PRACTICAL EXPERIENCE WITH EMULSION COLD IN-PLACE RECYCLING AND FOAMED ASPHALT FULL DEPTH RECLAMATION

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ABSTRACT

Enhanced asphalt pavement recycling and reclaiming techniques, such as cold in-place recycling (CIR) and full depth reclamation (FDR), are increasingly important to improved life-cycle performance and cost-effective pavement rehabilitation, particularly with escalating energy and asphalt binder costs. Asphalt pavement recycling contributes to sustainable transportation infrastructure through reduced natural resources requirements (aggregates, asphalt binders and fuels) and environmental impacts. Practical Canadian, American and Colombian applied design, materials and construction experience with CIR (emulsion and foamed asphalt) and FDR (foamed asphalt and lime/foamed asphalt) is used to illustrate the processing features, overall project design procedures (pavement section evaluation, reclaimed asphalt pavement properties, structural design, materials selection and mix design), construction requirements, appropriate specifications, quality control/quality assurance and anticipated flexible pavement performance involved. The performance of quality CIR and FDR has been positive and cost-effective, particularly for rutting resistance and reflective cracking mitigation. Innovations with CIR and FDR, such as improved mix design procedures, lime use (enhanced stripping resistance and strength development), laboratory characterization (moisture susceptibility, rutting resistance, resilient modulus and fatigue endurance), higher heavy traffic levels use, mechanistic pavement design parameters, including temperature relationships, incorporation in long-life asphalt pavement structures and probabilistic life-cycle costing, are presented with implementation guidance..
Keywords: cold-in-place, asphalt, recycling, foamed, full, depth reclamation, cracking

1. INTRODUCTION

"The New Black Gold. The soaring price of asphalt, driven by soaring oil prices, is wreaking havoc on cities' construction plans and contractors' bottom lines. High cost of asphalt steamrolls plans… liquid asphalt, the glue that holds roads together, has doubled in price to $500 a tonne in the past year." Chanakya Sethi, Globe and Mail, Report on Business, June 26, 2006 (SETHI, 2006).

"Will High Paving Costs Put Recycled Roads Back in the Fast Lane? Highway contractors reuse millions of tons of asphalt pavement every year. Now, with the price of liquid asphalt up more than 40% on average over the past 12 months, they are looking to recycle more. Standing in their way are transportation engineers who believe that reclaimed asphalt pavement does not perform as well as virgin material." Tudor Hampton, ENR, 2Q Cost Report, June 26, 2006 (HAMPTON, 2006).

"Asphalt Concrete Recycling in Canada. Asphalt recycling has become a key component of the Canadian paving industry and it is critical that the appropriate technology is adopted to ensure that the desired pavement quality is achieved… Experience indicates that asphalt recycling is technically sound, economically favourable and clearly contributes to sustainable development through materials, energy and landfill conservation." John Emery, Canadian Technical Asphalt Association, November 1991 (EMERY, 1991).

With increasing concerns for sustainable development and escalating petroleum product prices (fuels and lubricants), and spiking construction season asphalt cement prices (SETHI, 2006; HAMPTON, 2006), it is imperative that the full potential of the available cold and hot asphalt recycling and reclaiming technologies is utilized (ARRA, 2001; EMERY, 1991; INFRAGUIDE, 2005; KANDHAL, 1997). Not only are asphalt cement prices a current concern, but with refiners maximizing fuels production and more petroleum coker installations, there are already some supply problems, and availability constraints will undoubtedly grow (ILLIA, 2006). The recycling of old asphalt pavement materials has the advantages of reduced costs, conservation of natural resources (aggregates, fuels and particularly asphalt binders), reduced user impacts (particularly in-place recycling and reclamation) and overall preservation of the environment (sustainability) (ARRA, 2001; INFRAGUIDE, 2005). For instance, an old asphalt pavement currently has an inherent, in-place, materials value of about $39 per tonne (about four percent effective asphalt cement at $600 per tonne and about 96 percent aggregates at $15 per tonne), about twice the new asphalt cement and aggregates value it had when constructed about 15 years ago (EMERY, 1991); a significant asset if properly accounted for and optimally recycled to recover the investment.

The four main asphalt recycling and reclaiming technologies – recycled hot-mix asphalt (RHMA), hot in-place asphalt recycling (HIR), cold-mix asphalt recycling (in-place and central plant) and full depth asphalt reclamation (in-place and central plant) – are generally well established (ARRA, 2001; EMERY, 1991; INFRAGUIDE, 2005; KANDHAL, 1997; MURPHY, 1997; JOHARIFARD, 2005), including significant recent work on: the use of more reclaimed asphalt pavement (RAP) in Superpave design method RHMA (MCDANIEL, 2001), that should alleviate quality concerns and restrictive specifications (HAMPTON, 2006); the combination of cold in-place asphalt recycling (CIR) for reflective cracking mitigation with Superpave hot-mix asphalt (HMA) overlays for enhanced flexible pavement performance (BROOKS, 1998); and the use of full depth asphalt reclamation (FDR) with foamed asphalt as a stabilized asphalt base course in long-life asphalt pavements (EMERY, 2005).

For functionally deteriorated, but still structurally sound asphalt pavements, third generation HIR technology will generally be very cost-effective, with equivalent quality and performance, and less road-user disruption, compared to a thin overlay (HMA or RHMA) or milling/filling (HMA or RHMA) (JOHARIFARD, 2005). With the use of more long-life asphalt pavements, and the recognition of top-down cracking (TDC), HIR should have an increased role in asphalt pavement renewal. For new flexible pavement construction, resurfacing of composite pavements and strengthening overlays where reflective cracking is not a concern, Superpave RHMA is increasingly the asphalt paving industry standard (ARRA, 2001; INFRAGUIDE, 2005; KANDHAL, 1997; MCDANIEL, 2001).

It is very important, for optimal asphalt materials recycling during the rehabilitation of badly deteriorated asphalt pavements, to consider the technical and cost advantages of CIR for surface rehabilitation and FDR for full depth rehabilitation (ARRA, 2001; EMERY, 2005; INFRAGUIDE, 2005; MURPHY, 1997). Generally, with CIR recycling, the in-place processed RAP and added aggregate or RAP, if any, is mixed at optimum total fluids content with emulsion or foamed asphalt binder and cement or lime additive if required for stripping resistance and/or strength development (lime is preferred from testing and practical experience), placed and compacted (ARRA, 2001; INFRAGUIDE, 2005; MURPHY , 1997). With FDR recycling, the full depth processed RAP, some underlying granular material and added aggregate or RAP, if any, is mixed at optimum total fluids content with foamed asphalt binder and cement or lime additive if required (lime again preferred), shaped and compacted (ARRA, 2001; EMERY, 2005; INFRAGUIDE, 2005).

While the high cost of asphalt cement and Superpave technology limitations grab the headlines (HAMPTON, 2006; ILLIA, 2006; SETHI, 2006) and most applied asphalt technology research attention (MCDANIEL, 2001), quality CIR and FDR use is quietly growing, largely based on positive project performance experience and cost-effectiveness. This positive Canadian (17 years with CIR and 11 years with FDR), American and Colombian practical experience with CIR and FDR, and recent innovations to enhance and extend CIR and FDR use, are the focus here.

2. CIR AND FDR PROCESSES

2.1 Cold In-Place Asphalt Recycling (CIR)

CIR is an on-site process for the rehabilitation of badly deteriorated asphalt concrete surfaces, on both flexible and composite pavements, to depths of up to about 150 mm (INFRAGUIDE, 2005). Asphalt pavements exhibiting longitudinal and transverse cracking, map and alligator cracking, edge breakdown and cracking, potholing, bleeding, rutting and shoving distresses are candidates for CIR, subject to a pavement structural and drainage evaluation. While not covered here, central cold plant asphalt recycling (CCPR) produces a similar end product to CIR (ARRA, 2001). The general CIR process features, as shown in Photographs 1 and 2, are: old asphalt pavement milled and sized (milled to at least 90 percent of the existing asphalt depth to ensure reflective cracking mitigation, 75 to 125 mm depth typically and minus 37 mm sizing); about 1.5 to 2.0 percent emulsion (typically high float with polymer and sometimes rejuvenator) or foamed asphalt binder, plus water to optimum fluids content, mixed with processed material (may include additional aggregate or RAP and cement or lime additive); placement with a screed; compaction with high compactive effort rollers; curing and traffic compaction (typically about two weeks); and placement of a wearing surface (chip seal or asphalt concrete, depending on traffic level).

The evolving Canadian CIR (emulsion) experience since 1989 has generally been technically positive and cost-effective (BROOKS, 1998; EMERY, 1991; MURPHY, 1997; INFRAGUIDE, 2005):

- Well established and proven surface rehabilitation technique with many qualified contractors using a wide range of equipment (Photographs 1 and 2);
- Modifications developed for special conditions and/or improved economics such as aggregate or RAP addition (for voids control, strength, widening and/or additional structure), rejuvenator addition (to ‘activate’ more of the aged asphalt binder), fast curing emulsions (four to seven days), and hydrated lime addition (for stripping resistance and/or strength development);
- Used for a wide range of heavy vehicle equivalent single axle loadings (ESALs) pavement structures;
- Good rutting resistance and excellent reflective cracking mitigation as shown in Photograph 3;
- Pavement evaluation and structural design methods developed, including laboratory characterization for empirical and mechanistic designs (resilient moduli, M_r) and performance parameters (moisture susceptibility, rutting resistance and fatigue endurance);
- Cold Marshall (60ºC) mix design method widely adopted with Superpave gyratory compactor (SGC) methods being evaluated (very important to check tensile strength ratio, TSR, if moisture susceptibility of the high in-place air voids mix of concern);
- Agency materials and construction specification developed (Ontario Provincial Standard Specification 333 for instance (OPS, 2006));
- Recommend agency complete preliminary pavement evaluation and specify performance requirements, with separate pay items for drainage improvement, base repair, asphalt binder, added aggregate or RAP, processing (construction) and surfacing; and
- Recommend contractor be made responsible for materials, mix design, processing and quality control to meet performance requirements.

The Canadian CIR (foamed asphalt, cement/foamed asphalt and lime/foamed asphalt) experience, while only since 2002, is similar to American experience and like CIR (emulsion), technically positive and cost-effective, with the important advantages of a shorter curing time (typically two days) and longer Canadian construction season (BATEMAN, 2003; MARKS, 2005). (The term ‘expanded’ is used interchangeably with ‘foamed’ in Ontario.) Mix design procedures for CIR (foamed asphalt) are similar to those for FDR (foamed asphalt).

2.2 Foamed Asphalt Full Depth Reclamation (FDR)

There are several types of asphalt pavement FDR technologies in use as shown in Photograph 4 (ARRA, 2001; WIRTGEN, 2004): pulverizing/mixing/compacting without a binder (sometimes with an additive such as calcium or magnesium chloride); FDR with lime, pozzolanic and cementitious binders (quick or hydrated lime, lime or cement kiln dust, fly ash, lime/fly ash and cement/fly ash); and FDR with asphalt binders (emulsion, foamed asphalt, lime/foamed asphalt and cement/foamed asphalt). The focus here is on the growing use of quality FDR with foamed asphalt, which provides an asphalt stabilized base contributing significant strength to the pavement structure and eliminating reflective cracking (INFRAGUIDE, 2005).

Old Asphalt Pavement Milled and Sized. About 1.5 Percent High Float Emulsion Added and Mixed with Processed Material	**Processed Recycled Material Placed with Paver**	**Compaction Completed with Large Rubber Tired Roller** Seeley and Arnill

Photograph 1 Typical 1993 Ontario Highway Cold In-Place Recycling (CIR) With Emulsion Project

1996 CIR With Emulsion and First Ontario Superpave Hot-Mix Asphalt Overlay (BROOKS, 1998)	**1999 CIR with Emulsion Equipment Can Add Cement or Lime Slurry**	**2004 Paver Laid CIR with Foamed Asphalt**

Photograph 2 Cold In-Place Asphalt Recycling (CIR) Equipment and Processes

Surface Texture of Superpave Hot-Mix Asphalt (HMA) Overlay	**Condition of Superpave HMA in 2004 No Cracking**	**Condition of Adjacent 1997 Mill/HMA Overlay Project without CIR Significant Cracking**

Photograph 3 Performance of 1996 Cold In-Place Recycling (CIR) With Emulsion and Superpave Overlay, Photograph 2

The FDR (foamed asphalt) materials, design and construction technology and positive project experience since 1995 is very similar to that for quality CIR (foamed asphalt) since 2002 (BATEMAN, 2003). However, FDR (foamed asphalt, lime/foamed asphalt and cement/foamed asphalt) involves full depth homogeneous processing of the deteriorated asphalt pavement with a predetermined amount of underlying granular material plus the addition, if any, of aggregate and/or RAP. While not an in-place process, central plant foamed asphalt RAP stabilization is also growing (WIRTGEN, 2002; WIRTGEN, 2004).

The FDR foamed asphalt stabilization process (Photograph 4) consists of: full depth 'pulverizing' of the deteriorated asphalt pavement; mixing (one pass with pulverizing or two pass following pulverizing) pulverized RAP, underlying granular material, any added aggregate or RAP, any lime or cement (mix design) and foamed asphalt (typically two to three percent based on mix design), with a total depth range of about 150 to 450 mm; shaping; compaction with high compactive effort rollers; curing (typically one to two days); and placement of a wearing surface (chip seal or asphalt concrete depending on traffic level). The overall design procedure for FDR (foamed asphalt) is given after a review of CIR and FDR as four component systems and their behaviour compared to HMA.

Practical Ontario experience since 1995 with quality FDR (foamed asphalt), noting the importance of asphalt binder content and stripping resistance for durability of this high voids stabilized asphalt base (high TSR), has shown the following features: proven technology, cost-effective (based on project probabilistic life-cycle cost analysis, LCCA); good rutting resistance and fatigue endurance; rapid strength gain; and elimination of reflective cracking. The same general recommended agency and contractor responsibilities for CIR projects are also recommended for FDR projects.

Pulverizing Old Asphalt Concrete Pavement FDR Method without Stabilizing

Lime Stabilization of Old Asphalt Pavement/Granular Base Dominican Republic

Cement Stabilization Old Asphalt Pavement/Granular Base Mississippi

FDR Emulsion Stabilization SS-1 with Granular Material Added Nicaragua

FDR with Foamed Asphalt Ontario

FDR with Foamed Asphalt/Lime Georgia

Photograph 4 Full Depth Reclamation (FDR) Technologies – Equipment and Materials

3. CIR AND FDR FOUR COMPONENT SYSTEMS

3.1 Unique Properties of Foam

While asphalt technologists generally worry about the 'explosive' uncontrolled consequences of inadvertently mixing water with hot asphalt cement (similar to pouring cold water into hot cooking oil – a real foaming kitchen mess), the controlled injection of water (one to two percent) into hot asphalt cement foaming process developed by Csanyi in 1957 (actually steam injection in a foaming nozzle) (CSANYI, 1962; HOTTE, 1995) is still the basis of current in-place and central plant foamed and some warm asphalt processes (AsAc, 2002; CERVARICH, 2003). Professor Csanyi, in his 1962 paper "Foamed asphalt for economical road construction" (CSANYI, 1962), neatly summarized the technology. "Known as the foamed asphalt process, it utilizes the unique properties of foams. When asphalt cement is foamed, it increases tremendously in volume, its viscosity is materially reduced, and it becomes much softer at lower temperatures. Foaming also introduces energy into the asphalt, thereby modifying its surface tension and making it more sticky. It increases its ability to displace moisture from a surface and to coat a surface with a comparatively thin film. When the foam breaks and the energy is dissipated, the asphalt cement recovers its original properties with no change in its chemical composition. Through modified surface tension, cold, wet aggregates or soils can be used, and wet clayey lumps of soil can be permeated with asphalt. Because of the ability of foamed asphalt to coat mineral particles with thin films, the use of ungraded local aggregates in mixes becomes possible and the production of mastics of mineral dusts and asphalt is also feasible. Thus, through the use of asphalt cements as foam, materials heretofore considered unsuitable can now be used in the preparation of mixes for stabilized bases and surfacing for low-cost road construction." (CSANYI, 1962).

3.2 Four Component Systems

A CIR (emulsion or foamed asphalt) mix is a four component system, as compared to HMA and RHMA incorporating processed RAP, which are three component systems. For HMA, these phases/components are solid aggregates (including any filler, plus aggregate in RAP – sometimes termed 'black rock' – for RHMA), liquid (initially)/viscoplastic asphalt binder (asphalt cement, plus any aged effective asphalt cement in RAP for RHMA) and gaseous air. For a CIR emulsion mix, these components are solid aggregates (RAP plus added aggregates, if any), liquid (initially)/ viscoplastic asphalt binder (emulsion residual asphalt cement content plus some 'activated' aged asphalt cement from RAP, particularly if a rejuvenator is incorporated), gaseous air and liquid water. While the components of a CIR foamed asphalt mix are similar to a CIR emulsion mix, with foamed asphalt cement (hot asphalt cement foamed by the addition of one to two percent water) rather than emulsion as the asphalt binder, there is a very significant difference in the coating and binding mechanisms involved.

In a CIR emulsion mix, the RAP and most of the added aggregate are coated with emulsion (asphalt binder) during process mixing. The optimum water content, total fluids content (emulsion, added water and moisture in RAP) and mixing time are very important to optimizing the coating and compaction properties of the CIR mix as shown in Figure 1. However, a CIR or FDR foamed asphalt process mix, as indicated by Csanyi from the properties of foams (CSANYI, 1962), involves preferential coating of the fine, high specific surface area, aggregate particles with the low viscosity foam to form a 'mortar' (mastic) that binds the largely uncoated coarse particles together ('spot welding' binder) as shown in Photograph 5. It is imperative to recognize this 'affinity' of foamed asphalt for the fine aggregate in any foamed asphalt mix design (fines content and resistance to moisture for instance) and process (foamed asphalt expansion ratio and half-life for instance, Photograph 5).

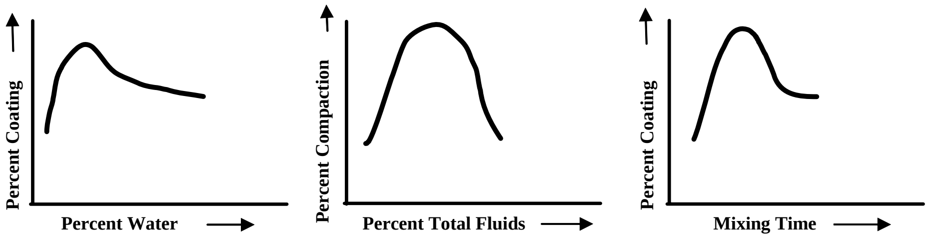
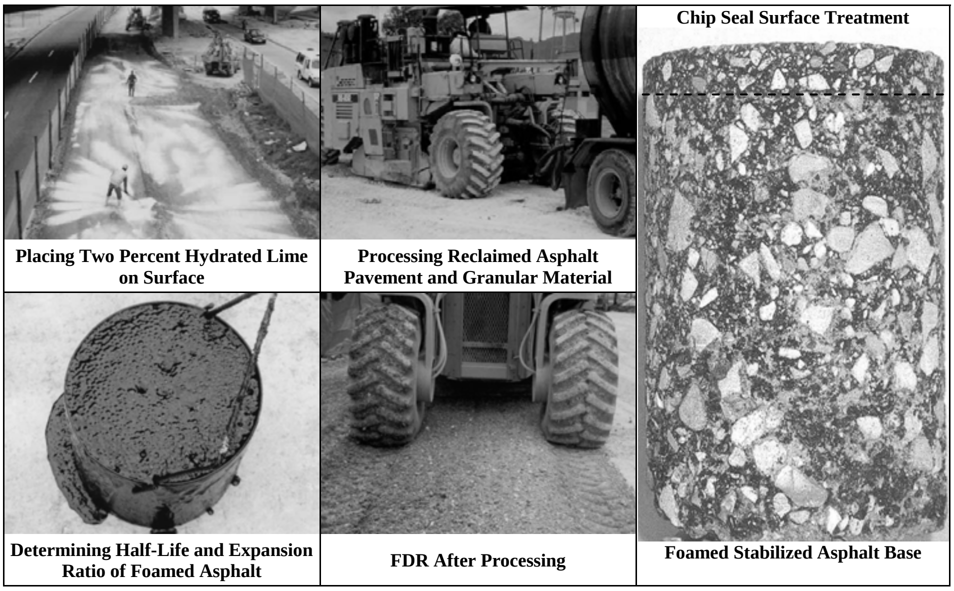


Figure 1 Optimizing Cold In-Place Recycled Asphalt (CIR) Mix Properties

The compaction of HMA forces the aggregate particles together to develop strength through an interlocking structure, with the hot asphalt cement acting essentially as a lubricating fluid that then cools to form a viscoplastic adhesive (binder). The processing, compaction and strength development of CIR emulsion mixes is highly related to the emulsion's behaviour, as indicated in five stages:

1. Processing/mixing of RAP (plus any added aggregate or RAP), emulsion and water (plus any added lime or cement) at optimum total fluids content (quality control monitoring very important) (MURPHY, 1997);
2. Emulsion breaking (brown) and asphalt cement 'droplets' attaching to aggregate (solvent and/or rejuvenator in emulsion will 'activate' some of the aged asphalt cement) following mixing;
3. Emulsion setting (black) and free water 'seeping' into the voids during placement;
4. Compaction with high compactive effort rollers and water in voids acting as a densification aid; and
5. Densification and serviceability achieved with aggregate particles in closest proximity attainable by compaction and traffic action, moisture content in equilibrium with ambient conditions (about two weeks of traffic densification and curing) and continuing increase in strength/stiffness with time (several years based on coring programs) (MURPHY, 1997).

The densification of CIR emulsion mixes is essentially between Proctor compaction of granular materials and cold Marshall compaction of asphalt mixes.



Photograph 5 Full Depth Reclamation (FDR) with Foamed Asphalt/Lime in Bogotá and Typical Appearance of Foamed Asphalt Stabilization

3.3 Processing, Compaction and Strength Development of CIR and FDR Foamed Asphalt Mixes

The processing, compaction and strength development of CIR and FDR foamed asphalt mixes have similarities to CIR emulsion mixes as four component cold systems, with mixing and compaction highly related to optimal total fluids content. However, the unique properties of foam, particularly its affinity for fines, require a somewhat different approach to materials selection and mix design (AsAc, 2002). For instance, prior to compaction, a foamed asphalt mix has the appearance of loose, brown granular material, as most of the coarse aggregate is not coated.

From a 1995 to 1997 review of available FDR foamed asphalt base stabilization project mix designs (WIRTGEN, 2004 (1st Edition); CSANYI, 1962, HOTTE, 1995) and initial Ontario project experience, a simple design and estimating guide was developed that has been validated over the past ten years for Canadian, American and Colombian projects (Photographs 4 and 5, noting the use of hydrated lime) as follows:

1. Preferred overall gradation (particle size):

minus 37.5 mm	100 percent
minus 19 mm	60 to 100 percent
minus 4.75 mm	30 to 60 percent
minus 600 µm	15 to 30 percent
minus 75 µm	7 to 15 percent;

2. Estimated foamed asphalt content:

Moisture susceptible mix (TSR test)

$$\text{Foamed asphalt (percent)} = \left(\frac{\text{percent aggregate}}{100} \text{ x } 4.5\right) + \left(\frac{\text{percent RAP}}{100} \text{ x } 1.5\right)$$

(plus hydrated lime (or equivalent slaked quick lime) of 0.5 to 1.0 percent)

Non moisture susceptible mix (TSR test)

$$\text{Foamed asphalt (percent)} = \left(\frac{\text{percent aggregate}}{100} \text{ x } 4.0\right) + \left(\frac{\text{percent RAP}}{100} \text{ x } 1.5\right);$$

3. Addition of hydrated lime (or equivalent slaked quick lime) for fines with plasticity (HOTTE, 1995):

Plasticity index (PI)	< 4	no hydrated lime (subject to TSR test)
PI	4 to 8	1 percent hydrated lime
PI	> 8	2 percent hydrated lime.

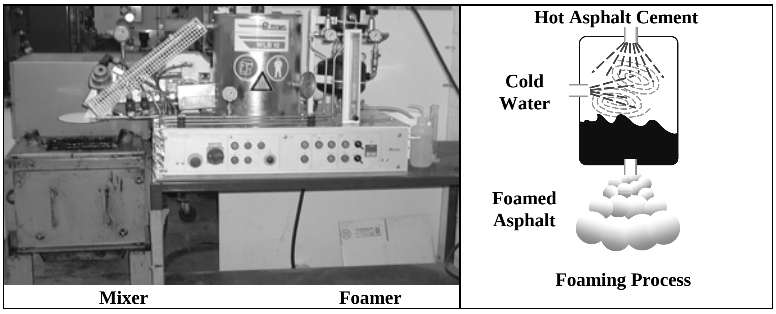
This estimating guide is used as the starting point for a CIR and FDR foamed asphalt mix design method, based initially on South African experience (WIRTGEN, 2004; AsAc, 2002) and the Asphalt Institute design method for emulsion cold mix (AI, 2002), that has been used since 1997 as part of the following overall evaluation and design procedure for over 80 FDR projects:

1. Obtain representative materials for the project based on the pavement evaluation – deteriorated asphalt pavement cores or sawn pieces (crushed in the laboratory to simulate processing), underlying granular material, asphalt cement (typically performance graded for site), any aggregate and/or RAP to be added, and hydrated or quick lime if required (or cement);
2. Determine the aged asphalt cement content and unwashed gradation of the crushed cores and any added RAP (ignition oven), and unwashed gradation of underlying granular material and any added aggregate (and moisture contents);
3. Determine the combined gradation of the crushed cores, underlying granular material, and any additional RAP or aggregate for the proposed proportions (typically add in two percent fines to simulate processing) – check that preferred overall gradation is met (minus 75 μm very important) and adjust proportions and/or add aggregate as necessary;
4. Determine the optimum Modified Proctor moisture content for combined gradation aggregates blend;
5. Determine the foamed asphalt expansion ratio and half-life for the hot asphalt cement (about 165ºC) for a range of water injection percents (0.5 to 2.0 percent typically) in the laboratory foamer (Photograph 6) and select the optimum water injection percent; an expansion ratio of greater than 10 (volume of foam divided by volume of hot asphalt cement) and half-life of greater than 10 seconds (time

for volume of foam to collapse 50 percent from its peak) are typically specified for foamed asphalt stabilization;

6. Compact the blended RAP/aggregates/water mixed with foamed asphalt at 75 blows per face to form Marshall method briquettes at typically 3.0, 3.5, 4.0, 4.5 and 5.0 percent foamed asphalt content (range depends on RAP richness) and total fluids content (foamed asphalt, RAP/aggregate moisture and added water) equal to optimum Modified Proctor Moisture content – proper laboratory mixing (Photograph 6) has been shown to be very important for coating and TSR strengths (AsAc, 2002) (150 mm diameter molds can be used for coarse foamed asphalt stabilized base and Superpave Gyratory Compactor (SGC) based methods are being developed);
7. Cure the briquettes for 24 hours in the mold at 25ºC, remove from mold and complete curing for 72 hours at 60ºC;
8. Test the briquettes and determine the optimum foamed asphalt cement content from Marshall property curves (tested for stability/flow dry at 25ºC), noting a high voids mix is involved (typically designing at 8 to 12 percent air voids); and
9. Determine the moisture susceptibility (TSR) for control and conditioned briquettes (vacuum saturated and soaked for 4 days at 25ºC), and incorporate anti-stripping additive (typically hydrated lime) and confirm efficacy, as necessary. Achieving adequate dry and conditioned stabilities (TSR greater than 70 percent typically specified) are the key to foamed asphalt base stabilization mix designs (to expedite the design process and timing, hydrated lime is typically added throughout the mix design process based on the design and estimating guide/local experience).

The four key components of the mix design process (simulation of field process) of foamed asphalt stabilization are a gradation with adequate fines, the foamed asphalt quality (expansion ratio and half life), proper blending and mixing, and achieving good resistance to moisture damage. The choice of cement or lime for strength development, fines content and/or stripping resistance is central to CIR and FDR with foamed asphalt, and covered through project experience in the following sections. The mix design procedure adopted for CIR with emulsion, based on Ontario experience, has been given in detail previously (MURPHY, 1997).



Photograph 6 Use of PTI Pugmill Twin Shaft Mixer and Wirtgen Laboratory Foamer to Simulate Field Processing and Mixing of Foamed Asphalt Stabilized Base in the Laboratory

4. CIR AND FDR OVERALL DESIGN AND CONSTRUCTION PROCEDURE

4.1 Overall Procedure

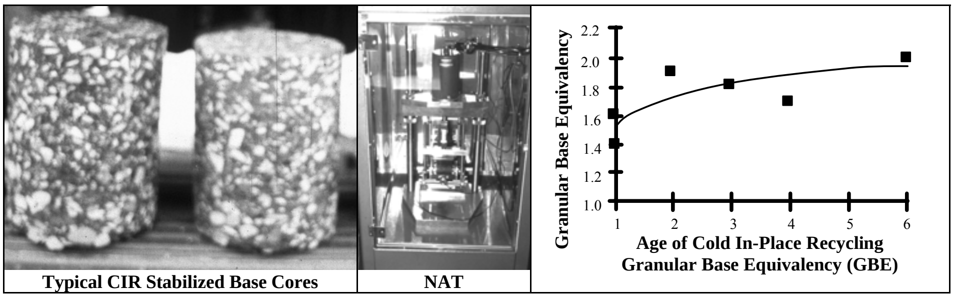
It is very important that an overall design and construction procedure for CIR (emulsion and foamed asphalt) and FDR (foamed asphalt) be followed as CIR and FDR project performance problems are usually related to an inadequate pavement structure for the heavy vehicle traffic and/or an in-place emulsion or foamed asphalt stabilized base of poor quality (low compaction, low strength and/or moisture damage). The following overall procedure has been adopted from practical project experience since 1991:

1. evaluate the deteriorated asphalt pavement section for suitability (drainage and structural adequacy) and appropriate rehabilitation method (CIR, FDR or other such as HMA overlay) (AI, 2000):
   a. complete a visual condition survey (distress types, extent and severity);
   b. assess the surface and subsurface drainage adequacy – poor drainage is the key cause of pavement failure;
   c. complete coring/borehole investigation to determine the thickness of the asphalt pavement and granular base/subbase, and to obtain representative samples for laboratory testing;
   d. assess the pavement structure adequacy – typically deflection testing with falling weight deflectometer (FWD) – in addition to seasonal variations, the deflection of a pavement section may vary along its length; to reduce the effect of both variables, a statistical process should be used when estimating the maximum deflection;
2. complete the pavement structural design (typically Asphalt Institute or American Association of State Highway and Transportation Officials (AASHTO) 93 method (AI, 2000) for CIR or FDR rehabilitation materials and method selected:
   a. typical granular base equivalency (GBE) values and structural layer coefficients (a_i) for CIR and FDR are given in Section 4.2; and
   b. the rehabilitation method selection should include a probabilistic, present worth method, life-cycle cost analysis to ensure the most cost-effective method is adopted;
3. complete the mix design for CIR (emulsion or foamed asphalt) or FDR (foamed asphalt);
4. complete the CIR or FDR rehabilitation project with contractor quality control; and
5. check project conformance with CIR or FDR specifications through agency quality assurance.

It must be emphasized that the long-term performance of any asphalt pavement rehabilitation project depends on the overall quality achieved throughout the pavement design, materials selection, mix design and construction.

4.2 CIR (Emulsion) Granular Base Equivalency Factors

While the current focus for the structural design of asphalt pavements is on mechanistic-empirical design concepts (AASHTO 2002 for instance), empirical methods such as the GBE method are quite helpful for estimating purposes and quick design checks. Previously reported research on appropriate GBE factors for quality CIR (emulsion) (MURPHY, 1997) is summarized in Photograph 7, and in Table 1 which is adapted from the Ontario Ministry of Transportation (MTO) 1990 Pavement Design and Rehabilitation Manual (MTO, 1990). It is important to note the CIR (emulsion) strength, resilient modulus (M_r) and GBE increase over several years, confirmed by field FWD testing and analysis, can be used to advantage in the more comprehensive mechanistic-empirical design methods.



Photograph 7 Determination of Cold In-Place Recycling (CIR) Granular Base Equivalency (GBE) Using Nottingham Asphalt Tester (NAT) (MURPHY, 1997)

Table 1 GBE Factors Used in Empirical Pavement Design Methods

Granular Base Equivalency Factors	
New Projects	GBE
Hot-Mix Asphalt (Including RHM and HIR)	2.00
Granular Base (Crushed, CBR ≥ 60)	1.00
Granular Subbase (CBR < 60)	0.67
OGDL (Not Recommended)	1.00
Resurfacing Projects	GBE
Old Hot-Mix Asphalt	1.25
Old Granular Base	0.75
Old Granular Subbase	0.50
Pulverized/Crushed RAP Blended Granular	1.00
CIR and FDR (Foamed Asphalt)	1.80
Reconstruction Projects	GBE
Old Hot-Mix Asphalt	1.00
Old Granular Base	0.60
Old Granular Subbase	0.40
Rubblized Base Concrete	1.0+

CBR is California Bearing Ratio
CIR is Cold In-place Recycled asphalt
FDR is Full Depth Reclamation
GBE is Granular Base Equivalency
HIR is Hot In-place Recycled asphalt
OGDL is Open-Graded Drainage Layer
RAP is Reclaimed Asphalt Pavement
RHM is Recycled Hot Mix asphalt

4.3 FDR (Foamed Asphalt) Characterization and Mechanistic Properties

A wide range of mechanistic properties, with M_r of greatest interest, have been indicated for FDR (foamed asphalt), most probably related to the wide range of materials, quality, testing methods and analysis involved (EMERY, 2005; WIRTGEN, 2004; HOTTE, 1995; AI, 2002). For this reason, it was considered imperative to test representative samples from projects that were essentially completed in accordance with the recommended overall procedure outlined in Section 4.1. With the assistance of Blount Construction and Miller Recycling (Atlanta), and as part of the Federal Highway Administration (FHWA) Local Technical Assistance Program (LTAP) in 2004, a sampling (Atlanta projects), laboratory testing (mainly M_r using the JEGEL Nottingham Asphalt Tester, NAT (EMERY, 2005; READ, 1996), and analysis M_r study was completed as summarized in Tables 2 to 4 and Figures 2 to 4.

It is of interest to note from Tables 3 and 4 that the FDR (foamed asphalt and lime/foamed asphalt) M_r values are: quite variable (Table 3); somewhat a function of in-place air voids (Table 3); generally quite high compared to HMA (Tables 3 and 4, and Figure 2); less temperature susceptible compared to HMA (crossover at about 30ºC in Figure 2), which can be incorporated in mechanistic designs for a site (pavement temperatures from LTPP for instance); fairly uniform through all the FDR depths (Tables 3 and 4); and low for the lower 15 to 25 mm of the FDR in contact with underlying material, more like a granular material (Table 4). The M_r values were also converted into AASHTO a_i and MTO GBE values as shown in Figures 3 and 4, with value limits of 0.5 and 2.0, respectively. From this study, it is clear that the use of mechanistic flexible pavement design methods can be use to advantage with the low temperature susceptibility FDR, and FDR asphalt stabilized base can form a component of long-life asphalt pavements (EMERY, 2005). The general study M_r findings for quality FDR are in accordance with FWD testing and back calculation.

Table 2 Foamed Asphalt Mix Design Proportions at Various Project Locations

Location	Material				Mix				Total Asphalt Cement Content (%)	Total Moisture Content (%)
	Reclaimed Asphalt (RAP) (%)	Granular Material (%)	Asphalt Cement (67-22) (%)	Hydrated Lime Addition (%)	Reclaimed Asphalt (RAP) (%)	Granular Material (%)	Asphalt Cement (67-22) (%)	Hydrated Lime Addition (%)		
Houze Way (Section A)	85.0	15.0	-	-	83.1	14.7	2.2	-	6.73	6.3
Houze Way (Section B)	49.5	49.5	-	1.0	48.2	48.2	2.6	1	5.22	5.9
Trammel Road	75.0	25.0	-	-	73.1	24.4	2.5	-	7.14	6.0
Jottem Down Road	74.5	24.5	-	1.0	73.0	24.0	2.0	1	6.72	6.5
McGinnis Ferry Road	-	-	-	-	-	-	-	-	-	-

Table 3 Average Material Characterization Properties for Various Full Depth Reclamation (Foamed Asphalt) Pavement Structures

Sample	Sample Location	Average Bulk Relative Density (BRD)	Composite Maximum Relative Density (MRD)	Average Air Voids (%)	Average Resilient Modulus @ 20°C (MPa)	Resilient Modulus After Conditioning (MPa)
HMA	Houze Way	2.363	2.538	6.9	7957	-
	Trammel Road	2.303	2.498	7.8	9031	-
	Jottem Down Road	2.380	2.492	4.5	7668	-
	McGinnis Ferry	2.296	2.535	9.4	4442	-
Top FDR	Houze Way	2.197	2.491	11.8	4804	-
	Trammel Road	2.065	2.405	14.1	2398	-
	Jottem Down Road	1.974	2.450	19.4	2989	-
	McGinnis Ferry	2.018	2.396	15.8	3337	-
Lower FDR	Houze Way	2.127	2.499	14.9	2540	-
	Trammel Road	2.044	2.403	14.9	2492	1564
	Jottem Down Road	1.907	2.535	24.8	1829	1199
	McGinnis Ferry	1.956	2.424	19.4	2566	1786

Notes: 1. All Average Values were Obtained Based on Testing Three Samples Excluding Outliers.
2. Lower Foamed Asphalt Samples were Immersed in Water for 24 Hours at Temperatures Between 20 and 25°C, then Drained and Dried Under Laboratory Ambient Air for 1 Hour Prior to Testing.

Table 4 Summary of Resilient Modulus (M_r) Testing Results for Houze Way

Layer Type	Average Resilient Modulus, M_r (MPa)			
	10°C	25°C	35°C	20°C
HMA	11809	5236	2115	7957
Top FDR	6582	4947	3087	5319
Lower FDR	5831	4536	2566	4457
Bottom FDR	1970	1639	994	2540

Notes: 1. All Resilient Modulus Values were based on Testing Three Samples and Excluding Outliers.
2. Testing Results at 20°C were Conducted Using a Different Set of Sample Specimens from the Same Coring Location as the Rest of the Testing Specimens.
3. Top FDR is top half of FDR core, Lower FDR is lower half of FDR core with lowest 15 to 25 mm removed and Bottom FDR is the removed portion (contact with underlying material).

While GBE and a_i values for any specific CIR (emulsion and foamed asphalt) or FDR (foamed asphalt and lime/foamed asphalt) rehabilitation should be evaluated (M_r testing), the following values are suggested for general guidance, when the recommended overall design and construction procedures have been followed with construction quality control and agency quality assurance:

"Good" quality CIR and FDR GBE ~ 1.5 a_i ~ 0.30;
"Very good" quality CIR and FDR GBE ~ 1.8 a_i ~ 0.35; and
"Excellent" quality CIR and FDR GBE ~ 2.0 a_i ~ 0.40.

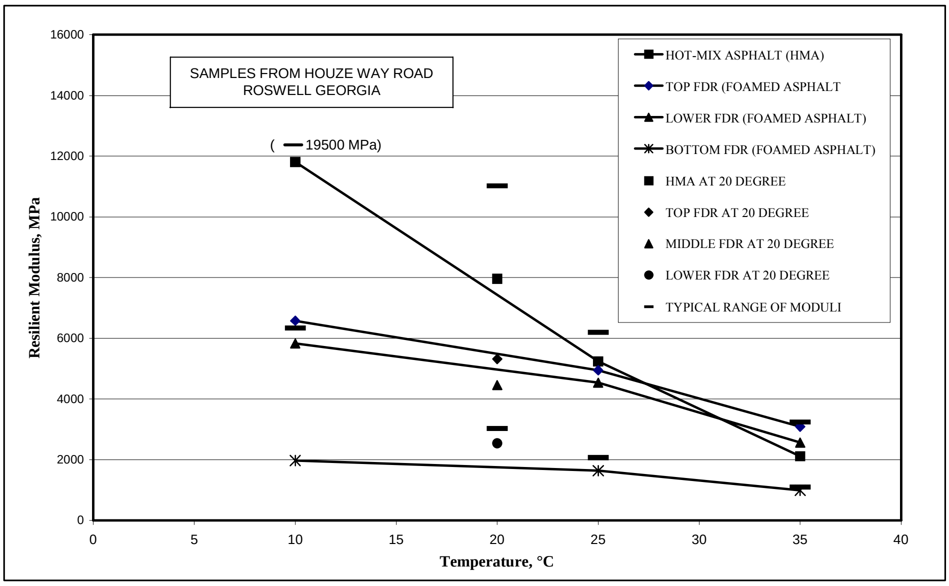


Figure 2 Resilient Modulus – Temperature Relationship. Hot-Mix Asphalt and Foamed Asphalt Stabilized Mix for Full Depth Reclamation (FDR)

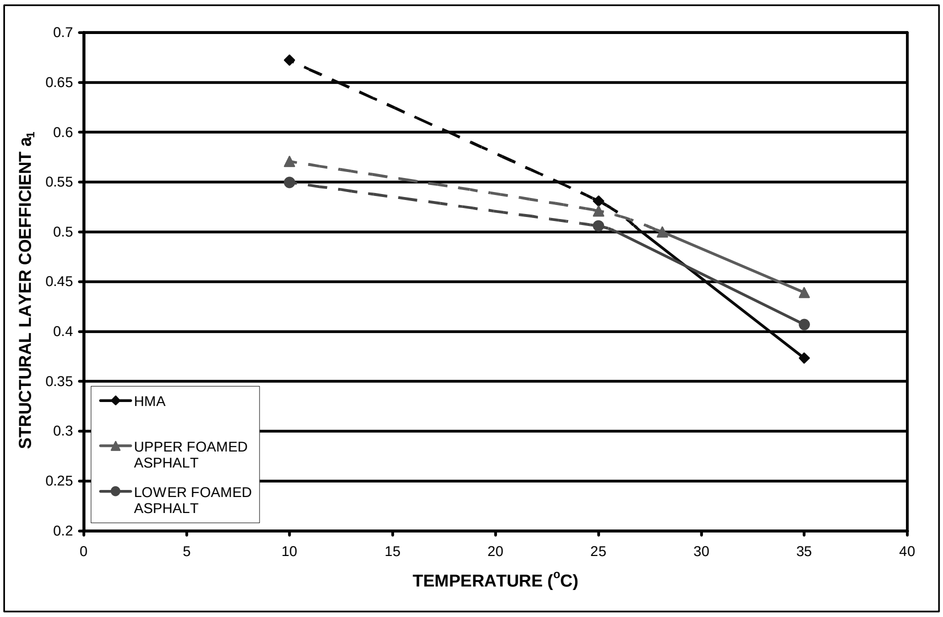


Figure 3 American Association of State Highway and Transportation Officials (AASHTO) 93 Structural Layer Coefficient (a_i) for Hot-Mix Asphalt and Foamed Asphalt

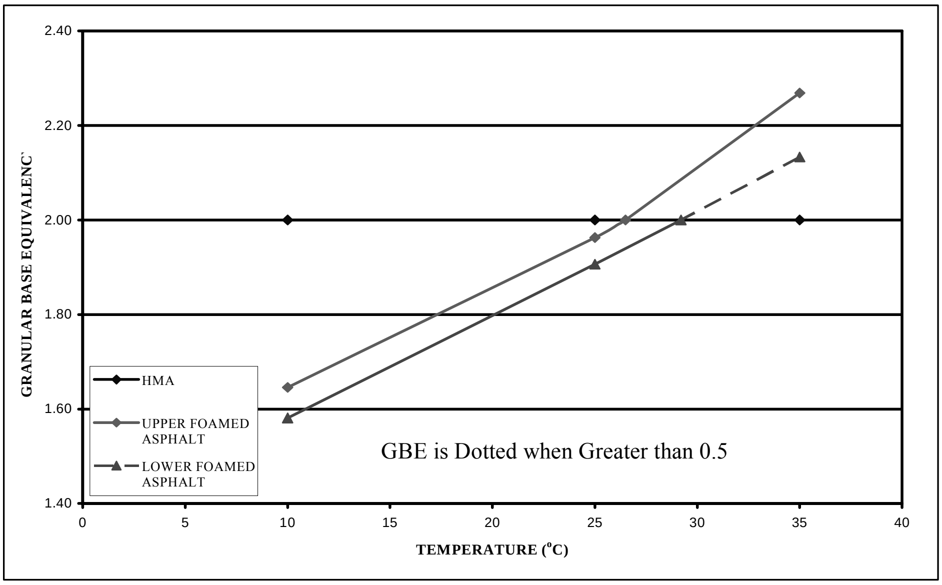


Figure 4 Ontario Ministry of Transportation (MTO) Granular Base Equivalency (GBE) Factors for Hot-Mix Asphalt and Foamed Asphalt

5. USE OF LIME WITH FDR (FOAMED ASPHALT)

While it appears that Portland cement (cement) has been the preferred additive for fines content, strength gain and/or stripping resistance for FDR (foamed asphalt) (WIRTGEN, 2004; AI, 2002), practical experience has shown that lime (hydrated or slaked quick lime), as shown in Photographs 4 and 5, is generally more effective for strength development and particularly stripping resistance (PETERSEN, 1988; HOTTE, 1995). Additionally, it is imperative that flexible pavement structures are not made too rigid or stabilized base shrinkage cracks reflect through the surfacing. A hydrated lime and corresponding cement effectiveness in FDR (foamed asphalt) evaluation was completed for the Bogotá, Colombia, major 2003 Transmilenio Las Americas urban expressway construction project shown in Photograph 5, including long-life asphalt pavement technology transfer (EMERY, 2005). Comparative FDR (foamed asphalt) mix designs were completed for 100 percent RAP, 50 percent RAP/50 percent granular material and 25 percent RAP/75 percent granular material, with hydrated lime or Portland cement, as summarized in Table 5 for the 50 percent RAP/50 percent granular material generally used for the Project.

The evaluation clearly showed the general strength development effectiveness of hydrated lime and particularly the critical TSR superiority of hydrated lime. From this evaluation, the following FDR (foamed asphalt/hydrated lime) mix design proportions were used on the Project as shown in Photograph 5 (up to 450 mm processing/mixing depth with shaping/compaction in up to three 150 mm lifts).

Table 5 Foamed Asphalt Mix Design Properties for 50 Percent Reclaimed Asphalt Pavement/ 50 Percent Granular Material Blend

Additive	Foamed Asphalt (%)	Voids (%)	Stability (N)	Flow (0.25 mm)	Tensile Strength, (kPa) Dry	Tensile Strength, (kPa) Wet	TSR (%)	Stiffness (MPa)
No Additive	3.0	13.0	53326	15.2	618	12	1.9	5799
	3.5	12.3	50991	16.9	785	80	10.2	4146
	4.0	11.6	48536	18.5	859	187	21.8	4479
1% Hydrated Lime	3.0	15.5	55742	15.6	532	312	58.6	3423
	3.5	14.6	57014	16.7	631	337	53.4	4310
	4.0	14.4	47688	19.5	769	394	51.2	4879
2% Hydrated Lime	3.0	14.8	57056	18.8	540	333	61.7	5766
	3.5	14.2	58014	20.1	552	361	65.4	3044
	4.0	13.6	52987	21.9	642	414	64.5	3292
1% Portland Cement	3.0	15.5	49808	16.4	576	138	24.0	4661
	3.5	14.8	54894	17.6	708	184	26.0	5389
	4.0	14.4	54131	18.1	836	255	30.5	4994
2% Portland Cement	3.0	16.3	52641	17.6	552	300	54.3	4523
	3.5	15.1	55427	20.0	650	366	56.3	5674
	4.0	13.0	53612	22.9	684	402	58.8	4020
3% Portland Cement	3.0	15.9	60577	16.4	600	386	64.3	4217
	3.5	14.9	52768	18.1	682	502	73.6	4660
	4.0	13.5	55891	20.2	638	544	85.3	4812

TSR is Tensile Strength Ratio

50 Percent RAP/ 50 Percent Granular Material Blend Foamed Asphalt Mix Design Proportions

	Material	Mix
Reclaimed Asphalt Pavement	50%	47.3%
Granular Material	50%	47.3%
Hydrated Lime	(2%)	1.9%
Asphalt Cement		3.5%
	100%	100%

Total Asphalt Cement Content (Residual Plus Added) = 4.88%.
Total Moisture Content (Residual Plus Added) = 4.2%.
Optimum Moisture Content = 7.7%.

This favourable experience with hydrated lime has become the standard approach with FDR (foamed asphalt), particularly to achieve the required TSR.

Canadian Shield INCO, Levack, Ontario	Kiruna Electric Haul Truck on Ramp Payload 50 Tonnes, 18 kmh Underground Ramp ~ 1000 m Deep	FDR with Emulsion (SC-1P) and Slurry Seal Used to Restore Underground Haul Road Smoothness and Durability

Photograph 8 Full-Depth Reclamation (FDR) with Emulsion Underground Haul Road (Ramp) at INCO's McCreedy East Mine, Levack, Ontario

6. CONCLUSIONS

Practical Canadian (from a depth of 1000 metres below the surface in Sudbury, Photograph 8), American and Colombian (to a height of 2650 metres in Bogotá, Photograph 5) experience has shown that enhanced asphalt pavement recycling techniques, such as CIR and FDR, clearly contribute to improved life-cycle performance, cost-effective pavement rehabilitation. It is imperative that the full range of asphalt recycling methods be adopted to reduce natural resource requirements and environmental impacts through sustainable asphalt pavements technology.

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