NEW DEVELOPMENTS
IN HOT IN-PLACE RECYCLING
OF ASPHALT PAVEMENTS

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ABSTRACT

Recycling of asphalt pavements has become a widely accepted practice, particularly in North America and Europe. Several technologies have emerged to fill the various rehabilitation needs, depending on local conditions, type of pavement, and the future use of the roadway. Both hot and cold recycling in a central plant are routinely practiced. Cold in-place recycling (CIR) and full depth reconstruction is used by many highway agencies to restore surfaces and stabilize existing roadways for future overlays. Hot in-place recycling (HIR) has been used sparingly during the past 50 years, and only since the late 1980s have acceptable processes and equipment been developed.

Much of the technological development, experience, and HIR technology has occurred in Canada, where highway agencies have embraced the concept and equipment manufacturers have provided innovations. The paper briefly describes the development and special characteristics of the various HIR processes. It describes the development of a new heating system that combines recirculating hot air with low-level indirect infrared components. In addition, a stirring mechanism has been incorporated in the heating system to ensure more uniform heating of the loose asphalt mixture and efficient removal of any moisture. The recirculated hot air is reheated, and then incinerated, thereby providing a significant improvement in air quality compared to previous generations of HIR equipment.

The data from early trials in British Columbia, Canada show that the productivity is increased and the quality of recycled pavement is improved. In recent years air quality has been a factor in the acceptance of HIR in North America. Monitoring of the quality of air released at the new heating system shows the particulate matter and other solids to be the lowest among HIR systems tested. Additional projects are currently underway in Europe using the latest version of this equipment that was developed by Martec Recycling Corporation and these may provide additional data for the presentation.

INTRODUCTION

Hot-In-Place Recycling (HIR) is defined as a process of correcting asphalt-pavement surface distress by softening the existing surface with heat, mechanically removing the pavement surface, mixing it with an asphalt binder, possibly adding virgin aggregate, and replacing the recycled material on the pavement without removing it from the original pavement site. HIR may be performed as either a single-pass operation that recombines the restored pavement with virgin material, or as a two-pass operation, wherein the recycled material is recompacted, followed by the application of a new wearing surface [1,2].

Standardization of the terminology in asphalt recycling is important to the industry for easier understanding among techniques and projects. For example, in this paper, HIR is used similarly to CIR, which means Cold-In-Place Recycling. The Asphalt Recycling and Reclaiming Association (ARRA) recognizes three basic HIR processes: heater scarification, repaving, and remixing [3].

TYPES OF HIR

Heater Scarification. Sometimes called a reshaping process, heater-scarification was originally developed by a Utah contractor [4,5] sometime in the 1930s. But common usage did not evolve until the 1960s. By the 1970s, further evolution moved the technology into more complex systems. This relatively simple process includes several steps as follows:

- Heating the old pavement surface,
- Scarifying the softened surface with a bank of stationary teeth,
- Adding a liquid recycling agent,
- Mixing and leveling the recycled loose mixture with an auger, and
- Compacting with a conventional roller.
The depth of scarification and treatment typically was about 20 to 25 mm [6,7]. Although 50 mm depth might have been achievable in some instances, it was rare. The resulting surface was not always smooth and uniform because of variable hardness in the old pavement surface. In addition, dips and bumps were not easily corrected and depth of scarification varied.

Repaving. When heater-scarification is simultaneously combined with an overlay of hot mix asphalt (HMA), it is called repaving. Often called the Cutler process, for its inventor, repaving is a process that started in the 1950s, and was upgraded in the 1960s [8]. The repaving process has several steps as follows:

- Heating (i.e., pre-heating),
- Scarifying using teeth or a rotary mill,
- Adding a recycling agent,
- Mixing the recycling agent and loosened mixture,
- Spreading and screeding the recycled mixture, and
- Placing a new HMA overlay.

Remixing. When additional materials are needed to recycle the pavement, such as mineral aggregate or virgin HMA, the remixing process is used. This approach permits upgrading the existing pavement with additional thickness and/or improving the old HMA by changing the aggregate gradation or adjusting the binder properties. The process is somewhat similar to the repave process, but usually more thorough heating and mixing is accomplished. [9,10,11,12]. Most of the remainder of this paper is focused on the remixing process and especially the process developed by Martec Recycling Corporation.

Early Development of HIR The first asphalt pavement was placed in the United States in 1870 [13]. By 1915, reuse of asphalt pavements in road structures was recognized as an important option for pavement rehabilitation [4]. Use of asphalt cement to stabilize recycled asphalt pavement probably dates back only to the 1930s or 1940s [14,15]. During this time period the first heater-planer machines were developed. However, the total quantity of pavement materials recycled by all methods from 1915 to 1975 is small in comparison to the amount that has been recycled since 1975 [14]. Today, asphalt-pavement recycling is commonly performed on highways and airport runways using several methods, including both hot and cold methods for both central plant and in-place recycling operations. Of these four methods, the most sweeping changes and innovations in North America in the last ten years have been associated with hot in-place recycling.

A chronological record of the evolution of HIR shows an increasing understanding and improvement on the concept. As indicated earlier, the modern era of recycling was initiated in the mid 1970s, but trials and experiments were tried much earlier. Several manufacturers have developed equipment with variations in the details and approach to to HIR, but most are similar in a broad sense. One or more pre-heater units that are usually the infrared type are used to warm and soften the pavement ahead of the others units. Some manufacturers utilize stationary tines or teeth to scarify the warm pavement, but most currently use rotating milling heads. These are similar to those used for cold milling, but require less power because the warm pavement is softer. Most systems can mill to a depth of 25-40 mm, although a target (desired) may be 50 mm or more.

The remixer unit, (examples shown in Figures 1 and 2) usually has a hopper to receive virgin HMA when needed. Some equipment picks the virgin HMA from a window, however, and blends it with the hot-milled RAP (recycled asphalt pavement). The RAP, recycling agent, and virgin HMA or aggregate are blended into the final mixture. Although some equipment designs have attempted to accomplish all the mixing on the pavement surface, this procedure has been rather unsuccessful. In fact, most specifying agencies call for pugmills to be used.

New Developments in Remixing Variations of the repave and remix process were developed in the mid and late 1980s and early 1990s and this technology is being used in North America. The HIR systems are often called multi-stage because of the progressive stages of preheating, hot milling, remixing, and paving. But, also, they are single step, meaning that the preheating was followed by a single milling operation, the full depth of milling was done in one pass of the cutting heads. These single stage equipment styles were utilized by several manufacturers, including Rorison-Wiley Blacktop, Wirtgen, Taisei Rotec, and others. Two-step and four-step processes were
developed by Pyrotech, Inc. and Artec, Inc., both of British Columbia, Canada. The idea was to take advantage of the ability to heat the top 12 or 25 mm of the pavement effectively. An improvement was introduced by Pyrotech when an afterburner was added to incinerate the smoke and vapors generated by high temperatures at the pavement surface [2].

Through the early 1990s, the further development of HIR technology seemed to reach a plateau. There were a number of HIR trains operating in the U.S. and Canada and they were using the various technologies. Because of the enormous potential of HIR, several user agencies began to seriously evaluate the effectiveness and conducted surveys of projects through key people who were directly involved.

As a result of these evaluations, the industry began to recognize the need for improvements. Among these were the obvious need to improve air quality since many processes caused excessive smoking. The equipment and processing was needed to provide higher mix temperatures and deeper recycling in order to obtain quality results. Details of needed improvements to the equipment operation included more power to climb grades, adjustable width, quieter operation, better ability to add virgin aggregates and mixtures as well as recycling agents, along with good instrumentation to monitor it all for improved quality control. Developing better procedures for selecting suitable projects would include more site evaluations and core sampling, and criteria to preclude those pavements unsuitable for HIR.

NEW DEVELOPMENTS

Accepting the challenge for innovation, a new company, Martec Recycling Corporation, was formed from a joint venture between Artec and Marubeni Corporation. Much of the 'conventional' approach to HIR was addressed through redesign of the equipment. A prototype Martec train was fabricated in Canada and used on several smaller projects. This train was then shipped to Poland for use by the contract manufacturer HSW who is now producing additional trains on behalf of Martec.

Many of the shortcomings of earlier models of equipment discussed above were addressed by Artec and later by Martec [20]. The key elements that are major improvements include:

- A heating system that combines hot air and low level infrared rather than traditional infrared,
- Diesel fuel for all heating and power units,
- A recirculating hot air system that also incinerates fumes, if any,
- Efficient heating, stirring, and drying of RAP on the road surface, and
- Final mixing of RAP, admix, recycling agent, in a pugmill.

As shown in Figures 3 and 4, the 64 meters long equipment train consists of four units plus a conventional paver and compaction equipment. A photograph of the equipment operating in Italy is shown in Figure 4. The HIR train has four distinct stages when in operation (forward speed about 5 to 7 meters per minute):

**Stage 1.** Two identical Preheater units, operating in tandem, heat and soften the existing asphalt pavement surface.

**Stage 2.** A heater/miller unit, the third machine, continues to add heat to the surface, then removes the softened asphalt mixture using rotary milling heads to a pre-determined depth. If needed, a recycling agent is added in this stage.

**Stage 3.** The fourth machine in the train is a heater/mixer. Heat is continued and a unique stirring blade system continually agitates the loosened material and exposes the RAP to hot air and IR sources. This process increases the drying and heating so the end result temperature is closely controlled.

**Stage 4.** At the conclusion of heating and drying, the recycled mixture is lifted by slat conveyor into a pugmill mixer. If additional virgin hot mix or aggregates are needed, they are introduced to the pugmill via a
hopper at the front of the heater/mixer unit along with the recycled materials and thoroughly blended.

**Stage 5.** The finished recycled mixture is then transferred to a conventional paving machine and the pavement is spread and compacted using traditional paving methods.

There are several key innovations in the new equipment and procedures. These are aimed primarily at obtaining faster and more uniform heating without burning the surface of the old pavement. And in the process, air quality problems become essentially non-existent.

The heating system used in each of the four units in the train are fueled by diesel rather than propane or butane, although these options are available. Large burners (10 million BTU) on each unit heat air and blow the heated air directly onto the pavement through small holes in a full-sized 'manifold' made up of large heating tubes. The air temperature ranges up to about 600°C, much lower than that from direct IR heating. The rapidly circulating air heats and dries the surface and then is vacuum-returned (at about 350°C) to the burner where the recirculated air is re-heated and at the same time, smoke or fumes, if any, are incinerated. Additional heating of the pavement is provided by secondary low level infrared energy from the hot manifold.

A common problem in HIR is the removal of water from the surface of the pavement as well as from within the old HMA. Even in the driest weather, one or two percent water is trapped in asphalt concrete and can range much higher depending on the weather, local conditions and the quality (air voids) of the pavement. A limiting factor of HIR is the inability to raise the RAP temperature (even after milling) much above 100°C, until the water has evaporated. In most previous HIR systems, this has been a serious constraint because direct IR only heats the material and does not provide any mechanism to remove the water vapor.

In the Martec HIR system, hot air impinges directly on the pavement in the first three units, the two preheaters and the heater/miller. Surface moisture is readily removed by the vacuum exhaust return. After milling, the RAP is in a loose state, exposing many surfaces to hot air, quickly drying the material. Unit four, the heater/mixer, has unique stirring devices that plow through the loose RAP, continuously exposing new surfaces and permitting the vaporized water to be removed. It is this final heating and drying that provides the means to raise the temperature adequately for paving, but controlled enough to prevent burning of the asphalt binder. Typical temperatures measured behind the recycle train are 110°C to 130°C with no visible signs (such as smoke) of overheating [16].

The options for various approaches to HIR include both 100 percent recycle and remix. The 100 percent recycle is often used where an existing pavement has proper aggregate gradation, but the surface has rutted or cracked. In most of these cases no recycling agent is added unless it is needed to correct a slight binder deficiency. Remix options include adding virgin HMA, and/or additional asphalt binder or recycling agent. Also, the existing pavement can be upgraded by adding coarse or fine aggregate along with additional binder or recycling agent to improve the mixture quality and pavement thickness. The equipment accepts admix materials in the hopper at the front of unit no. 4, from which it is fed by conveyor directly into the pugmill along with the recycled mixture. Up to 30 mm additional pavement thickness may be added in this manner, for a total thickness of 80 mm.

**PROJECT EVALUATION**

Projects completed in Canada are the best documented, since most of the recent developments in HIR have been conducted there. Long term performance is not yet well documented, although numerous projects were constructed as early as 1987. It is difficult to generalize about how well pavements are recycled, because each project is different. But it is fair to say that the objectives were met on most projects. For example, the earlier HIR projects conducted in British Columbia by Pyrotech and Artec were usually rejuvenated with recycling agent, so the binder was softened as noted by viscosity and penetration test results.

The early trials using the Martec HIR equipment in British Columbia have provided an opportunity to assess the Martec HIR process. A good project for this evaluation of mixture properties was a section of Highway 1A in Abbotsford, British Columbia, recycled in October 1994. It is good because a recycling agent was not used, so the properties of the asphalt mixture and binder could be compared before and after HIR. The HIR process was selected
by B.C. Ministry of Transportation and Highways because the pavement was rutting prematurely after only one year of service. Testing was conducted by both the B.C. Ministry [16] and Terra Engineering Ltd., a geotechnical and materials engineering consulting firm based in Vancouver, B.C. [17].

Table 1 shows a summary of data from the Abbotsford project. The data from core samples taken at four locations show that the air voids increased almost 1.0 percent. The gradation of the aggregate after HIR was finer, but the dust (< 0.075 mm) increased only 0.4 percent. As would be expected, the asphalt content did not change. The viscosity increased only slightly from 305 to 318 (mm²/sec) and the penetration decreased only one point (dmm). These data would indicate that the hot air-- infrared heating was relatively gentle and age-hardened the binder only insignificantly.

As indicated earlier, the smoke produced by the Martec equipment was remarkably low when compared to earlier versions of HIR equipment. An opportunity to do detailed emission tests was provided at Penticton, B.C. in June 1995 and were conducted on Preheater No. 2, estimated to be the most severe point in the train for emissions. One of the most noticeable air quality measures is opacity, or percent visible emissions over a given period of time. The Martec equipment was given an opacity reading of: <1 (95% of the time) and proved to be much lower than other projects tested [18].

There is an analogy in this hot air and vacuum back recirculating system and the conventional drum mixer asphalt plant. During the early development of the drum mixer [19] it was discovered that the asphalt binder did not burn and age rapidly even though it was exposed to direct high temperatures from the burner. The reason was the very low level of oxygen available in the drum during heating and mixing; most of the oxygen was consumed in the fire of the burner and the hot gases heating the asphalt mixture contained little oxygen for aging of the asphalt. It would appear that the recirculated and reheated hot air used in the Martec HIR is similarly very low in oxygen, providing little opportunity for aging. And this is a major advantage for HIR since the potential for burning and aging of earlier HIR systems has been high.

SUMMARY AND CONCLUSIONS

During the past twenty plus years, the concept of HIR has grown steadily and more rapidly in the late 1980s and early 1990s. Early attempts were limited by equipment that was not quite up to the job yet. But the development of companion technologies such as cold milling and hot central-plant recycling have added to the knowledge base and have spurred equipment and materials improvements that are useful to HIR.

Through the early 1990s, the techniques and equipment developed by the pioneers in organizations like Artec, Pyrotech, Wirtgen, Cutler, Jackson, and Taisei, have incrementally approached the goal of being able to recycle at depth and placed an acceptable high quality asphalt pavement that can directly compete with other HMA pavements. There have been shortcomings that need further attention, but it appears that many of these have been overcome by new ideas introduced by Martec. Of considerable concern, and a factor that has held back more rapid acceptance of HIR, is the poor quality often associated with these projects. A major step is the development of a system for the hot air and low level indirect infrared heating with recirculating vacuum return of fumes and smoke that are incinerated. Also, the hot air has provided a means to remove moisture in the RAP, thus permitting easier and higher temperatures for mixing and laydown. The use of diesel fuel rather than propane to fire the heaters will be much more practical, cheaper, and safer. The ability to recycle deeper and faster to increase productivity will make HIR even more economical than the already impressive savings for many projects. Guidelines for selecting suitable HIR projects are important so that the process is used where most effective. Further education and training will be needed to help expand the HIR industry and this is being accomplished through the efforts of manufacturers, highway agencies, contractors, and others.

It would appear that the next generation of HIR can incorporate these concepts along with many other smaller improvements in instrumentation, quality control, better training and education so that the HIR industry will rapidly gain wider acceptance. Several organizations are applying effort to improve the industry. For example, ARRA has a committee on HIR and the AASHTO-AGC-ARTBA Task Force 40 on HIR is to develop analysis criteria for evaluation of the potential for an asphalt pavement to be rehabilitated via hot in-place recycling and to develop guide specifications. One would expect to see more improvements and growth of HIR over the next few years.
REFERENCES

16. Oliver, M.F., Memorandum re: Highway 11, Delair-Beck Road, QA Artec Hot In-Place Recycle, Oct. 5-6, 1994, Province of British Columbia, Ministry of Transportation and Highways, Burnaby, B.C., Canada, November 24, 1994.
Table 1 - Summary of test data from trial project at Abbotsford, B.C., Canada; Oct. 1994. *

<table>
<thead>
<tr>
<th>Property</th>
<th>Before Recycling</th>
<th>After Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>From core samples:</td>
<td></td>
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</tr>
<tr>
<td>Thickness of top lift (mm)</td>
<td>54.</td>
<td>56.</td>
</tr>
<tr>
<td>Air Voids (%)</td>
<td>3.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Bulk Specific gravity (kg / m³)</td>
<td>2379.</td>
<td>2387.</td>
</tr>
<tr>
<td>Compaction (% of Marshall)</td>
<td>100.3</td>
<td>98.5</td>
</tr>
<tr>
<td>Marshall Samples:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Specific gravity (kg/m³)</td>
<td>2415.</td>
<td>2432.</td>
</tr>
<tr>
<td>Theoretical Max Specific gravity (kg/m³)</td>
<td>2506.</td>
<td>2498.</td>
</tr>
<tr>
<td>Air Voids (%)</td>
<td>3.6</td>
<td>2.6</td>
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<tr>
<td>Stability (N)</td>
<td>10,072.</td>
<td>10,105.</td>
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<tr>
<td>Flow (0.25 mm units)</td>
<td>9.3</td>
<td>10.2</td>
</tr>
<tr>
<td>Aggregate Gradation:</td>
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<td></td>
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<tr>
<td>Sieve size (mm)</td>
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<td>19.00</td>
<td>100.0</td>
<td>100.0</td>
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<tr>
<td>12.50</td>
<td>92.3</td>
<td>94.9</td>
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<tr>
<td>9.50</td>
<td>81.5</td>
<td>82.4</td>
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<td>4.750</td>
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<td>2.360</td>
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<td>1.180</td>
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<td>0.600</td>
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<tr>
<td>0.300</td>
<td>12.8</td>
<td>14.0</td>
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<tr>
<td>0.150</td>
<td>7.1</td>
<td>8.3</td>
</tr>
<tr>
<td>0.075</td>
<td>5.2</td>
<td>5.6</td>
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<tr>
<td>Asphalt Binder:</td>
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<tr>
<td>Asphalt content (% total mix)</td>
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<td>5.0</td>
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<tr>
<td>Recovered (Abson) asphalt properties</td>
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<tr>
<td>Kinematic viscosity @ 135°C (mm²/sec)</td>
<td>305</td>
<td>318</td>
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<tr>
<td>Penetration @ 25°C (dmm, 100g/5 sec)</td>
<td>36</td>
<td>35</td>
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(Ref.17)

* Average of four sets of core samples from four locations on the 4-lane highway.
<table>
<thead>
<tr>
<th>Hot In-Place Recycling System</th>
<th>Emission Factor (kg/Mg)</th>
<th>Carbon Monoxide (CO)</th>
<th>Nitrous Oxides (NOₓ)</th>
<th>Sulphur Oxides (SOₓ)</th>
<th>Particulate Matter (PM)</th>
<th>Total Hydrocarbons (THC)</th>
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<tr>
<td>Martec (Artec)¹ 1994</td>
<td></td>
<td>0.0085</td>
<td>0.0014</td>
<td>0.0017</td>
<td>0.0009</td>
<td>0.0007</td>
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<td>AR2000 Diesel fuel</td>
<td></td>
<td>4 units</td>
<td>heat: hot air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrotech ²,³ (1992)</td>
<td></td>
<td>0.2940</td>
<td>0.0150</td>
<td>na</td>
<td>0.0025</td>
<td>0.0131</td>
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<td>Propane fuel 3 units heat: IR</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Artec ²,³ (1989)</td>
<td></td>
<td>0.0907</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>0.0069</td>
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<tr>
<td>Propane fuel 4 units heat: IR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Pyrotech ²,³ (1991)</td>
<td></td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>0.0420</td>
<td>na</td>
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<tr>
<td>Propane fuel 3 units heat: IR</td>
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<td></td>
<td></td>
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<tr>
<td>Asphalt central Plant ⁴</td>
<td></td>
<td>0.0191</td>
<td>0.0180</td>
<td>0.1461</td>
<td>na</td>
<td>0.0140</td>
</tr>
<tr>
<td>(Stack) ⁴</td>
<td></td>
<td>1 unit</td>
<td>heat: burner</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Notes to table:
1. The AR2000 Super Recycler manufactured by Artec utilizes a unique re circulating hot-air system to safely and efficiently heat the existing asphalt pavement. No ancillary emission control devices are necessary on the AR2000.
2. The three separate infrared systems analyzed are typical of hot in-place recycling systems which utilize emission control devices to collect and incinerate pollutants created during the process.
3. Some data has been provided by an independent industry consultant from confidential reports.
4. Data take from: Table 8.1-5 Emission Factors for Selected Gaseous Pollutants From a Conventional Asphaltic Concrete Plant Stack. (Figures compiled from mean source test results of a 400 plant survey.) AP-42, Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources. Published by the Environmental Protection Agency (EPA) of the United States. (Date of latest supplement: Sept. 1990).
5. Megagram (Mg) is used to represent 1 metric ton, or 'tonne'. (Ref: McCall, 1995)
Figure 1. The three-unit Pyrotech Pyropaver 300E HIR Remixer train. This system heats and mills in two stages, or steps, removing one-half of the depth in each step. (Ref. 20)

Stage One: Preheater 1  Preheater 2

Stage Two: Heater Miller  Stage Three and Four: Heater Mixer

Figure 2. The four-unit Martec AR 2000 Super Recycler HIR train is about 75 m. long and is followed immediately by a paving machine and rollers. Stage One preheaters warm the pavement surface. In Stage Two, heating continues, then the top 50 mm is milled off. Stage Four includes additional heating and drying of the loosened RAP using a unique on-grade stirring system, then lifts the hot RAP into the pugmill along with other materials.
Figure 3. Martec Heater-Mixer Unit. Stages three and four are accomplished in this fourth unit of the train shown in Figure 2. The final heating step includes stirring and removal of any remaining moisture. The virgin HMA or aggregate is transported from the hopper to the pugmill and the recycled HMA is picked up from the surface and deposited in the pugmill, along with any added recycling agent. The ready-to-use recycled mixture is then dropped directly into the paver, spread and compacted.

Figure 4. The Martec AR 2000 operating in Italy during early trials. Note the absence of smoke that usually accompanies conventional HIR trains.