage of this approach is that it provides a rapid and simple method to determine the estimated emulsion content. The laboratory tests used are widely accepted. The results appear to produce the optimum emulsion content within a fraction of 1 percent. For most recycle projects where preservation or restoration of an existing pavement is the primary objective, the estimated emulsion content is adequate for the final recommended design.

Estimation of Amount of Water Required

To ensure adequate dispersion of the emulsion and complete coating of the RAP, addition of water to the mix is usually required. A saturated surface damp condition is desired. To determine the total liquids content, the modified Oregon State Highway Division test method OSHD TM-126 is used (*3*, Vol. 2). The test determines how much total liquids a particular recycle mix can tolerate. Thus, once the estimated emulsion content is determined, the modified OSHD TM-126 test is conducted on the mix to determine the total liquids content. Briefly, the total liquids test is conducted as follows (see OSHD-TM-126 for complete details):

1. Samples are prepared at the final estimated design emulsion content and at incremental water contents (e.g., 0.5, 1.0, and 1.5 percent). Each sample weight is recorded.
2. Each sample is placed and rodded in a split mold in two lifts.
3. Each sample is gradually compressed to a total load of 25 kips: 1 min to achieve 20 kips plus ½ min to achieve the additional 5 kips. The 25-kip load is held for 1 min.
4. The specimen weights are then determined. The difference between the initial sample weight and the weight of the compacted specimen is the liquid loss.

The total liquids content that results in a liquid loss of 0.035 to 0.14 oz (1 to 4 g) is used as the desired total liquids content. From this, the water content can be calculated (total liquids content minus estimated emulsion content).

Seal Versus Overlay

The decision to seal or overlay must be predicated on the structural design assumptions of the roadway. Minimal surface sealing such as a fog seal would be used on a pavement that is expected to perform satisfactorily for a short time or as part of a stage-type reconstruction. The type and amount of traffic to use the recycled surface also influences whether a seal is necessary and the type of seal. Fog seals, chip seals, double chip seals, hot mix overlays, and open-graded emulsion mix overlays have been used successfully. All agencies now recommend that all cold recycled mixes have, as a minimum, a chip seal placed on their surface.

CONSTRUCTION OPERATIONS

Proper project selection, preconstruction investigation, and estimation of emulsion and water contents are fundamental to the success of a CIR project. The project can still fail, however, if proper construction procedures are not followed.

CIR consists of milling the existing asphalt pavement to a specified depth, mixing the RAP with water and asphalt emulsion, depositing the mixture in a windrow, and paving and compacting with conventional paving equipment. Figure 6

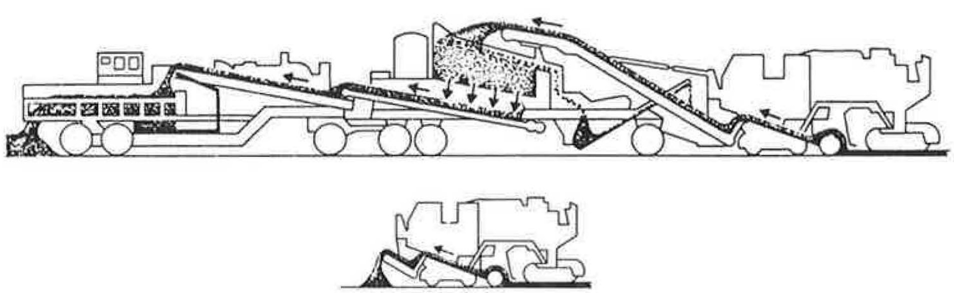

FIGURE 6 Equipment normally used in CIR treatments: *top*, full train with mill, screen deck, crusher, belt scale, and pug (laydown with a standard paving machine); *bottom*, single unit train with asphalt emulsion sprayed into mill chamber.

shows the two types of CIR equipment that have been used successfully in Oregon. After excess water has been allowed to evaporate from the CIR mat (usually 3 to 14 days), the mat is recompacted and either sealed with a chip seal or overlaid before the arrival of autumn weather conditions. A more detailed discussion of construction operations appears later under the heading "Controlling Construction Operation To Achieve Optimum Results."

QUALITY ASSURANCE GUIDELINES

Even if one develops the best mix design and construction specifications, the project may fail if the engineer and contractor are not fully informed of the limitations of CIR mixtures. This section discusses some ways of minimizing problems with cold recycling that should be considered on all projects.

Engineer Orientation

When using cold recycle for the first time, it is important to alert the project engineer about what is expected from the new procedures. In cold recycling there are objectives or expectations different from those associated with hot mix. Some of the areas that should be considered in use of cold recycling are as follows:

1. Is the CIR to be a stabilized base with a surface course?
2. Will the CIR be used instead of a leveling course?
3. Will the CIR be used, with a chip seal, as a wearing course?

The project engineer should be made aware of the importance of the procedures listed in this paper and what the results mean to the completion of a successful project. These procedures should also be stressed to the contractors at the prebid conference and to the contractor at the preconstruction conference.

A postconstruction debriefing with the project engineer provides a valuable source of information for modification of future contracts. Also, using a project engineer experienced in CIR to train other engineers helps to minimize problems on future CIR projects.

Contractor Qualifications

Although most agencies do not have specific provisions for contractor prequalification, the following contractor qualifications are desirable:

1. Knowledge of paving materials;
2. Experience in all types of bituminous paving, but particularly cold mixes;
3. Ability to coordinate, manage, and supervise a multifaceted, high-production project; and
4. Prior experience with cold recycling.

The contract specifications may preclude some of the contractors from bidding because of the lack of adequate equipment. Contractors that are not properly equipped will not be able to provide an acceptable product.

Field Testing and Quality Control

CIR may still be considered more of an art than a science. Experience is still the best teacher in determining what to do. In addition to required testing and measurements, continual visual examination during and after construction is required for successful CIR projects.

Special provision should be made to ensure adequate proportioning, mixing, curing, and compaction of the recycled asphalt pavement. Several factors will influence the behavior and performance, including

- Size gradation,
- Pavement and air temperature as well as solar heating,
- Amount of emulsion and water added,
- Temperature of emulsion and mixing water,
- Curing time, and
- Compaction.

Control of these factors through regular testing and evaluation reduces the potential for problems. Observations have shown the following factors to be important:

1. Using too much asphalt emulsion or recycling agent will result in an unstable mix that is subject to rutting and shoving. Too little asphalt emulsion may cause the mixture to ravel. Minor raveling is acceptable.
2. Excessive mix water may cause the asphalt to flush to the surface and will retard curing. Too little mix water results in mix segregation, raveling under traffic, or high void contents.
3. Coarse gradation of the processed RAP may cause problems with laydown, segregation, dragging, and excess voids. Fine gradation tends to reduce the mix's tolerance for water and emulsion deviations.
4. Water required for mixing is generally in excess of that required for compaction. Curing or removal of excess water, or both, will generally be required before adequate compaction can be achieved.

Depending on the weather, curing may take place in a matter of a few hours, or it may be a few days or longer. To minimize problems associated with curing of the emulsion, ODOT has introduced the practice of heating the mix water and the emulsion to the 120°F to 140°F range. Although this process does not significantly increase the mixture temperature because of the relatively small proportion of liquids in the mix, it is the opinion of field personnel experienced in CIR construction that the practice reduces curing problems in cool or damp conditions. One experienced inspector believes that heating the water reduces the need to increase the emulsion content when conditions are cool. The practice of heating the water may cause problems of breaking and curing too fast, however, where windrow temperatures would be in excess of 120°F.

Controlling Construction Operations To Achieve Optimum Results

Table 2 summarized ODOT's recommendations for field quality control. Most of the items presented in Table 2 are straightforward and not subject to error. The challenges of field control are in two major areas: verification and adjustment of emulsion and water content, and proper compaction and traffic control procedures.

"If Things Aren't Going Well, Key on the Water or Emulsion"

These are the words of an ODOT project manager with extensive experience in CIR. They stress the criticality and uncertainty of maintaining proper mix proportions in the variable conditions of the field.

The central laboratory should have provided estimated emulsion requirements for areas where milling samples were taken. Observation of the entire project referenced to milling locations should indicate whether patching has been done subsequent to the millings, or whether the pavement is more variable than the design would indicate. Either of these occurrences can serve as a warning to expect changes in emulsion content or other problems. If the milling locations are representative of the pavements to be recycled, design emulsion contents should be reliable.

If observation of the project indicates poor drainage or heavily shaded areas, or both, expect RAP to have higher moisture content than the milling samples tested in the lab, and therefore anticipate that the amount of water to be added will be less than that estimated in design. Heavily shaded areas will also serve as a warning that emulsion curing will be slow and that 24-hr traffic control should be anticipated.

The normal procedure is to start construction with the water and emulsion contents designed for the pavement. Experienced CIR inspectors and construction supervisors then verify or adjust the quantities of liquids added through several procedures. They conclude that the mix is too wet or too dry by holding and squeezing the windrowed material in their hands, standing on the windrow, and noting the way they sink, observing the nurse tank track imprint in the edge of the windrow, or observing the way the windrow "slumps" as it is deposited. What they are looking for is thorough coating of the RAP material and workability. After initial rolling, the color of the mat should be brown rather than shiny black. On the basis of these observations, liquid addition may be increased, decreased, or remain the same. Obviously, these procedures are subjective, highly dependent on the experience of the inspectors and construction supervisors. Objective, quantifiable procedures are needed.

The use of the Kelly ball (ASTM C360) to replace these subjective tests has been investigated, but with inconclusive results. It is known that constructible pavements resulted when Kelly ball displacements 30 sec after placement on a leveled section of windrow ranged between 1.75 and 2.5 in. (mean of 2 in. for readings taken) and when the ball sank an additional 0.1875 in. during the next 30 sec. It is not known whether mixtures with improper emulsion and water contents would have similar displacements and rate of displacement.

Checking gradation is an objective method of adjusting emulsion content. On the basis of the percentage of RAP passing the ¼-in. sieve, variations from the design basis may be noted and adjustments made in accordance with Figure 6. Significant variations from the gradation upon which the design is based will be visually apparent to the experienced observer.

The total liquids test, OSHD-TM 126 (*2*), provides a rational way of checking emulsion and water contents, but since the test takes 45 min, the information is not available for immediate adjustment. Liquids loss from this test should target a range of 0.035 to 0.14 oz (1 to 4 g) with losses of up to 0.35 oz (10 g) being acceptable. If loss is greater, cut back on water added. If loss is less, add additional water. The liquid lost should only be slightly discolored. Dark liquid lost in-

TABLE 2 RECOMMENDED FIELD QUALITY CONTROL PROGRAMS

Tests	Frequency	Purpose
RAP gradation	1/2 mile	Identify changes in pavement material
Emulsion content and water content	Continuous meter reading	Verify design content
Emulsion content and water content	Daily tank sticking	Verify meter reading
Total liquids	1/2 mile	To adjust water
Liquid loss color	1/2 mile	To adjust emulsion content
Emulsion and mix water temperature (when heating is required)	1/2 mile	Assure proper temperature
Mix temperature	1/2 mile	Verify minimum laydown temperature
Emulsion quality	Every 50 tons	Check product consistency
Depth and width	Random	Establish pay items
Smoothness	Random	
	Optional Tests	
Extracted gradation	Random	Information only (after recycle)
Extracted asphalt content	Random	Information only (after recycle)
Viscosity/penetration	Random	Information only (after recycle)

dicates too much emulsion; clear liquid lost indicates possibly insufficient emulsion. When in doubt, err on the side of too little emulsion.

The paving ahead of the mill should be examined for the presence of "fat" spots or unstable mixes. The emulsion content should be dropped 0.2 percent in areas that appear slightly fat and 0.4 percent in areas that are obviously unstable and rutted. These adjustments are made only if field samples are not taken at the exact locations of the distress.

Adjustments to emulsion content should also be made on the basis of the appearance of the mat after initial compaction, assuming that the pavement is reasonably uniform. Additional emulsion should be added (up to +0.2 percent) if the mat remains brown or is prone to raveling. At the other extreme, the emulsion content should be reduced 0.2 percent if the mat is very black and shiny and no raveling is apparent, if pushing or rutting occurs under traffic, or if bleeding or flushing occurs. The recycled pavement should have a brown appearance for at least 24 hr.

In general, when there is too much water in the mixture, the material looks wet and cannot be compacted. It "shoves" and has the appearance of an overrolled hot mix. If there is too little water, the mixture looks dry, the RAP material will not show uniform coating, and the compacted mat will ravel.

When making adjustments to what has been a satisfactory operation, the amount of total liquids is generally kept at the same level. In other words, if emulsion content is reduced 0.2 percent, water addition is increased by the same amount; if emulsion content is increased, water addition is decreased accordingly.

Balling of fines may occur. The problem usually results from inadequate mixing, excessive emulsion, or excessive fines.

A problem that may occur that is related more to the paver than to the liquids content is segregation of the mat. Segregation at the center of the panel is usual, resulting in a very open appearance. The paver may require modification to minimize this segregation.

Compaction, Traffic Control, and Rerolling

Specifications will provide guidelines for compaction. However, it is important to remember that the purpose of initial rolling is simply to get the material set. It is not desired to seal the surface initially. Moisture must get out so that the material may cure. It is important not to overroll, which may be manifested by the flushing of emulsion or fines, or both, to the surface. The paving machine should stay close to the recycling train or single unit train, but the breakdown roller should stay well back, particularly when working in cold temperatures or compacting fine materials.

Generally, recycling operations should not be undertaken or continue unless weather conditions and forecasts indicate that at least 3 hr of 90° windrow temperatures are likely. If this guideline is followed, traffic may be allowed (with speed limitations) on the mat at the conclusion of rolling operations. If shaded areas or weather conditions inhibit curing, 24-hr traffic control may be required. If it is anticipated that areas will not set up and will ravel, a very light application of tack coat may be made as a preventive measure. This application consists of either the emulsion being used for recycling or an SS1 diluted with an equal quantity of water and applied at a rate of 0.08 gal/sy, followed by applications of choke sand. As long as this application allows moisture to escape from the mat, it is preferred to increasing the emulsion added to the RAP, since excess emulsion may lead to instability at a later date.

About 1 week after traffic has been allowed on the mat, the mat is once again rolled to remove any wheeltrack rutting and to seal the surface. Rerolling should not be allowed until excess moisture has evaporated from the mat. One way to determine that adequate drying has taken place is to leave total liquids briquettes along the roadway to experience curing conditions identical to those experienced by the mat. When the briquettes no longer lose weight, moisture content has reached equilibrium.

Sealing

A well-constructed CIR mat will rut if sealed too soon or crack if not sealed before winter conditions. A minimum moisture content before sealing should be specified, and some type of seal should always be installed before the onset of freeze-thaw conditions.

Lime

CIR projects may require the addition of lime to the RAP. Preliminary investigation indicates that the addition of lime greatly accelerates the curing process (*6*). To date, the most efficient method for introduction of lime is to spread granulated lime uniformly ahead of the milling machine, introduce water to slake the lime, roll the granules to allow dispersion of the lime into the mix, and use the milling machine to disperse the lime into the mix. From a process control point of view, the following are critical:

1. The proper amount of lime to achieve the desired concentration in the mixture and the proper breakdown of the lime granules in order that the lime be completely dispersed into the mix in a fashion that will allow coating of RAP/aggregate particles should be noted.
2. Mix and milling head water addition should be reduced to compensate for the addition of water to slake the lime.

Postconstruction Evaluation

Work performed during the period 1984 to 1991 by ODOT indicates that the most common problems encountered include rutting, raveling, cracking, and local failures. Causes of and solutions to these problems are summarized in Table 3.

Rutting is considered to be the most serious problem. However, it can be corrected by re-recycling as follows:

1. In cases with excess emulsion, re-recycle the distressed area and increase the depth of cut to pick up additional material.
2. In cases of flushing, re-recycle (without going any deeper and without adding recycling agent or emulsion) and delay the initial compaction period.

TABLE 3 PAVEMENT PROBLEMS IN CIR MIXES—CAUSES AND SOLUTIONS

Type	Causes	Solutions	Comments
Rutting	• Too much emulsion • Sealing surface during laydown • Early application of chip seal	• Proper mix design • Limited vibratory compaction and prohibit pneumatic rollers until mix is stable • Allow cure period to reduce moisture to 1.0-1.5% (usually 2 weeks of good weather)	Occurs within the first few days after construction or during hot weather the season following recycling
Raveling	• Cool weather/shaded areas • Slow setting asphalt emulsion • Inadequate traffic control • Insufficient asphalt emulsion	• Preheat mixing water • Fog seal areas experiencing raveling • Use pilot cars	Occurs within first few hours after opening surface to high speed traffic
Cracking	• Open-graded nature of mix • Freeze-thaw action if not sealed • Insufficient structural section • Improper asphalt emulsion • Rolling too soon	• Require a sand or fine chip seal on all low to medium trafficked roads • Use an open-graded emulsion mix or hot mix on heavily travelled roads • Allow drying prior to compaction	Can occur during first winter if surface is not sealed and mix is subject to numerous freeze-thaw cycles
Local Failures	• Inadequate base • Wet subgrades	• Identify these areas prior to recycling • Dig out, rebase, and patch prior to recycling	These frequently occur on low volume highways with little or no base rock. Since CIR has little strength during the first 24 hrs, truck traffic will break up new CIR surfaces

CONCLUSIONS

Conclusions to be drawn from this paper include the following:

1. Project selection is an important factor for successful CIR. Trying to recycle pavements with soft base or wet subgrade, inadequate width, inadequate depth of AC pavement, or extremely variable RAP properties, for example, is futile. See Figure 3 for a list of projects to avoid.
2. Maintenance of proper proportions of emulsion and mix water during recycling is the biggest challenge in the field. Design of proper emulsion and water contents and procedures for verifying and adjusting them in the field are critical.
3. Initial compaction (rolling) of the recycled mat is intended to set rather than seal the surface. Trapping excess moisture in the mat is detrimental to performance.
4. Placing a chip seal on the CIR mat before winter conditions is essential to prevent moisture and freeze-thaw damage to a pavement with high voids content (10 to 15 percent). However, the pavement must not be sealed too soon, trapping excess moisture in the mat. Specifications should preclude sealing the CIR mat if moisture exceeds 1.5 percent.

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