Whitepaper:
Cold-in-Place Recycling with Expanded Asphalt Mix
(CIR EAM/FOAM) Technology
COLD IN-PLACE RECYCLING WITH EXPANDED ASPHALT MIX (CIR EAM/FOAM) TECHNOLOGY

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INTRODUCTION
There is a growing interest in sustainability in the area of pavement construction that maximizes the utilization of existing pavement materials in maintenance, reconstruction and rehabilitation activities. The emphasis on sustainability has led to establishing a new terminology in pavement design and construction among which “Sustainable pavements” has emerged. Sustainable pavements has been defined as those pavements that are safe, efficient, environmentally friendly meeting the needs of present-day users without compromising the needs of future generations (Chan et al. 2009). Cold in-place recycling (CIR) is considered the most environmental-friendly and cost-effective method among the various in-place recycling techniques which has gained this specific technology a widespread acceptance among pavement agencies worldwide. In the CIR process, a portion of the existing asphalt concrete layer(s) is milled off, and the reclaimed material is mixed with appropriate amounts of selected recycling agent and other chemical additives, then spread and compacted to produce a base layer. The recycling agent is commonly asphalt-based emulsion or cold-foamed asphalt, or an emulsified engineered recycling agent. The mineral filler additive can be Portland cement, lime, kiln dust, fly ash or a combination of these products. In the CIR process, the existing asphalt surface is not heated prior to milling, and the reclaimed material is not shipped to a plant for processing, but processed in-place. It is clear that the CIR technology addresses the above definition and criteria of sustainability by (1) optimizing the use of natural resources, (2) reducing energy consumption, (3) reducing greenhouse gas emissions, (4) limiting pollution, (5) improving health, and risk prevention, and (6) ensuring a high level of user comfort and safety (Chan et al. 2009).

Benefits of CIR Technology
The use of CIR technology in pavement rehabilitation and reconstruction has been on the rise in the last two decades because it offers many advantages that include:

Environmental Benefits:
- Conservation of natural non-renewable resources through reusing and salvaging both aggregates and asphalt in existing pavements,
- Reducing or eliminating disposal of old distressed pavement materials that are inherent in conventional rehabilitation methods,
- Full use of the materials in the existing pavement. That is, CIR establishes a “zero waste” approach to pavement rehabilitation where the entire existing asphalt concrete layer is processed and reused in-place without the need for off-site transportation of waste materials. Therefore, spoil sites do not have to be found and the volume of new material that has to be imported from quarries is minimized. For that reason, haulage is drastically reduced or
totally eliminated, and as a result the overall energy consumption is significantly reduced, as are the greenhouse emissions and the damaging effect of haulage vehicles to roadways in the vicinity of the project site and traffic delays resulting from this increase in construction traffic.

- CIR consumes less energy due to use of in-place construction activities compared to other rehabilitation treatments, as shown in Figure 1. The energy savings (in production, transport, and placement) of various treatments compared to conventional hot mix asphalt overlay is estimated as follows:
  - Warm mix asphalt 14%
  - Hot in-place recycling 16%
  - Recycled asphalt (20%) in hot mix 21%
  - Recycled asphalt (30%) in hot mix 25%
  - Full depth reclamation with expanded (foamed) asphalt (stabilized base) 60%
  - Cold in-place recycling 80%

Because of reduced energy usage, greenhouse gas emissions are also reduced.

- The environmental benefits of CIR and CIRAEM over traditional HMA mill 4 inches and HMA overlay 5 inches were estimated as follows (Lane et al. 2008): (a) 62% savings in aggregate consumption, and (b) savings in greenhouse gas emissions as 52% less carbon dioxide emission, 54% less nitric oxide/nitrogen dioxide emission, and 61% less sulfur dioxide emission.

![Figure 1. Energy consumption by various HMA paving techniques (After Chappat and Bilal 2003).](image)
**Structural Benefits:**

- In-place recycling of existing deteriorated asphalt concrete pavement significantly controls or eliminates the occurrence of reflective cracking on new asphalt concrete overlays.
- Pavement surface irregularities and cracks can be effectively interrupted, and surface based rutting, bumps, dips, potholes, patches, and raveling distresses eliminated. Initially damaged asphalt concrete layer is converted in a more homogenous and stronger layer through in-place recycling.
- The structural capacity and ride quality of recycled damaged asphalt concrete layer can be improved.
- CIR materials stabilized with either emulsion or foamed asphalt develop strength relatively fast, especially when foamed asphalt is used as the stabilizing agent.
- CIR materials stabilized with bituminous materials (emulsion or foamed asphalt) have higher durability compared to other CIR materials stabilized with lime or cement because finer particles are usually locked-up by encapsulation in the bitumen (Wirtgen 2012), thus preventing these fine materials from reacting to water and from any pumping potential. Additionally, compared to other stabilization products, CIR materials stabilized with bituminous products demonstrate visco-elasto-plastic properties with improved shear properties (Wirtgen 2012).

**Safety Benefits:**

- Safety to public and construction workers is improved because some CIR projects can be opened to traffic in as little as 60 minutes prior to overlay placement. Typically, CIR construction can proceed as fast as 1-2 lanes miles per day; thus decreasing the inconvenience to the public and exposure of construction workers compared to other more intrusive rehabilitation techniques.
- CIR is performed in a single pass from milling to placing using a specialized recycling equipment train, which can be accommodated within the width of one traffic lane.
- CIR is performed with less construction equipment on the roadway compared to other rehabilitation treatments. Additionally, fewer trucks enter and leave the project site resulting in improved traffic safety.
- In-place construction and relatively high production rates compared to conventional methods improve safety by reducing traffic disruption, user inconvenience, and extended exposure of construction workers and the driving public.
- CIR process is less intrusive to local residents, businesses and emergency vehicles. It provides for immediate access after the train passes.
Construction Benefits:

- Shorter construction times can be achieved with CIR compared to alternative rehabilitation methods; thus reducing project costs and providing the intangible benefit for the road user in terms of reduced traffic disruption.
- Cross section profile, crowns, and cross slope drainage, can be manipulated as needed with CIR.

Economic Benefits:

- Conservation of energy due to use of in-place/on-grade construction activities (no hauling of material to and from the plant). In CIR, no fuel is required for heating the asphalt layer, resulting in significantly reduced energy consumption compared to other rehabilitation treatments.
- Significant saving in material cost due to full utilization of existing asphalt concrete without the need of virgin materials or the disposal of the milled off asphalt concrete material. Note that recycled pavements can also be recycled again as required.
- Because of the significant savings that can be achieved, available limited funding can be stretched to benefit other projects.
- Pavements rehabilitated with CIR methods can proceed at a faster rate than with other technologies, and as such user delays and lane closures can be minimized resulting in considerable savings in travel time and user delay expenses. Some CIR projects involving foamed asphalt can be opened to traffic in as little as 60-90 minutes, and an overlay may be placed and the project completed in as little as 2-3 days (to allow for curing).
- The above benefits combined generate about 20-40% cost savings, makes cold recycling a most attractive process for pavement rehabilitation in terms of cost effectiveness.
- An example comparison between conventional rehabilitation with overlay and CIR with foamed asphalt for an actual project (Catamaran Street, Foster City with 149,600 ft² paved surface area) is given below:
  - Conventional rehabilitation:
    - 32,000 ft² of existing asphalt concrete repair = $176,000
    - 3” asphalt concrete overlay = $252,824
    - Total = $428,824 (would’ve taken 5 days to complete).
  - CIR-foam:
    - 4” CIR with foamed asphalt = $157,080
    - 2” asphalt concrete overlay = $171,666
    - Total = $328,746 (took about 2 days to complete).
  - This project was bid using conventional methods and Value Engineered delivering a Net saving through using CIR-foam=$100,078 (~23%) while eliminating 3 days of traffic closures.
**Construction Method**

The CIR process usually uses 100% of the reclaimed asphalt pavement (RAP) generated on the project. The CIR process (utilizing asphalt emulsion or engineered recycling agent) is traditionally performed in the following steps (MTAG 2008):

1. The existing asphalt concrete layer(s) is milled to a depth of 2-6 inches,
2. The reclaimed material is sized, and, if necessary, virgin aggregate is added to achieve target gradation,
3. The reclaimed material is then mixed in-place with the selected additives (asphalt emulsion or emulsified recycling agent, and chemical additives or mineral filler, such as lime, cement, fly ash, etc.),
4. The reclaimed material is graded down and then compacted,
5. The reclaimed material is then cured as prescribed by the mix design in order to dry the free moisture and allow the asphalt emulsion or engineered recycling agent to cure.
6. Depending on the structural needs, a wearing course such as a chip seal, slurry seal, or a structural HMA overlay of a pre-designed thickness is placed on top of the compacted CIR layer. The purpose of the wearing course is to protect the pavement from water ingress and traffic damage by abrasion, and to obtain the required texture and skid resistance.

For a better process control, uniformity, and production rate, the CIR process is commonly performed using a single-pass equipment recycling train with an average production rate of about 1-2 lane-miles per day. The CIR equipment train, schematically shown in Figure 2, consists of a milling machine, a trailer mounted screening and crushing unit, and a trailer-mounted pugmill mixer, a pick-up conveyor, and a paving machine (FHWA 2011). The milling machine cuts the pavement to the desired depth, profile, and cross slope shape, and then deposits the reclaimed material into the crushing and screening unit. All materials are passed over the screens, and the oversized materials are returned to the crusher for additional processing, and subsequently sent back to the screening unit for additional resizing. From the screens, the reclaimed asphalt pavement (RAP) material is transferred into the pugmill mixer on a conveyor belt that also weighs the RAP material. Then, liquid recycling agent (either asphalt emulsion or engineered emulsion) is added to the RAP material in the pugmill using a computerized metering system that is locked into the feed belt for accurate measurement and control. The recycling agent is pumped into the twin shaft pugmill for thorough blending of the recycling agent with the RAP material. From the pugmill, the completed mixture is deposited into either a windrow or directly into the paver’s hopper. The final step in the CIR train involves the placement of the recycled mix on the roadway.
CIPR utilizing the Foamed Asphalt or Expanded Asphalt Method utilizes a shorter recycling train, typically the Wirtgen 3800 CR recycler. The 3800 CR recycler utilizes the same platform as the Wirtgen 2200 CR, but is supplied with a full-lane, 12 ½ ft (3800 mm)-wide milling drum in addition to an optional screed that matches the milling width (or may be extended by an additional 2’ to accommodate a wider section of paving, which on some projects may eliminate an additional pass). The 3800 CR recycler offers the ability to cold in-place recycle a full-lane of pavement by reclaiming the existing asphalt concrete to a predetermined depth. The material is then treated within the mill housing, with foamed asphalt binder, stabilizing the reclaimed material with either foamed asphalt, or any other stabilizing medium such as asphalt emulsion. Once the material is treated, it is laid down and compacted utilizing a vibrating, tamping screed to grade and then prepped for compaction. No windrow elevator, pickup machine, or additional paver is required. Therefore, the use of the 3800 CR train saves labor, fuel and equipment costs, in addition to reducing the carbon footprint of the project. As will be shown later, the operation of the 3800 CR is identical to the schematic shown in Figure 5.

Figure 3-a shows a picture of an actual CIR equipment train operating on one project, and Figure 3-b shows a close up of the Wirtgen 3800 CR. As can be noticed from Figure 3-a, the CIR process maintains an organized and clean construction site that poses minimal interruption to traffic in adjacent lanes and ensures a great level of public safety.
Figure 3. CIR equipment train operating on a recycling project (a) a clean process with minimal interruption to traffic in adjacent lanes, and (b) a close-up for the Wirtgen 388 CR recycler.

The CIR process is different from the full depth reclamation (FDR) process in two areas (MTAG 2008): (1) FDR incorporates the entire asphalt concrete layer and substantial amount of the underlying base material, and (2) unlike FDR, the CIR process requires time to dry (aerate) the free moisture from the mix and cure the asphalt emulsion or recycling agent before final compaction completed or a wearing surface course or overlay is placed on top. However, CIR utilizing foamed asphalt can incorporate aggregate base layers and in some cases subgrade layers that are non-plastic.
**Project Selection**

Cold in-place recycling (CIR) has been successfully used in the rehabilitation of all types of pavements including highways and city and county roads with low, medium, or high traffic volumes, parking lots, and even airport taxiways and runways. Additionally, it has been effective in treating a variety of distresses that affect flexible pavements. In order to determine whether a given project is candidate for CIR, the engineer must identify the types of distresses affecting the flexible pavement and the cause(s) of these distresses by conducting a preliminary pavement evaluation for the project site.

Table 1 summarizes the various types of distresses that commonly affect flexible pavements and the appropriateness of the CIR process to remedy these types of distresses. Color coding was used in Table 1 to demonstrate the appropriateness of the CIR process for the predominant distress affecting the pavement. As can be seen from Table 1, the CIR technology is suitable for treating most of the distresses known to affect flexible pavements; whether functional or structural, load-associated or non-load associated. The structural condition represents the pavement's ability to carry the design load, and as such structural deterioration results from mechanisms that act on the pavement that reduce its load-carrying capacity. On the other hand, functional condition is concerned with factors that only influence the ride quality and safety but do not necessarily result in reduction of structural capacity. It is common that an increase in the structural distress severity usually leads to functional failure.

**CIR WITH FOAMED (EXPANDED) ASPHALT**

Until the mid 1990’s, nearly all cold in-place recycling was performed using asphalt-based emulsions (Eller and Olsen 2009), which can be divided into three categories (Cross 2013):

- Polymer modified emulsion: these tend to improve fatigue and thermal resistance without reducing stability. Example products include HFMS-2P and HFE-150P,
- Solvent free emulsions (CSS) with lime: these products tend to improve early strength and moisture resistance. They also cure more rapidly than some other similar products. Examples include CSS, and
- Engineered emulsions (CSS-1 Special): These provide for controlled curing and breaking, and are formulated to resist raveling, rutting, moisture damage, with improved crack resistance.
Table 1. Appropriateness of CIR as a rehabilitation technology to remedy various distress types affecting flexible pavements (after ARRA 2001)

<table>
<thead>
<tr>
<th>Most appropriate</th>
<th>Least appropriate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutting (F) (LA)</td>
<td>Raveling (F) (NA)</td>
</tr>
<tr>
<td>Fatigue cracking (S) (LA)</td>
<td>Bleeding (F) (NA)</td>
</tr>
<tr>
<td>Longitudinal cracking (S) (NA)</td>
<td>Skid resistance</td>
</tr>
<tr>
<td>Transverse cracking (S) (NA)</td>
<td>Swells (S, F) (NA)</td>
</tr>
<tr>
<td>Reflection cracking (S) (NA)</td>
<td>Bumps (F) (NA)</td>
</tr>
<tr>
<td>Slippage cracking (S) (LA)</td>
<td>Sags (F) (NA)</td>
</tr>
<tr>
<td>Block cracking (S) (NA)</td>
<td>Depressions (S) (NA)</td>
</tr>
<tr>
<td>Potholes (S, F) (NA)</td>
<td>Strength problems</td>
</tr>
<tr>
<td>Corrugation (S) (NA)</td>
<td></td>
</tr>
<tr>
<td>Shoving (F) (LA)</td>
<td></td>
</tr>
<tr>
<td>Ride quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Edge cracking (S) (LA)</td>
</tr>
<tr>
<td></td>
<td>Shoulder drop off (F) (LA)</td>
</tr>
</tbody>
</table>

(F)= Functional, (S)= Structural, (LA)= Load Associated, (NA)= Non-load Associated.

In recent years, a new recycling technology utilizing cold-foamed asphalt as the stabilization agent has been used in recycling projects globally. Although the use of cold foamed asphalt as the recycling agent in CIR project has been limited throughout the United States, the use of this technology has been steadily increasing for the many advantages that it offers relative to the traditional CIR process involving the use of asphalt emulsion or engineered recycling agents. In this technology, foamed asphalt is used in lieu of emulsified asphalt or engineered emulsified recycling agent.

The idea of asphalt foaming dates back to 1956 and is attributed to L. Csanyi of Iowa State University. In the foaming process, a small quantity of cold water is introduced into hot asphalt, causing water expansion into steam, which in turn produces foamed asphalt. As the asphalt foams, its volume increases 10-30 times and its viscosity is greatly reduced. A schematic of the foaming process is shown in Figure 4.

The expansion in the use of the foaming technique in construction activities for roadway rehabilitation applications (for producing cold-foam coated mixes) began in the 1990’s and the technology has since gained wider acceptance among equipment manufacturers, roadway contractors, and agencies alike. Cold foamed asphalt (also called expanded asphalt) has been widely used in full depth reclamation (FDR) in which the asphalt and base layers are pulverized and mixed in-situ with foamed asphalt, compacted to form a new base, and finally overlaid with a structural asphalt concrete overlay.
On a larger scale, the foaming process is used to produce cold-foamed asphalt materials on the project site using a specially-designed expansion chamber integrated with the pulverization, mixing, and paving equipment train. In the expansion chamber, a small quantity of water (about 2-3%) is injected into hot bitumen at a temperature of about 176 °C (350 °F). The low viscosity of the foamed (expanded) asphalt enables it to be dispersed in and mixed with cold, moist aggregate and RAP materials. This is illustrated in Figure 5 which shows a schematic of the reclaiming processes incorporated with the asphalt foaming technology for recycling an existing asphalt concrete layer. As can be seen in Figure 5, in the recycling train, hot asphalt cement is pumped through an expansion chamber, into which a small quantity (~2-3%) of cold water is injected. At contact, water immediately vaporizes creating countless tiny bubbles within the hot asphalt cement which cause it to rapidly expand (foam) inside the mixing chamber. The foamed (expanded) asphalt is mixed with the processed RAP material. Additional water is usually added to achieve optimal moisture content necessary for compaction of the mixture. In lieu of foamed asphalt, an asphalt emulsion or engineered recycling agent can be injected. Mineral fillers such as portland cement can be introduced into the mixture by spreading the additives on the pavement surface upstream of the pulverization machine, or by injection of Portland cement in the form of grout into the mixing chamber. As with conventional CIR using emulsions, the mixture material is profiled and compacted to form a CIR layer. This
combination of CIR and expanded asphalt technologies results in a 100% recycled material and the combined process is usually referred to as Cold In-place Recycled Expanded Asphalt Mix (CIR EAM/FOAM) technology.

![Diagram of CIR EAM/FOAM process](image)

**Figure 5. CIR EAM/FOAM showing asphalt layer recycling and addition of foam**
(Witgen 2006)

Depending on the design of the recycling equipment, the emulsion or expanded foamed asphalt is injected into the mixture either in (i) the mixing chamber of the pulverization machine as shown in Figure 5 and more closely as shown in Figure 6, or (ii) in the mobile mixer when this function is performed with a machine distinct from the pulverization machine. In either way, the major difference between emulsions (asphalt emulsion or engineered recycling agent) and foamed asphalts is that the emulsion is generally prepared in a plant then supplied to the job site, whereas foamed asphalt is produced and used on-site.

Unlike other stabilizing agents used in CIR that rely on coating the aggregate for strength improvement, foamed asphalt relies on non-continuous binding between aggregate particles. This is achieved due to the foaming process that significantly increases the asphalt volume through formation of millions of tiny asphalt shards that bind to the fines in the pulverized material. The foamed asphalt tends to coat smaller RAP particles that are attached to the larger particles. The coated smaller particles tend to act as a glue to bond larger particles to create a cohesive mastic structure (Kim et al. 2011 J Materials p. 961-968).
Figure 6. Mixing chamber of the pulverization machine in which the foamed asphalt is injected (Wirtgen 2012).

Figure 7 demonstrates the difference between binding and coating of particles evidenced from the color of the cores representing CIR materials stabilized with expanded asphalt and asphalt emulsion, respectively.

Figure 7. Foam stabilized and emulsion stabilized cores (from Cross 2013).
CIR EAM/FOAM Benefits

CIR technology, whether with traditional asphalt emulsions or engineered recycling agents, is considered a sustainable pavement rehabilitation technique with a long list of benefits as discussed earlier in this report. The CIR EAM/FOAM even provides a vast number of additional benefits compared to CIR with asphalt emulsions or engineered recycling agents, primarily owing to the use of expanded asphalt as the stabilizing agent. These benefits include:

1. Unlike engineered products, foamed asphalt is made using bitumen, water, and air and as such it is an off-the-shelf product and not “engineered”.
2. Unlike asphalt emulsion that is produced in a plant under strict quality control practices, foamed asphalt is produced on the job site during construction.
3. Foamed asphalt binds aggregates but asphalt emulsion coats aggregate, thus requiring larger amounts of asphalt. It is often referred to these two processes as binding technology vs. coating technology. Besides requiring lesser amount of asphalt binder, foamed asphalt also requires less water than other types of cold mixing.
4. Unlike using asphalt emulsions and engineered emulsions, foamed asphalt can be used under some adverse weather (Eller and Olson 2009).
5. CIR with expanded asphalt is less dependent on warmer and drier weather usually necessary for CIR with asphalt emulsion and engineered emulsions for curing. Therefore, the use of expanded asphalt in CIR tends to accelerate the construction timeline while extending the window for construction (Chan et al. 2009).
6. No evaporated volatiles are generated while producing foamed asphalt, compared to that commonly generated with HMA and cutback emulsions.
7. Foamed asphalt products can be stockpiled without binder runoff or leaching, and remains workable for a relatively long time compared to other CIR stabilization products (Eller and Olson 2009).
8. Foamed asphalt can incorporate geotextile interlayer in the mix design, which makes the technology applicable to all asphalt concrete layers with or without a geotextile interlayer.
9. Because foamed asphalt does not coat aggregate in the mix (rather it binds the aggregate), it poses no issue with the material sticking to car tires or foot traffic during construction. This allows for opening the compacted recycled layer sooner to traffic compared to using other stabilizing agents.
10. Curing time can be as little as 2-3 days when foamed asphalt is used in CIR compared to longer times (up to 2 weeks) when asphalt emulsions and engineered recycling agents are used. In terms of construction expediency, this means that one can recycle and overlay and complete a project within only 3 days.
11. Foamed asphalt does not require any supplemental compaction once initial compaction has been reached; typically within 60-90 minutes after
placement. A fog seal and sand are applied, and the road is ready to receive traffic.

12. Because most distressed pavements when pulverized tend to produce measurable amount of fines, foamed asphalt can be used effectively in CIR involving fines in the range of 5-20%.

13. CIR materials stabilized with foamed asphalt can attain higher strength compared to traditional asphalt emulsion and engineered recycling agents. For example, CIR-emulsions have a structural layer coefficient ranging from 0.10 to 0.30 per inch whereas the layer coefficient of CIR-foam ranges from 0.13 to 0.36 per inch according to AASHTO (Kowlaski and Starry 2007). These values are to be compared to the layer coefficients of HMA which ranges from 0.2 to 0.44 per inch and that of asphalt concrete base from 0.2 to 0.38 per inch. It is clear that the structural layer coefficient of CIR-foam is close to that of the HMA and HMA base.

14. To evaluate the effect of higher layer coefficient of CIR-foam compared to CIR-emulsion on asphalt concrete saving, consider a 6 inch CIR layer. Assuming that the layer coefficient of CIR-foam is 0.36 and that of the CIR-emulsion 0.30 (maximum values of the ranges given above), the structural number (SN) contribution to any given flexible pavement structure would be equal to:
   a. SN(CIR-foam)= 6 in×0.36=2.16 inches
   b. SN(CIR-emulsion)=6 in×0.30=1.8 inches

Therefore, the structural number contribution of the CIR-foam layer is 0.36 inches greater than that of a CIR-emulsion layer of equal thickness. In terms of CIR thickness, a 6-inch CIR-emulsion layer would have the same structural number as a 5-inch layer of CIR-foam. This is a saving of 1 inch recycling if one chooses to use foamed asphalt as the stabilizing agent in lieu of asphalt emulsion. Assuming that the layer coefficient of HMA surface layer is 0.44 (maximum value), the structural number difference between the two CIR types is equivalent to 0.36 in/0.44=0.82 inches (~21 mm). Therefore, the use of foamed asphalt in stabilizing a six-inch CIR layer in lieu of asphalt emulsion can result in a saving of 0.82 inches of the required asphalt concrete to provide the same service life. These calculations are on the high side based on the maximum structural layer coefficients that were found in the literature. However, on the conservative side, a reduction in the HMA overlay thickness by 0.35 inches for a stabilized 4-inch layer and by 0.50 inches for a stabilized 6-inch layer can be realized when a CIR-foam is used in lieu of a CIR-emulsion. This is based on using structural layer coefficients of 0.28 and 0.32 for CIR-emulsion and CIR-foam, respectively which can also result in savings in terms of CIR layer thickness reduction by 0.5 inches and 0.75 inches for the 4 and 6 inch-layers, respectively. Since Caltrans assigns a gravel factor of 1.5 for CIR-emulsion, then this reduction in thickness corresponds to a gravel factor of 1.7 for CIR EAM/FOAM.
15. CIR EAM/FOAM materials usually have higher shear strength and resistance to flexural fatigue than emulsion stabilized materials. Additionally, CIR EAM/FOAM materials generally demonstrate better resistance to moisture damage.

16. CIR EAM/FOAM technology contributes many credit points under the various LEED® programs. The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™, developed by the U.S. Green Building Council (http://www.usgbc.org/); is a nationally accepted benchmark for the design, construction, and operation of high performance green buildings. It has also been used for rating and crediting innovative asphalt pavement construction practices that promote sustainability and have positive impact on the environment (NAPA 2013).

CALIFORNIA EXPERIENCE WITH CIR EAM/FOAM
The use of foamed asphalt in CIR applications has been limited in the United States; however, it has lately started gaining momentum due to the many benefits that this technology possesses compared to using traditional stabilization products. As mentioned previously, CIR is limited to recycling 2-4 inches of the existing asphalt concrete. Whereas foamed asphalt was not widely used in CIR, foamed asphalt has been used on a number of full depth reclamation (FDR) projects throughout the state where all the existing asphalt concrete and a portion of the base layer are recycled.

CIR EAM/FOAM on State Highways
The first project on a state highway utilizing CIR with foamed asphalt was constructed in April 2005 on I-80 in Placer County, CA between PM 14.3 and PM 33.3. The mainline structural section consisted of 0.60 ft of asphalt concrete, over 0.80 ft of cement treated base, over 1.0 ft of aggregate subbase (Caltrans 2006). Traffic on this segment of the highway accounted for a 20-year design TI of about 14 to 14.5 (41-55 million ESALs).

The project was originally designed as a “mill and fill with asphalt concrete overlay” as follows: Mainline: mill off 0.3 ft, and replace with 0.30’ HMA 1 ½” mix, 0.25’ HMA ¾” mix, and finally 0.10 ft RAC Type O, and Shoulder: mill off 0.25’existing pavement, and replace two lifts each 0.25’ HMA ¾” mix. The project required the contractor to work nights and to back-fill any milled areas in the same shift (Caltrans 2006). Negotiation between the Contractor and Caltrans lead to the decision to recycle the existing pavement to a depth of 0.35 ft, mix the grindings with cement slurry and foamed asphalt, and running the mixture through a tamping screed and performing final compaction. A total of 87 lane miles were cold in-place recycled with foamed asphalt. This project was the highest volume roadway in the United States to be recycled and, prior to surfacing with overlay, immediately opened to traffic (Kowalski and Starry 2007). Due to roadway layout considerations, it was decided to pre-grind the pavement surface prior to recycling in order to
maintain existing cross slope in sections. After recycling was completed, compaction proceeded and ended within 30 minutes and consisted of breakdown rolling coverage with one steel drum roller, intermediate rolling with two coverages of a steel drum roller and three coverages of the pneumatic compactor (Kowlaski and Starry 2007). After compaction was completed, the surface of the recycled new base was fog sealed with Cationic Quick Setting CQS1 asphaltic emulsion. To allow for curing of the CIR base, the design called for a minimum of 3 days prior to overlay placement, but the maximum curing times was set at 7 calendar days. The recycled base was opened to traffic in about 4 hours; a short closure time that was found to improve traffic flow through the construction zone with reduced traffic delay. Savings were achieved through eliminating the need to haul the milled material between the project site and the stockpile location which was determined at 4,700 haul trucks with an estimated haul travel distance saving of about 235,000 miles, and a total cost saving of approximately $58,700 on diesel fuel (at $2.50/gal). Additional savings from implementing a CIR-foam strategy were estimated as 112,100 tons of aggregate and 2,800 tons of asphalt cement.

**CIR EAM/FOAM on Counties and City Roadways**

Unlike Caltrans at the present, counties and cities throughout California have taken advantage of the vast number of features that CIR EAM/FOAM offers. In 2011, 2012, and to date (June 2013) over than 5,768,260 ft² (~640,920 SY) of roadways for various cities and counties in California has been recycled utilizing CIR EAM/FOAM. A list of projects completed in years 2011, 2012 and throughout the first 6 months of 2013 is shown in Table 2.

Numerous city and county agencies, and Caltrans have been implementing CIR for a number of years on many projects across California, mainly using asphalt emulsions and engineered recycling products. Cold in place recycling with foamed-asphalt is an attractive alternative that has proved to provide similar or better performance than the traditional CIR. Additionally, many other benefits and cost savings could be realized with the use of foamed asphalt as the recycling agent in CIR as explained earlier.
Table 2. Projects recycled with CIR EAM/FOAM and constructed by FMG in years 2011, 2012 and first half of 2013.

<table>
<thead>
<tr>
<th>Job No.</th>
<th>Owner</th>
<th>Status</th>
<th>General</th>
<th>Project Name &amp; Location</th>
<th>Square Footage</th>
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<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>Avaya Rock Trucking</td>
<td>FMX</td>
<td>Avaya Rock Trucking</td>
<td>9888 Russell Road</td>
<td>256,942</td>
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<tr>
<td>2</td>
<td>City of Salinas</td>
<td>DEHM</td>
<td>City of Salinas</td>
<td>E. Lushendoza Ave</td>
<td>41,019</td>
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<td>Status</td>
<td>General</td>
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<td>--------</td>
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<tr>
<td>1</td>
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<td>EID</td>
<td>CSN</td>
<td>Tully Rd &amp; First St</td>
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<td>FMG</td>
<td>Campus Loop Dr</td>
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<td>Peavy</td>
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Current Project Backlog

<table>
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<th>General</th>
<th>Project Name &amp; Location</th>
<th>Square Footage</th>
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<td>EID</td>
<td>Peavy</td>
<td>Santa Teresa Blvd, Tully Ave</td>
<td>599,000</td>
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<td>EID</td>
<td>Peavy</td>
<td>McPherson Ave/Evelyn Ave</td>
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<td>Alameda County</td>
<td>EID</td>
<td>FMG</td>
<td>San Leandro Ave, 225</td>
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<td>2,102,957</td>
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<td>7,466,257</td>
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</table>

DESIGN OF PAVEMENT STRUCTURES WITH CIR EAM/FOAM

The design of pavement utilizing cold in-place recycling with CIR and FDR technologies requires:

1. Careful evaluation of the project site to determine its candidacy for recycling as explained in an earlier section of this report. This requires performing a detailed surface distress survey.
2. Evaluation of structural adequacy of the various existing layers to determine their suitability for holding future traffic and environmental loadings. This requires coring to determine materials types and thicknesses, and deflection testing using falling weight deflectometer (FWD) and back calculation to determine in-situ resilient moduli of all layers.
3. Sampling of asphalt concrete material to be recycled and stabilized, and performing mix design in the laboratory and testing.
4. Conducting engineering analysis and design of the overlay thickness that needs to be placed over the recycled layer utilizing strength, layer thickness, and other engineering properties data obtained for both the existing and recycled layers.
5. Development of effective material specifications and construction details,
6. Implementation of quality construction techniques to ensure a successful recycling project.

The use of empirical method to design the pavement rehabilitation strategy and evaluate the HMA overlay requirement is commonly used by most agencies. In California, the deflection reduction method for overlay design may be used (HDM 2008). This requires deflection testing to determine the 80th percentile deflection. Additionally, a gravel factor for the recycled layer must be assumed (e.g., HDM assumes a gravel factor of 1.5). Another empirical method that may be used for this type of design is the AASHTO procedure based on the 1986 AASHTO guide (AASHTO 1993). This method uses layer coefficients for the structural layers similar to using gravel factors in the Caltrans empirical procedure. For materials recycled with bitumen emulsion, the layer coefficient can range to a maximum of 0.30 per inch, and for materials recycled with foamed asphalt it can range to a maximum of 0.36 per inch (Kowalski and Starry 2007). These values should be compared to the layer coefficient of asphalt concrete that can range to a maximum of 0.44 and that of an asphalt concrete base that can range to a maximum of 0.38 (Kowalski and Starry 2007).

The advanced procedure based on mechanistic-empirical (ME) concepts can also be used for designing pavement structures consisting of CIR EAM/FOAM layer. In the ME procedure, the critical primary responses (stresses, strains) in the pavement structures are computed using multilayer elastic theory and then used in empirical models describing the relationship between number of applied traffic and environmental loading cycles and a set of performance thresholds to describe failure of pavement in terms of fatigue cracking, rutting, and ride quality. Whereas the resilient modulus of the CIR layer may be used in the engineering analysis with the ME procedure, the use of advanced bituminous material characterization to describe the response of the CIR EAM/FOAM layer to traffic loading and environmental condition (temperature) is more favorable and results in a more accurate design. The ME procedure utilizing MEPDG software was used in performing analysis of pavement structures recycled with CIR EAM/FOAM compared to structures recycled with engineered emulsions, as will be shown in a later section of this report.

CONSTRUCTION OF CIR EAM/FOAM PROJECTS
As discussed earlier in this report, the existing surface distress condition largely determines the appropriateness of CIR for a given flexible pavement. Besides surface distresses, other factors play an important role in this determination, among
which are (1) when the pavement requires more than 30% dig-out, (2) when there are no spoil sites at a reasonable distance from the project site, (3) when short construction times (closure window) and single-lane closure are critical.

In CIR EAM/FOAM projects, the equipment train is specifically designed to have the capability of recycling thick asphalt concrete layer in a single pass. While there might be slight variations in the CIR EAM/FOAM construction, FMG Inc. follows the following steps:

- **Preliminary investigation**- Conduct
  (1) Conduct visual pavement inspection and coring, (2) Perform sampling of existing roadway materials to account for changes in the pavement, and (3) perform mix design in the laboratory.

- **Pre-Mill/Wedge Cutting**- This includes
  (1) Lowering all existing utilities, iron, manholes, remove pavement markers, etc., and (2) Pre-milling/ wedge-cutting existing pavement (if necessary) to accommodate the fluff of recycled material and the required thickness, as well as make room for wearing course.

- **Cement spreading**- The cement spreader is usually ahead of the equipment train by about 50 ft spreading cement over a pre-dampened pavement surface, at an average rate of about 1% by weight of RAP.

- **Cold in-place foam recycling**- In this process, (1) The machine pulverizes, processes, and replaces 3-6 inches of the pavement, and (2) Once the material is treated, it is compacted to 98% relative compaction, typically using 2 to 3 steel drum rollers followed by a 12-15 ton pneumatic roller. The compacted CIR
EAM/FOAM layer is ready to receive traffic in as little as 60 minutes.

- **Fog seal and Sand-** (1) Spread sand over the fog-sealed surface, (2) Open traffic immediately, (3) No rutting, no supplemental compaction necessary, and (4) Material is usually cured within 2-3 days.

- Place wearing course- After 2-3 days (depending on moisture content), place wearing course such as an asphalt concrete overlay over the recycled surface.

**CIR EAM/FOAM MIX DESIGN**

CIR EAM/FOAM is considered granular in nature and behaves between a Class II aggregate base and an HMA. The CIR EAM/FOAM material is not coated as is the case with asphalt and engineered emulsion, but it is said to be like welded as explained earlier. Typical HMA tests such as Rice Specific Gravity, Percent Voids, S-Value, Marshall Stability, and Flow are not applicable to CIR EAM/FOAM materials.

The mix design is performed in accordance with the Wirtgen Cold Recycling Technology manual (Wirtgen 2012) and is summarized in the flowing sections.

**RAP Gradation**

Most literature requires the gradation of RAP as follows (Cross 2013):

- With 1-2% cement, the RAP’s percentage passing sieve No. 200 should be in the range of 5-20%
- With 100% RAP, the RAP’s percentage passing sieve No. 200 <5%
- 100% passing the 1 1/2 inch screen
- 90% passing the 3/4 inch screen

An example of gradation of RAP from an actual project (Baffin Rd., Foster City, CA) is given in Figure 8. The gradation of RAP is controlled by the (i) rate of recycle, (ii)
condition of the teeth on the milling machine, and (iii) condition and strength of the existing asphalt concrete.

Determine Optimum Foaming Characteristics

Cold foamed asphalt must be produced with an optimal expansion ratio (ER) and optimal half-life. The quality of the foamed asphalt is controlled by the asphalt binder temperature and the amount of water injected into the hot asphalt. These values generally range from 280 to 320°F (135°C-160°C) and 1.5-3.5%, respectively. The expansion ratio ER and half-life of the foamed asphalt must be measured to determine the optimal asphalt-water ratio and asphalt temperature. The expansion ratio is a measure of the viscosity of the foam and determines how well the asphalt binder will disperse in the mixture (Wirtgen 2012). It is calculated as the ratio between the maximum volume of the foam relative to the original volume of asphalt. The half-life is a measure of stability of the foam and provides an indication of the rate of collapse of the foam (Wirtgen 2012). It is calculated as the time in seconds it takes the foam to collapse to half of its maximum volume. The foam ER increases (5-15 times) as the amount of injected water increases, but the half-life of the foamed asphalt decreases as the amount of injected water increases. In order to find the optimal foamant percentage which results in the maximum possible expansion ratio and half-life, a plot like that shown in Figure 9 is produced. As shown in Figure 9, Wirtgen (2012) recommends using:
• minimum acceptable half-life of 6 seconds, and
• minimum acceptable expansion ratio of 8%

To determine the range of water percentage injected to foam the asphalt, the range is split in half as shown in Figure 9. This figure shows an optimum foamant water content of 3% (by weight of asphalt) which is the amount of water that needs to be injected into the hot asphalt to foam it such that it will produce the maximum possible ER and half-life values.

![Figure 9. Determining optimal foamant water content based on expansion ratio and half-life of foamed asphalt (From Wirtgen 2012).](image)

In order to determine the optimal foaming characteristics CIR EAM/FOAM in the laboratory, a special laboratory-scale asphalt foaming unit (plant) is used, as shown in Figure 10. The laboratory foaming unit is capable of producing foamed asphalt under a variety of asphalt temperatures, water content, and air pressure during the foaming process. The laboratory-scale foaming plant enables performing a number of tests to determine the foamed bitumen properties.
Determine optimal foamed asphalt content based on tensile strength

With the foamed asphalt produced in Step 1 above, various specimens of RAP are prepared at various foamed asphalt contents for testing with the indirect tensile strength test [ASTM D6931 - 12 Standard Test Method for Indirect Tensile (ITS) Strength of Bituminous Mixtures]. Figure 11 shows the device used to test for indirect tensile strength, in which the specimens are loaded diametrically. A certain percentage of mineral filler such as cement or lime is added to the mixtures in order to meet strength, gradation, or other requirements. Indirect tensile strength tests are conducted on both cured dry and cured soaked samples; and the indirect tensile strength (ITS) is determined for both types of samples. A number of briquettes (usually 6) to be tested for indirect tensile strength are compacted using the Marshall compaction method (AASHTO T 245). The samples are extruded and placed in an oven to cure at 105°F (40°C) for 72 hrs. After the samples have been removed from the oven and let cool to room temperature they are tested for ITS. Samples are split equally to be tested for ITS both in dry (3 briquettes) and wet conditions (3 briquettes). In order for the mix design to be acceptable, the ITS of all tested specimens must conform to the following minimum values:

- ITS-dry>250 kPa (37 psi)
- ITS-wet>225 kPa (33 psi)
The retained tensile strength (also called tensile strength ratio-TSR) is then determined as the ratio of the ITS-wet to ITS-dry for all samples prepared with various foamed asphalt contents. The Wirtgen Manual (Wirtgen 2012) requires that the TSR is a minimum of 50%, otherwise a mineral filler must be added or its amount increased (up to 1-2%) if it is already present in the mix. If this does not solve the problem, further investigation of the mix will be required. The TSR vs. foamed asphalt content data is plotted and the foamed asphalt content corresponding to the maximum TSR is determined. Figure 12 shows an example from an actual project (Baffin Rd. in Foster City, CA) utilizing PG 64-16 binder with foaming water of 3% and an asphalt temperature of 180°C. In Figure 12, the plot describing indirect tensile strength tests versus foamed asphalt contents clearly shows a maximum TSR achieved at a foamed asphalt content of 2.25%. Note that in Figure 12, a 1% cement content was used in the mix.
Determine compaction water content
In order to determine the optimal compaction water content required for maximizing the dry density of the mix, various samples are prepared, using California Test 216, with the selected optimal foamed asphalt content (e.g., 2.25% in Figure 12 above) and various compaction water contents. Density results against moisture content are plotted and the moisture content corresponding to the maximum density is determined. Figure 13 shows the compaction-density results and plot (based on percentage of water added) for the Baffin Street project. It is shown in Figure 13 that the optimal moisture content that maximizes wet density is 4.9%.
**Mix Design Report**

The mix design report must provide the information presented in Table 3 below.

**Table 3. Mix design parameters and example data from the Baffin Rd. project.**

<table>
<thead>
<tr>
<th>Mix design parameters</th>
<th>Example</th>
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<td>Asphalt binder grade for making the foamed asphalt</td>
<td>PG 64-16</td>
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<td>Asphalt binder temperature for producing foamed asphalt</td>
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<tr>
<td>Percentage of injected water for foaming the asphalt or optimum foaming water content to produce a minimum of 6 seconds of half-life and a minimum of 8% of expansion ratio (% of asphalt by weight)</td>
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</tr>
<tr>
<td>Percentage of cement, lime, or any other additive to be added to the mix</td>
<td>1% cement Type II</td>
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<tr>
<td>Optimum asphalt foam content</td>
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<tr>
<td>Optimum compaction moisture content (dry weight basis)</td>
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<td>Particle size distribution data (showing % passing various sieves as required)</td>
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<td>Results of strength tests</td>
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<td>Foamed asphalt half-life versus Expansion ratio data</td>
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<tr>
<td>Maximum density per California Test 216</td>
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</tr>
<tr>
<td>Compaction moisture content to produce maximum density per California Test 216</td>
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</table>
PROPOSED SPECIFICATION

An example specification for CIR EAM/FOAM is given in the Appendix of this report. The quality control for acceptance along with pay factors based on ITS-wet and compaction density are also provided. The project acceptance is performed by first dividing the project into lots of 3,000 square yards each (2,500 ft long x 12 ft wide). The project acceptance is performed by first dividing the project into lots of 3,000 square yards each (2,500 ft long x 12 ft wide). The Engineer will sample and test each lot prior to acceptance. Each sampled lot is accepted if:

- ITS-dry > 37 psi
- ITS-wet > 33 psi
- The average relative compaction of a lot > 98% of the maximum wet density as measured using California test 216, but no single test shall be less than 96% relative compaction

A deduction for each lot if test results (both ITS and density) within the lot are outside the specifications is applied using reduced payment factors provided in the proposed specification shown in the Appendix.

Figure 14 below shows results of the moisture density testing using California Test 216 as part of the Quality Control (QC) testing plan for Lot #3 of the Baffin Rd. project. Figure 15 shows results of the nuclear gauge density test for the same lot. Figure 16 shows ITS values performed on the same lot of the Baffin Rd. project. According to the test results for Lot# 3 shown in Figures 14-16, no deduction on either density or indirect tensile strength will be applicable for all the results exceeding the specified minimum requirements.
Figure 14. QC test for maximum wet density using California Test 216 for Lot #3 of the Baffin Rd. project.
Figure 15. Nuclear gauge density tests as part of QC testing plan for Lot #3 of the Baffin Rd. project.
Engineers (Mechanical) Properties of CIR EAM/FOAM

CIR EAM/FOAM possesses a number of unique properties compared to conventional CIR using asphalt emulsions or engineered recycling products. Besides the numerous advantages of CIR EAM/FOAM over traditional CIR discussed earlier in the report, CIR EAM/FOAM also offers many engineering properties that are helpful for ensuring improved pavement performance. In the following sections, the engineering mechanical properties of CIR materials stabilized with foamed asphalt compared to those of CIR stabilized with conventional asphalt emulsions and engineered emulsion products are compared.

Curing Rate and Strength Development

Curing of asphalt stabilized materials (emulsion and foam) is the process where the mixed and compacted layer loses its moisture through evaporation, particle charge repulsion, and pore pressure induced flow paths (Wirtgen 2012). Curing of the CIR material occurs both while the material is exposed to air and after it is compacted and surfaced with an overlay or surface treatment. The curing period depends on a number of factors that include weather conditions such as day and nighttime air
temperatures, humidity level, rainfall activity, wind speed, materials characteristics such as layer thickness, compaction level and in-place void ratio, type of asphalt used, moisture content, and the drainage characteristics of the materials below the CIR layer (Kim et al. 2011). The curing of the CIR layer is important because overlaying the CIR surface before adequate curing has completed (i.e., adequate moisture loss has occurred) can result in premature failure of the CIR layer and the HMA overlay (ARRA 2001).

Many laboratory and field studies on CIR curing indicated a strong dependency of curing rate on both the CIR temperature and curing duration (Kim et al. 2011). Many agencies specify a minimum curing duration (such as 7 or 14 days) or a certain drop in the moisture content before an overlay or surface treatment could be placed on top of the CIR layer, or a combination of curing duration and moisture content drop. Some agencies require that the residual moisture content of the CIR layer after curing to not exceed a certain amount such as 1.0 - 2.0%. The FHWA (2009)'s survey revealed a wide variation in moisture content or curing duration requirements among state agencies: AZ, IA, SD, VT, WA require moisture content to drop to a level that does not exceed 1.5%, CO and KS to a level not exceeding 1.0% and 2.0%, respectively, while DE, ID, MA, MA, NE, NV, NH, NY, OH, and PA require a minimum curing period of as little as 4 days to as long as 45 days (Kim 2011, FHWA 2009). In the United Kingdom, the curing period is specified as a minimum of 36 hours (AIPRC 2002), while Ontario, Canada specifies a minimum 14-day curing period with conventional CIR, and only 3 days when using CIR EAM/FOAM assuming that tensile strength and compaction requirements have been achieved (Chan et al. 2009).

In CIR-emulsion, water is an intrinsic component. Therefore, breaking of the bitumen emulsion must take place before curing can occur through water migration and loss by evaporation (Wirtgen 2012). In CIR-foam, curing occurs as a result of water migration during compaction, and continues with repulsion of water by the bitumen and loss by evaporation. Therefore, in CIR-foam the curing process tends to be faster.

It is the curing and related moisture content reduction that results in increasing the tensile and compressive strength and stiffness of the bitumen stabilized material. The initial moisture content and rate of loss of moisture through the curing process is important in the early age of the layer because of the susceptibility of the layer to permanent deformation in the early period of repeated loading. Therefore, it is always beneficial to keep the compaction water content as low as possible, because the lower the degree of saturation, the greater the resistance to permanent deformation. Because CIR-emulsions typically have higher moisture contents than CIR-foam, CIR-emulsions require a longer curing period; thus the strength develops much slower in such mixes than in the CIR-foam mixes. This is illustrated in Figure 17 (Wirtgen 2012). The stabilized layer will continue to gain strength, though at
lower rate, over several years after placement; thus resistance to permanent deformation continues with time.

![Figure 17](image)

**Figure 17. Development of strength with time after placement for bitumen stabilized mixes (BSM) stabilized with foamed asphalt and emulsion (From Wirtgen 2012).**

**Tensile Strength**

Kim et al. (2011) compared the indirect tensile strength (ITS) of CIR samples (100 mm in diameter and 63.5 mm in length) molded, compacted (using gyratory compaction at 25 gyrations), and oven-cured (covered in room temperature) for various curing periods. The ITS test is the most commonly used test for evaluating the moisture susceptibility of asphalt mixtures. Both foamed asphalt (base PG 52-34) and engineered emulsion HFMS-2s were used in preparing the samples. The CIR-foam specimens were prepared with 2% foamed asphalt and 4% moisture content, while the CIR-emulsions prepared with 3% emulsified asphalt (equivalent to 2% asphalt because 67% of emulsion is asphalt) and 3% moisture content. Table 4 shows the mixture design parameters of both stabilization agents used in the experiments.
Table 4. Mixture preparation parameters for CIR-foam and CIR-emulsion specimens (From Kim et al. 2011).

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>CIR-foam</th>
<th>CIR-emulsion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt binder</td>
<td>PG 52-34</td>
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</tr>
<tr>
<td>Emulsified asphalt</td>
<td>—</td>
<td>HFMS-2s</td>
</tr>
<tr>
<td>Foaming temperature (°C)</td>
<td>170°C</td>
<td>—</td>
</tr>
<tr>
<td>Foaming water content (%)</td>
<td>1.3%</td>
<td>—</td>
</tr>
<tr>
<td>Foamed asphalt content (%)</td>
<td>2.0%</td>
<td>—</td>
</tr>
<tr>
<td>Emulsified asphalt content (%)</td>
<td>—</td>
<td>3.0% (2:1 asphalt + 1% venous water)</td>
</tr>
<tr>
<td>Moisture content of RAP (%)</td>
<td>4.0%</td>
<td>3.0%</td>
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<tr>
<td>RAP source</td>
<td>Story County and Clayton County</td>
<td></td>
</tr>
<tr>
<td>Compaction method</td>
<td>gyratory compactor at 25 gyrations</td>
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</tr>
<tr>
<td>Specimen size</td>
<td>Diameter: 100 mm and height: 63.5 ± 0.5 mm for indirect tensile strength test; diameter: 100 mm and height: 150 ± 0.5 mm for dynamic modulus and repeated load test</td>
<td></td>
</tr>
<tr>
<td>Number of specimen</td>
<td>3 specimens/batch</td>
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</tr>
</tbody>
</table>

Curing was allowed to occur in two steps: (i) initial curing in the air from 0, 1, 3, and 5 hrs before molding, and (ii) curing in covered molds for 0, 7, or 14 days. It was found that the ITS of both CIR-foam and CIR-emulsion samples increased as the initial curing time increased. During the initial curing, the CIR-foam specimens showed higher ITS than the CIR-emulsion counterparts. This is because CIR-foam materials could lose moisture more quickly during the initial curing in the air than the CIR-emulsion specimens as the emulsified asphalt takes more time to release water while breaking than foamed asphalt. The CIR-foam specimens generally gained most of their tensile strength much more rapidly than the CIR-emulsions when samples were allowed to cure in the mold for up to 14 days. It was noted that the ITS for CIR-foam specimens remained nearly constant while that of CIR-emulsion continued increasing slowly. Generally, despite some variations, it was observed that the CIR-foam specimens gained relatively higher tensile strength than the CIR-emulsion specimens upon curing up to 14 days. Therefore, the CIR-foam materials have a better resistance to flexural fatigue than emulsion-stabilized CIR.

Figure 18 shows the effect of curing (at 25°C and 45°C), in terms of reduction in moisture content, on the ITS of both CIR-foam and CIR-emulsion specimens. As can be seen from Figure 18, CIR-foam samples exhibit relatively higher ITS values than the corresponding CIR-emulsion samples.
Figure 18. Tensile strength gain as the moisture content drops with curing at 25°C and 45°C (a) CIR-foam, and (b) CIR-emulsion. From Kim et al. (2011).

Additional testing by Kim et al. (2011) to study the effect of water soaking on CIR-foam and CIR-emulsion samples was also performed. All samples were cured in air for 5 hours to a moisture content of 1.5%, and then oven-dried at 40°C for 3 days. The specimens were then placed in a water bath at 25°C for 24 h to simulate heavy rain on CIR layer in the field. ITS testing was conducted on the specimens to investigate the influence of the 24-hr moisture submersion. Figure 19 shows the average ITS of 3 cured and 3 cured and saturated CIR specimens, and the percent loss in ITS. As shown in Figure 19, the ITS decreased after submersion of specimens in water for 24 hrs. The CIR-emulsion specimens retained higher ITS than CIR-foam specimens after 24 hrs water submersion. Therefore it is important that any access
of water to CIR materials be prevented or minimized especially with CIR-foam materials.

Figure 19. Effect of moisture saturation on ITS (From Kim et al. 2011)

**Dynamic Modulus**
The CIR mixtures (both CIR-foam and CIR-emulsion) were also subjected to dynamic modulus testing using the repeated load test (RLT) with the use of Asphalt Mixture Performance Tester, AMPT, or what used to be called Simple Performance Tester, SPT (Kim et al. 2011). Samples were prepared with the gyratory compactor at 25 gyrations and cured at room temperature for 5, 10, 20, 30, and 90 hrs. The dynamic test was performed at 21.1°C and a 10 Hz loading frequency. Figure 20 shows the average dynamic modulus of CIR-foam and CIR-emulsion specimens from two RAP sources. As can be seen from Figure 20, CIR-foam specimens attained higher dynamic moduli compared to the CIR-emulsion specimens from the two RAP sources. Trend lines were added to Figure 20 for Story County RAP material stabilized with foam and emulsion to highlight the increase in modulus of CIR-foam compared to the CIR-emulsion. As shown, the CIR-foam specimens of the Story County RAP exhibited about 1 GPa (145 ksi) higher modulus than the CIR-emulsion at early ages after curing (5 hrs) but the difference increased to about 2 GPa (290 psi) after 90 hrs of curing. Figure 20 also shows that the modulus of all CIR mixtures increased as the moisture content of the mixtures decreased. Table 5 below provides comparison of the dynamic modulus values for the foamed asphalt versus those of the CIR-emulsion HFMS-2s for RAP obtained from Story County.
Figure 20. Comparison of dynamic modulus of CIR-foam and CIR-emulsions at various curing durations. The red continuous curve represents the overall trend for the CIR-foam and the green dashed curve represents the CIR-emulsion for Story County RAP material (from Kim et al. 2011).

Table 5. Dynamic modulus at 21.1 °C as function of curing time and type of stabilizing agent (emulsion vs. foamed asphalt) with RAP obtained from State Hwy 210 in Story county, IA (Kim et al. 2011)

<table>
<thead>
<tr>
<th>Curing time (hr)</th>
<th>Dynamic modulus in GPa and (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CIR-foam (PG 52-34)</td>
</tr>
<tr>
<td>5</td>
<td>1.50 (217)</td>
</tr>
<tr>
<td>10</td>
<td>2.00 (290)</td>
</tr>
<tr>
<td>20</td>
<td>2.40 (348)</td>
</tr>
<tr>
<td>30</td>
<td>2.50 (362)</td>
</tr>
<tr>
<td>90</td>
<td>3.90 (565)</td>
</tr>
</tbody>
</table>

**Permanent Deformation (Rutting) Performance**

Kim et al. (2011) conducted additional RLT experiments on CIR mixtures to investigate the effect of stabilization agent, RAP source, curing duration, and moisture content on flow number and accumulation of plastic strain under repeated loading. The cumulative plastic strain is used to investigate the rutting potential of CIR mixtures. All samples were cured for 10 hrs while exposed in air at room temperature, then encased in plastic molds and cured in an oven for 0, 7,
and 14 days at 45°C (this temperature was selected to represent the temperature of the CIR base layer constructed in summer). Repeated load tests were also conducted at 45°C with a loading stress of 69 kPa. Figure 21 shows the cumulative strain against the number of load cycles measured at three curing times for both types of CIR mixtures prepared with RAP from Story County. It is evident from Figure 21 that the CIR-foam specimens exhibited a slower rate of development of permanent strain (and permanent deformation) and would take much greater number of loading cycles before a certain level of plastic strain could be attained compared to the CIR-emulsion specimens. The number of cycles at which a more rapid strain accumulation starts to occur is referred to as Flow Number (FN), which represents the onset of the tertiary flow primarily caused by shear deformation of the CIR mixture. The large FN values for the CIR-foam mixtures indicate the significantly higher resistance of the CIR-foam mixes to permanent deformation compared to the CIR-emulsion counterparts.

Dynamic modulus
Lee et al. (2009) carried out detailed dynamic modulus testing of CIR materials obtained from various projects (various RAP sources) and stabilized with two engineered emulsion (EE) namely CSS-1h and HFMS-2p and foamed asphalt (PG 52-34) at various stabilizer contents. The dynamic modulus testing was carried out using AASHTO test method 62-03: “Determining Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures”, and the AMPT. The tests were conducted at various temperatures (4.4, 21.1 and 37.8 °C) and 6 loading frequencies (25, 10, 5, 1, 0.5, and
The study concluded that CIR-foam mixtures consistently achieved higher modulus than CIR-engineered emulsions at all frequencies. Results of the testing for both the CIR-foam and the two CIR-emulsions are summarized in Table 6 below.

Table 6. Comparison of dynamic modulus (in kPa) between CIR-foam and CIR-emulsions at 5 Hz loading frequency (Lee et al. 2009).

<table>
<thead>
<tr>
<th>RAP Source</th>
<th>Temp.</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>Emulsified Asphalt Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscatine County</td>
<td>4.4C</td>
<td>9,260,231</td>
<td>9,181,951</td>
<td>9,291,246</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>3,810,100</td>
<td>3,510,521</td>
<td>3,434,058</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,162,021</td>
<td>1,023,112</td>
<td>905,963</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Webster County</td>
<td>4.4C</td>
<td>8,090,801</td>
<td>9,064,688</td>
<td>8,410,998</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>4,299,403</td>
<td>3,614,785</td>
<td>3,551,912</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,577,202</td>
<td>1,246,724</td>
<td>1,270,187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardin County</td>
<td>4.4C</td>
<td>5,812,187</td>
<td>6,832,786</td>
<td>6,574,383</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>3,205,106</td>
<td>3,226,876</td>
<td>2,704,904</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,438,043</td>
<td>1,359,439</td>
<td>1,062,643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montgomery County</td>
<td>4.4C</td>
<td>7,642,139</td>
<td>7,026,591</td>
<td>7,645,225</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>3,304,670</td>
<td>3,503,103</td>
<td>3,138,026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,359,350</td>
<td>1,150,393</td>
<td>1,073,900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bremer County</td>
<td>4.4C</td>
<td>8,023,216</td>
<td>7,725,436</td>
<td>6,830,521</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>4,038,295</td>
<td>3,182,999</td>
<td>2,941,016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,401,083</td>
<td>1,103,308</td>
<td>1,020,963</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lee County</td>
<td>4.4C</td>
<td>6,437,550</td>
<td>6,225,184</td>
<td>6,085,517</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>2,024,039</td>
<td>2,053,526</td>
<td>2,838,679</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,309,096</td>
<td>1,433,081</td>
<td>1,267,247</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wapello County</td>
<td>4.4C</td>
<td>8,205,216</td>
<td>7,527,753</td>
<td>7,462,912</td>
<td></td>
</tr>
<tr>
<td>21.1C</td>
<td>3,991,876</td>
<td>3,266,873</td>
<td>3,037,524</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.0C</td>
<td>1,308,758</td>
<td>1,326,037</td>
<td>1,196,037</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIELD PERFORMANCE

CIR EAM/FOAM is quite limited in California, and as such performance studies on highway pavements rehabilitated with CIR EAM/FOAM are also limited. In Canada, CIR EAM/FOAM has been used extensively on many roadways and highways since 2003.

The Ministry of Transportation Ontario (MTO) constructed a 5-km CIR EAM/FOAM test section on Highway 7 in 2003 next to an 8-km section constructed with conventional CIR utilizing emulsions (Lane and Kazmierowski 2005). During construction, indirect tensile strength tests were conducted on samples obtained from both CIR sections. FWD testing before construction, immediately after construction, and one year later was conducted to determine the change in strength with time and to compare the two CIR methods. Additionally, resilient modulus testing on CIR-emulsion and CIR EAM/FOAM samples indicated that modulus is statistically similar. FWD testing immediately after construction showed the deflections for CIR EAM/FOAM to be lower than those for CIR-emulsion with 95% statistical significance, but these deflections reached the same range, for both processes, after one year in service (one year curing). The back calculated resilient
moduli from the one year FWD deflections indicated that both the CIR-emulsion and CIR EAM/FOAM materials have statistically similar strength in terms of resilient modulus (Lane and Kazmierowski 2005).

Additional testing and analysis after 5 years in service was also performed by Chan et al. (2009). Evaluations performed included annual pavement condition surveys, roughness measurements and rutting measurements. Both the CIR-emulsion and CIR EAM/FOAM sections appeared to perform similarly (i.e. no statistical differences were found) since the first year of construction until the time of the study (5-years after construction). Regarding rutting, some differences in rutting were noticed at year 3 after construction, but then the differences diminished at year 5, probably due to the curing of CIR-emulsion and CIR EAM/FOAM at different rates in early years that subsequently evened out at year 5. Finally, backcalculation of resilient modulus from FWD data revealed that the modulus of CIR EAM/FOAM was initially higher than that of CIR (up to year 3) and then the modulus of the two CIR mixtures became statistically similar in the following 2 years (Chan et al. 2009). The mean deflection was also found to be statistically similar between CIR-emulsion and CIR EAM/FOAM section for all the years since construction in 2003 and for the next 5 years.

Lane and Kazmierowski (2005) obtained samples of CIR-emulsion and CIR EAM/FOAM mixes and stored them to cure for 6 months. Briquettes were made for determination of dry and wet indirect tensile strength. Testing revealed that the CIR EAM/FOAM samples attained higher dry and wet indirect tensile strengths than the CIR-emulsion specimens. Further analysis of specimens’ density revealed that the CIR-emulsion specimens could not be compacted to the same level of compaction as the CIR EAM/FOAM samples, therefore their densities were lower, which could explain the reduced indirect tensile strengths measured in the laboratory. In order to investigate whether CIR EAM/FOAM mixes are superior to CIR-emulsion mixes with regard to density, cores were obtained from the in-service pavement sections 8 months after construction. Statistical analysis indicated that there was no statistical difference in density between the cores of either material. Therefore, it was concluded that the ITS of both CIR materials must be similar.

Limited analysis of the resilient modulus of CIR EAM/FOAM layer compared to that of an asphalt layer was performed for the California CIR EAM/FOAM project on I-80 (Caltrans 2006). Two sections, each about 5000 ft long, were constructed; one with 4 inch CIR EAM/FOAM base layer, and the other with 4 inch asphalt concrete base (1 1/4 “ maximum aggregate size), both overlaid with 1.5 inch hot mix asphalt (3/4” aggregate). Both sections were underlain with 2 inches of existing asphalt concrete over 11 inches of cement treated base (CTB) over subgrade. Falling weight deflectometer (FWD) testing was conducted on both sections, and back calculation was performed to determine the resilient modulus of all layers in the two sections. Figure 22 shows the back calculated resilient modulus of the asphalt concrete
surface layer combined with the CIR EAM/FOAM layer versus that for the asphalt concrete layer with the asphalt concrete base. Note that both the asphalt concrete overlay and the base layer are of same thickness between the two sections. Additionally, all other lower layers are of similar materials and thickness between the two sections. Therefore, the main difference between the two pavement sections investigated is the type of base layer: CIR EAM/FOAM vs asphalt concrete base. The back calculated resilient modulus of the CIR EAM/FOAM layer combined with the asphalt concrete thin overlay is roughly 25% lower than that of the asphalt concrete base with the asphalt concrete overlay (Caltrans 2006).

![Figure 22. In-situ resilient modulus of the asphalt concrete overlay combined with either the CIR EAM/FOAM layer or the asphalt concrete base (Caltrans 2006).](image)

THEORETICAL ANALYSIS
Pavement Structures

In order to compare the performance cold-in place recycled pavements using foamed (expanded) asphalt and engineered asphalt emulsion, theoretical analysis was conducted using the Mechanistic-Empirical Pavement Design Guide (MEPDG) software. For this analysis, various flexible pavement structures varying in the type of stabilization agent used in stabilizing the existing asphalt concrete layer were selected. The pavement structure to be rehabilitated with cold in-place recycling and overlaid with asphalt concrete overlay consists of the following materials and thicknesses (from bottom to top):

- Subgrade (A-6) with resilient modulus \( M_r \) of 14,500 psi,
- Aggregate base (A-1-a), 6 inches thick, with \( M_r = 40,000 \) psi,
- CIR (foam or engineered emulsion), 4 inches thick, and
- Asphalt concrete overlay (PG 64-10), 3 inches thick.
Characterization of Asphalt-Treated Materials
The modulus of the asphalt concrete overlay as a function of temperature and frequency (traffic speed) was estimated based on mix volumetrics, and as described in MEPDG (2013). For the CIR-foam, the dynamic modulus data provided by Lee et al. (2009) were used, and are shown in Table 6. The binder used in producing the foam asphalt was PG 52-34. The engineered asphalt emulsions were CSS-1h and HFMS-2p. These two engineered emulsions were selected from the two major categories of cationic and anionic. Anionic emulsions have negatively charged asphalt droplets and cationic emulsions have positively charged asphalt droplets. The CSS-1 is cationic and HFMS-2p is anionic. Because the modulus values can vary with the RAP source as evident in Table 6, the modulus was averaged over all sources (counties). Table 7 shows the final modulus values of the three types of CIR mixtures for the various test temperatures and frequencies.

Table 7. Measured dynamic modulus at various temperatures and frequencies for the three stabilization agents (foamed asphalt PG52-34 and two engineered emulsions).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Temperature (°C)</th>
<th>Dynamic modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CIR-Foam</td>
</tr>
<tr>
<td>0.1</td>
<td>4.4</td>
<td>4280</td>
</tr>
<tr>
<td>0.1</td>
<td>21.1</td>
<td>1370</td>
</tr>
<tr>
<td>0.1</td>
<td>37.8</td>
<td>540</td>
</tr>
<tr>
<td>0.5</td>
<td>4.4</td>
<td>5400</td>
</tr>
<tr>
<td>0.5</td>
<td>21.1</td>
<td>1979</td>
</tr>
<tr>
<td>0.5</td>
<td>37.8</td>
<td>738</td>
</tr>
<tr>
<td>1.0</td>
<td>4.4</td>
<td>6000</td>
</tr>
<tr>
<td>1.0</td>
<td>21.1</td>
<td>2386</td>
</tr>
<tr>
<td>1.0</td>
<td>37.8</td>
<td>903</td>
</tr>
<tr>
<td>5.0</td>
<td>4.4</td>
<td>7600</td>
</tr>
<tr>
<td>5.0</td>
<td>21.1</td>
<td>3648</td>
</tr>
<tr>
<td>5.0</td>
<td>37.8</td>
<td>1400</td>
</tr>
<tr>
<td>10.0</td>
<td>4.4</td>
<td>7696</td>
</tr>
<tr>
<td>10.0</td>
<td>21.1</td>
<td>4296</td>
</tr>
<tr>
<td>10.0</td>
<td>37.8</td>
<td>1710</td>
</tr>
<tr>
<td>25.0</td>
<td>4.4</td>
<td>9048</td>
</tr>
<tr>
<td>25.0</td>
<td>21.1</td>
<td>5137</td>
</tr>
<tr>
<td>25.0</td>
<td>37.8</td>
<td>2200</td>
</tr>
</tbody>
</table>

Temp(°F)=32+1.8×T(°C). 1MPa=145 psi.
Because the modulus values were reported for only three temperatures, as shown in Table 7, while modulus values for at least 5 temperatures will be needed in the MEPDG, master curves were constructed for each of the mixtures based on the time-temperature correspondence principle that utilizes the equivalency between frequency and temperature. The master curve will allow computation of dynamic modulus for temperatures and frequencies other than those used in testing. All the empirical constants in the master curve equation (MEPDG 2013) were derived by nonlinear minimization of the sum of the square of the error of the master curve sigmoidal model using Excel’s optimization solver function. Subsequently, the master curve equation was used to determine the modulus values at the two missing temperatures (10°F and 130°F). Finally, the complete modulus-temperature-frequency data were used to describe the modulus of the CIR mixtures as required by the MEPDG Level 1 material characterization. Figure 23 shows the data for the three mixtures used in producing the master curves and the obtained master curves.

![Figure 23. Measured dynamic modulus values plotted against reduced time used to develop master curves of the three stabilization agents.](image)

Two observations regarding the modulus versus the log of reduced time shown in Figure 23 must be made:

1. It is obvious that the modulus (stiffness) of CIR-foam material is consistently higher than that for the CIR-CSS mixtures, which in turn is higher than that of the CIR-HFMS mixtures for all temperatures and frequencies tested.
2. The CIR mixtures exhibited a viscoelastic behavior similar to a conventional asphalt concrete. Therefore, such materials must be treated in the analysis in
the same way as an asphalt concrete layer rather than assigning a fixed
dynamic modulus value as most commonly done when analyzing pavement
structures consisting of a CIR layer.

**Traffic and Climate**
The traffic used in the simulation was based on the MEPDG national default load
spectra with annual average daily truck traffic (AADTT) of 1,500. This level of traffic
produces traffic index (TI) TI of approximately 12 for a design life of 20 years. The
climate of Fresno, CA was used in the analysis.

**Simulation Results**
The performance of each of the three pavement structures (with three CIR mixture
types) was analyzed using the MEPDG software. Figure 24 shows the bottom-up
fatigue cracking and top-down longitudinal fatigue cracking in the asphalt concrete
overlay for a 20-year period. It is shown that while the CIR-foam outperforms the
other two CIR-emulsion types in both types of cracking, the differences are
relatively small.

Figure 25 shows the development of rutting both in the CIR layer and the total
rutting affecting the entire pavement. As shown, the CIR-foam exhibited reduced
rutting compared to the other two CIR mixtures (30% less compared to CIR-CSS and
60% less compared to CIR-HFMS at year 20). Regarding the total rutting, the
pavement with CIR-foam exhibited about 0.1 inch less rutting at year 20 compared
to pavement with CIR-HFMS, and 0.05 inch less compared to the pavement with
CIR-CSS.

Finally, the IRI was similar (with pavement with CIR-foam slightly lower roughness)
for the three pavement structures analyzed.
Figure 24. Development of cracking in asphalt concrete overlay over the 20-year design period: (a) Bottom-up fatigue cracking, and (b) Top-down longitudinal cracking.
Figure 25. Rutting performance of the pavements with the three CIR materials: (a) CIR layer rutting, and (b) total pavement rutting.
SUMMARY AND CONCLUSIONS

There is a growing interest in sustainability in the area of pavement construction that maximizes the utilization of existing pavement materials in maintenance and rehabilitation activities. Cold in-place recycling (CIR) is one of those sustainable technologies that is considered the most environmentally-friendly and cost-effective methods of all in-place recycling techniques. In the CIR process, a portion of the existing asphalt concrete layer(s) is milled off, and the reclaimed material is mixed with appropriate amounts of the selected recycling agent and other chemical additives, then spread and compacted to produce a base layer. The recycled layer receives some sort of surface treatment or a structural overlay depending on traffic loading conditions.

CIR technology has gained considerable momentum in the last two decades because of the many advantages and benefits that this technology offers at the environmental, structural, safety, construction, and economic levels. Most CIR projects involved using either asphalt emulsion or engineered emulsified recycling agent as the stabilization agent. In recent years, cold foamed asphalt (also called expanded asphalt) has been introduced and successfully used as the stabilization agent on many CIR projects in lieu of emulsified asphalt or engineered emulsified recycling agent. Unlike “engineered” recycling agents, expanded asphalt is made using bitumen, water and air and is an off-the-shelf product. Also, unlike other traditional stabilization agents (engineered or asphalt emulsion), expanded asphalt is produced on the job-site and does not require manufacturing in a strict-quality control plant. Historically cold foamed asphalt has been used mainly in full depth reclamation where all the asphalt concrete and portions of the aggregate base are recycled. The use of expanded asphalt in CIR projects has been limited throughout the United States. Unlike other conventional stabilizing agents used in CIR that rely on coating the aggregate for strength improvement, foamed asphalt relies on non-continuous binding between aggregate particles. This technology is commonly referred to as Cold In-place Recycled Expanded Asphalt Mix (CIR EAM/FOAM) or Cold Foam In-Place Recycling.

CIR EAM/FOAM provides a number of benefits compared to CIR with asphalt emulsions or engineered recycling agents, primarily owing to the use of expanded asphalt as the stabilizing agent. These include the ability to open the recycled layer to receive traffic 60-90 minutes after completing compaction, placement of the overlay or surface treatment within 1-3 days, and extending the construction season because of the relatively lower sensitivity of CIR EAM/FOAM to weather conditions. Currently, many counties and cities throughout California have taken advantage of the vast number of features that CIR EAM/FOAM offers. Since 2011, FMG; a leader in cold in-place recycling with expanded asphalt, has completed the construction of more 5,300,000 ft² of CIR EAM/FOAM projects on roadways of various cities and counties in California. As a sign of wide acceptance, approximately 14 agencies
within Northern California alone either already have or are currently considering CIR EAM/FOAM as a bid item in the next year.

Numerous laboratory studies investigating the benefits of CIR EAM/FOAM compared to traditional CIR-emulsion have shown the advantages of CIR EAM/FOAM to traditional CIR-emulsion materials. Additionally, the few actual pavement performance studies comparing test sections rehabilitated with CIR EAM/FOAM and CIR-emulsions have also demonstrated similar or better performance between the two types of recycling.

REFERENCES


APPENDIX

Sample Specifications for Cold In-Place Recycling Expanded Asphalt Method

39-7.1 Minimum Qualifications for Cold In-Place Recycling Expanded Asphalt Method (CIR-EAM) Contractor

The contractor directly responsible for providing the cold in place recycling activities shall provide minimum qualifications for the Engineer’s approval prior to being awarded the project. The minimum qualifications shall include:

- At least two years’ experience providing cold in-place recycling services

- A list of five (5) or more successful cold in-place recycling projects with a list of references, including contact information

- The resume of a cold foam expert with a minimum of five (5) years’ experience providing QA/QC services on cold in-place recycling projects. This individual shall oversee quality control duties throughout the project.

39-7.2 Mix Design

A minimum 30 days prior to starting the Cold in Place Recycling the contractor will take samples of the existing pavement, prepare, and submit a mix design for the Engineer’s approval. The mix design shall be prepared in a lab certified to perform the tests specified. The mix design shall be performed in accordance to the Wirtgen Cold Recycling Manual, ED 2010, or other method approved by the Engineer.

Minimum criteria used for acceptance of the proposed mix design will be:

- Dry Indirect Tensile Strength > 250 kPa (37 psi)
- Minimum Wet Strength 225 kPa (33 psi)

The design submittal must indicate the following information:

- Cold in Place Recycling CIR equipment and method proposed

- Grain Size Distribution Report

- Bitumen Grade
- Bitumen Content
- Bitumen Source
• Water Content
• Cement or Lime Content
• Cement or Lime Source
• Cement or Lime Grade
• Any other additives
• Results of Mix Design indicating strength
• Bitumen Foaming Half-life vs. Expansion
• Optimum Foaming Water Content Required (to produce a half-life of 6 seconds and an expansion ratio of 8:1)
• Maximum Density per Cal 216
• Bulk density of recommended oil content
• Test results of the Mix Design

39-7.3 Quality Control and Assurance

Provide a quality control plan (QCP) that describes the organization, responsible parties, and procedures you will use to:

1. Control quality
2. Determine when corrective actions are needed (action limits)
3. Implement corrective actions

The QCP must contain copies of the forms that will be used to provide all required inspection records and sampling and testing results. On the form used to record and report the quality control measurements, also show the job mix formula information.

As part of the QCP the contractor will provide a contingency plan that describes the corrective actions you will take in the event of equipment break down or material out of compliance.

39-7.3.1 Contingency Plan

The contingency plan must include any corrective actions including repairing and reopening the roadway to traffic using hot mix asphalt in compliance with Section 39, "Hot Mix Asphalt," of the City of San Jose Standard Specifications (Standard Specifications) or temporary bituminous surfacing in compliance with these special provisions.

Hot mix asphalt must:

1. Be hot mix asphalt (Type A)
2. Use 1/2-inch aggregate grading
3. Use asphalt binder grade PG 64-10 or PG 64-16
Temporary bituminous surfacing must:

1. Be commercial quality bituminous material

Meet with the Engineer at least 7 days before starting cold-in-place recycling work to review the QCP and contingency plan.

**39-7.3.2 QC Laboratory**

Provide a certified testing laboratory and personnel to perform quality control inspection, sampling and testing.

Provide the Engineer with unrestricted access to the laboratory, sampling and testing sites, and all information resulting from job mix formula and quality control inspection and testing activities. Proficiency of testing laboratories and sampling and testing personnel must be reviewed, qualified, and accredited by Caltrans Independent Assurance Program before starting cold-in-place recycling work.

Perform inspection, sampling and testing at a rate sufficient to ensure that cold-in-place recycling mixture, placement, compaction and finishing complies with the specifications.

**39-7.3.3 Production**

Divide the project into 3,000-square yard lots. For each lot:

1. Determine the actual recycle depth at each end of the milling drum at least once every 300 feet along the cut length
2. Take and split a sample of the CIR mixture from a location approved by the Engineer. Split the samples into 2 parts and label the containers with location and station. Submit 1 split part to the Engineer and use 1 part for your testing. Briquettes samples shall be prepared within three (3) hours.
3. On every third sample taken, perform a field gradation for material passing the 1-inch through No. 4 sieves.
4. Determine in place density and relative compaction of 10 random locations per Cal 231. Use the submitted Job Mix density as the basis of comparison for initial test. Perform a confirmation maximum density per lot or when material type changes.
For each day measure or calculate and record the following information:

1. Length, width, depth of cut and calculated weight in tons of material processed
2. Weight of recycling agent added in tons
3. Percentage of added recycling agent in the lot’s CIR mixture by weight
4. Weight of recycling additive used in tons (if used)
5. Percentage of recycling additive in the lot’s CIR mixture by weight (if used)
6. Ambient and compacted recycled pavement surface temperatures
7. Rate off of seal coat application
8. Rate of sand cover application

Once per working day measure and record the half-life and expansion ratio of the bitumen to be used during recycle. The bitumen sample must be taken from a test nozzle that is controlled by the recycler. Bitumen must provide an expansion ratio of at least 8:1 and a half-life of at least 6 seconds.

Any time the bitumen temperature drops below 160 degrees Celsius the half-life and expansion must be tested for each lot at the beginning of each lot.

If the bitumen cannot achieve the required half-life and expansion properties recycling shall be suspended until a satisfactory result is achieved.

Make adjustments during CIR operations for optimum quality. If adjustments are made, document the reason for the change and identify on the daily quality control inspection records and sampling and test results.

The Contractor shall be responsible for the quality of construction and materials incorporated into the Project. The Contractor’s QC measures shall ensure that operational techniques and activities provide integral and finished material of acceptable quality.

Contractor sampling and test shall be performed to control the processes and ensure material compliance with the requirements of the Contract.

The Contractor shall perform all Quality Control testing and sampling for the project. All QC sampling and testing shall be performed by technicians certified by the State of California for that particular material and all laboratory testing shall be performed by laboratories accredited by Caltrans Independent Assurance Program for the test methods required.

Contractor shall furnish copies of all test results to the Engineer or other authorized Department representative within 24 hours of completing the test of the acquired
39-7.4 Placement

CIR shall be to a depth as stated on the project plans within the lines and grades of the project plans and specifications or as directed by the Engineer.

Placement of the CIR materials will be in accordance with Section 39 of these specifications.

39-7.4.1 Recycling Equipment

A single-unit self-propelled cold recycling machine with a down cutting cutter head shall be capable of pulverizing and recycling the existing hot-mix asphalt pavement to a maximum depth of 6 inches (0.12m), incorporate the foamed asphalt and compaction water, and mix the materials to produce a homogeneous material.

The milling and mixing unit must be equipped with a gradation control bar that will stabilize the milled surface during milling to prevent the pavement from chunking. The minimum power of this machine shall be 950 hp. The machine shall be capable of pulverizing and recycling not less than 12ft 6ins (3.8 m) wide in each pass.

The machine shall have two independent systems for adding foamed asphalt and metered water with each system having a full width spray bar with a positive displacement pump interlocked to the machine's ground speed to insure that the amount of foamed asphalt and compaction water being added is automatically adjusted with changes to the machine’s ground speed. Each additive system shall have its own spray bar equipped with 2 nozzles per foot of spray bar. The foamed asphalt spray bar must be electrically heated. Individual valves on the spray bar shall be capable of being turned off (in pairs) as necessary both foamed asphalt and water to minimize overlap on subsequent passes.

The single unit must also have a tamper bar screed attached to the milling and mixing unit. The tamper bar screed must have the ability to tamp at varying frequency. The screed shall have slope control and the ability convey material out the side of the screed if there is a surge of material between the mixing chamber and the screed. The mixing unit and screed combination must have electronic grade controls.

39-7.4.2 Fog Seal and Sand Spreading

If directed by the Engineer at the end of each day’s production the contractor shall apply a uniform fog seal to the surface at a rate of 0.12 gal/sq. ft. and shall meet SS1H “Fog Seal’ Cut 50. If directed by the Engineer, sand shall be spread at a rate of
1.0 to 2.0 pounds per square yard. Exact spread rate shall be determined by the Engineer. Remove excess sand from the CIR surface. Sand cover shall be spread by means of a self-propelled spreader equipped with a mechanical device that will spread the sand at a uniform rate over the CIR surface. The area treated shall be capable of holding traffic at the end of each day’s production without any deformation or damage to the surface.

The Contractor will use their knowledge and expertise to deliver a product that meets the requirements of this section and contract.

39-7.5 Acceptance

The project shall be divided into lots 2500 linear feet long and 12 feet wide, or 3,000 square yards, extending along the lane lines of the roadway. If one day’s production will be less than 2500 linear feet that day’s production shall be a lot. If one day’s production is one lot plus an additional amount, the additional work shall be a separate lot. The Engineer will sample and test each lot prior to acceptance. Frequency of testing will be at the Engineer’s discretion.

Acceptance will be based on the following criteria:

A. Dry Indirect Tensile Strength >250 kPa (37 psi); Minimum Wet Strength 225 kPa (33 psi)
B. The average Relative compaction of a lot shall be a minimum of 98% of the maximum wet density as measured by Cal 216. No single test shall be less than 96% relative compaction.

For lots outside of the acceptance criteria the Engineer determines a deduction for each test result outside the specifications using the reduced payment factors shown in the following tables:

A- ITS Test Results

<table>
<thead>
<tr>
<th>% of Minimum Wet Strength (225 kPa)</th>
<th>Pay Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 100%</td>
<td>100%</td>
</tr>
<tr>
<td>&gt; 98%</td>
<td>98%</td>
</tr>
<tr>
<td>&gt; 96%</td>
<td>96%</td>
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<tr>
<td>&gt; 94%</td>
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<tr>
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<td>92%</td>
</tr>
<tr>
<td>&gt; 90%</td>
<td>90%</td>
</tr>
<tr>
<td>&lt; 90%</td>
<td>Remove at Engineers Sole Discretion</td>
</tr>
</tbody>
</table>

B- Compaction

% of Relative Compaction

56
as Measured By Cal 216

<table>
<thead>
<tr>
<th>Average Density Per Lot</th>
<th>Pay Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 98%</td>
<td>100%</td>
</tr>
<tr>
<td>&gt; 97%</td>
<td>95%</td>
</tr>
<tr>
<td>&gt; 96%</td>
<td>90%</td>
</tr>
<tr>
<td>&gt; 95%</td>
<td>85%</td>
</tr>
<tr>
<td>&gt; 94%</td>
<td>Remove at Engineers Sole Discretion</td>
</tr>
</tbody>
</table>

In the event a lot is subject to both pay factors, they will be cumulative. (i.e., An 90% pay factor for ITS and a 95% pay factor for Compaction equals a 86% cumulative pay factor. 0.90 X 0.95 = 0.86)

39-7.6 Method of Measurement

The unit of measurement for Cold In-Place Pavement Recycling shall be per square yard for the depth specified in the contract. The area to be paid shall be the length measured along the centerline of the roadway multiplied by the average perpendicular width.

Additional excavation/recycling performed by the Contractor outside the lines provided in the Plans shall not be measured and compensated by the Department without approval by the Engineer.

39-7.7 Basis of Payment

Cold In-Place Pavement Recycling shall be paid for at the contract unit price per square yard adjusted by the pay factor. This amount shall be full compensation for all work necessary within the dimensions shown on the Plans or specified herein, including but not limited to pulverizing existing pavements, additional materials, stabilizing agent(s), mineral filler, water, grading, compaction, sampling, testing and for all materials, labor, tools, equipment, hauling permits, mobilization and any incidentals necessary to complete the work.

END OF TEXT