INTRODUCTION
During the Arab Oil Embargo of 1973, the price of crude oil quadrupled to $12 per barrel. Subsequently the price of asphalt, the bottom of the crude oil barrel, also increased significantly during this time and the cost of highway construction and rehabilitation rose dramatically. Contractors and equipment manufacturers quickly recognized that recycling reclaimed asphalt pavement (RAP) could provide many benefits and opportunities. Milling machines were developed, hot mix asphalt plants were modified to allow the addition of RAP to mixes, and soil stabilization equipment was redesigned to reclaim existing pavements in-place.

Technological improvements to the early asphalt pavement recycling methods and equipment have made the process more feasible as a rehabilitation method. New hot and cold mix plants and several types of powerful in-place recycling equipment are now available; and performance based testing and mix design methods have improved greatly. The high price of asphalt, the need to conserve energy, the reduced availability of high quality aggregates and the dwindling supply of landfill space provided the incentive for these advances. However, the major factor in the rapid growth of recycling was the excellent performance of recycled pavements.
APPLICATION

Until the mid-90's, almost all asphalt cold recycling had been done with emulsions. In recent years one of the fastest growing "new" recycling technologies is the use of foamed or expanded asphalt (which was actually discovered in the 1950's in the USA). Foamed asphalt is produced when a small quantity of cold water is introduced into hot asphalt. As the asphalt foams due to the expansion of the water to steam, its volume increases 10 to 30 times and its viscosity is greatly reduced, enabling it to be dispersed in and mixed with cold, moist aggregates and RAP. The renewed interest in foamed asphalt technology has largely been due to the development of laboratory and field equipment that allows foamed asphalt to be produced safely under precisely controlled conditions. Precise control of the foamed asphalt process is necessary due to the nature of reclamation itself, as well as the behavior of the foamed asphalt. The foamed asphalt must be of a certain temperature and mixed in the correct proportion to water. Furthermore, the gradation of the reclaimed material must meet certain ranges in order for the foamed asphalt to become a sound pavement layer (See Figure 1).

![Figure 1](image.png)

Olmstead and Fillmore Counties in Minnesota have implemented foamed asphalt recycling technology to some degree of success. Fillmore County uses foamed asphalt recycling exclusively, and has not performed an HMA overlay in many years. In October 2007, Minnesota Department of Transportation (Mn/DOT) representatives took a field trip to several roads in Fillmore County constructed using foamed asphalt. Many of the roads were 5 years old, or more, and exhibited little to no cracking, rutting, or other distress. Olmstead County has not experienced the level of success that Fillmore County has, for unknown reasons. It is the aim of this study to examine the differences of in-situ conditions, as well as any other factors, that may have lead to these varying levels of success. Furthermore, the ultimate goal is to develop a guidance or specification that will assist City, County, and State officials when considering or implementing a foamed asphalt job. (See Appendix A for a list of foamed asphalt projects completed in Minnesota).
BENEFITS
Foamed asphalt was discovered in 1956 by Iowa State University Professor Ladis Csanyi. Professor Csanyi produced foamed asphalt by introducing steam into hot bituminous asphalt. Some time later, Mobil Oil Co. improved on the technique by adding atomized water to the hot bitumen. This is the method currently used to produce foamed asphalt, however, it did not come in to common use until the early 1990’s due to patenting and other factors. Prior to the 1990’s, recycling techniques were being explored in countries such as the USA, Australia, and South Africa; as well as several European Countries. Laboratory testing of foamed asphalt material had progressed over the years as well. This provided an environment that was ripe for the implementation of foamed asphalt on a larger scale. As a result, equipment manufacturers began to improve the safety and efficacy of the foaming systems in order to provide services for the increasing demand for recycled pavements and foamed asphalt materials.

The benefits of using foamed asphalt recycled pavement rehabilitation are many, two of which are arguably the most prominent in the current political and economic climate. Those two benefits are the relative environmental friendliness of using foamed asphalt with RAP versus hot mix, and its economic feasibility i.e. equivalent pavement strengths can be constructed using foamed asphalt with RAP, for an upfront cost similar to or less than new pavement construction. Some other benefits that foamed asphalt with RAP provides are:

- Foamed asphalt can be used with 5-20% fines
- Increased shear strength and resistance to flexural fatigue
- Reduction of moisture susceptibility
- Can be compacted immediately after injection of foamed asphalt and sufficient mixing
- May be stockpiled without binder runoff or leaching, remains workable for a relatively long time
- Foamed asphalt can be used under some adverse weather conditions (light rain or cold weather)
- No evaporated volatiles as with HMA or cutback emulsions
- Reduction in transportation costs, foamed asphalt requires less binder and water than other types of cold mixing
LABORATORY AND MIX DESIGN PROCEDURES

In order to select and characterize the optimum foaming properties of an asphalt, the expansion ratio and half life of the foamed asphalt must be quantified. The expansion ratio of foamed asphalt is defined as the ratio of the maximum volume attained by the foamed asphalt material, divided by the original volume of the binder. The half-life is defined as the amount of time it takes for the foamed asphalt to lose 50% of the maximum volume attained during the initial foaming process. Expansion ratio is an indicator of how well the foamed asphalt will coat the paving materials, while half-life is an indicator of the foam’s overall stability (See Figure 2). In Figure 2, the expansion ratio is 24, and the half-life is 20 seconds.

Figure 2. Graph showing Expansion Ratio and Half-Life concepts.

Selection of Asphalt Temperature and Percent Water

The expansion ratio and half-life of a particular asphalt depends on the chemical constituents of the asphalt, its temperature, and the amount of water used for foaming. The expansion ratio and half-life are inversely related in that, for a given temperature, the expansion ratio increases with increasing amounts of added water, while the half-life decreases with increasing amounts of added water. The optimum amount of added water can be determined from laboratory testing by first identifying expansion ratios and half-lives for discrete sets of temperatures and water contents. The results are then plotted against water percent content on the x-axis (See Figure 3). The optimum amount of added water typically ranges from 1 to 4 percent, and varies depending on the asphalt used. The optimum amount of injected water (at a corresponding asphalt type and temperature) should be chosen by using the graph to cross reference water content with a corresponding expansion ratio greater than 10 and half-life greater than 12 seconds. The optimum asphalt temperature is chosen in a similar fashion.
Selection of Optimum Asphalt Content – Mix Design

The first step in the mix design process is to determine the gradation of the materials to be recycled, as well as the asphalt content of a representative sample of the RAP materials. The optimum water content and maximum dry density of the representative sample are determined by AASHTO T180 (standard moisture-density relationship). If gradations reveal that the recycled material does not contain the required 5-20% fines necessary for proper binding of the foamed asphalt, as much as 2% (by total weight) Portland cement may be added to provide cementitious bonding, as well as retained tensile strength. Addition of more than 2% portland cement is not recommended in order to avoid cracking. In the case of full depth reclamation (FDR), lime may be added if the Plasticity Index (PI) of the reclaimed granular material is 10 or greater. It is important to note that lime or cement should be added and mixed thoroughly with the reclaimed materials before injection of the asphalt. The timing of the additives and subsequent compaction processes performed in the field should closely parallel the procedures performed in the laboratory in order to be sure that the aggregate material will provide sufficient strength in combination with the use of a particular asphalt source.

The samples of aggregate types present in the reclaimed materials are then tested with a range of foamed asphalt percentages to see how they react together. The typical aggregate types and ranges of foamed asphalt are:

- Milled material/filler material: 1, 2, 3, 4, 5% asphalt by mass
- Crushed stone/sand mix: 2, 3, 4, 5, 6% asphalt by mass
- Sandy material: 3, 4, 5, 6, 7% asphalt by mass

Each material type is combined with the specified amount of foamed asphalt and compacted, cured (with Marshall compactor), measured for bulk density, and tested for indirect tensile strength (ITS) in both wet and dry conditions. The optimum asphalt content is determined from a plot of ITS versus foamed asphalt content of a material type.
The optimum asphalt content is generally selected as the value that gives the maximum wet ITS.

**Strength of Foamed Asphalt in Pavement**

The strength of a foamed asphalt pavement layer has been shown to provide adequate structural resistance to failure in many projects around the world, as well as several projects in Minnesota. Adequate strength is derived from foamed asphalt through proper mix design and laboratory procedures, careful investigation of field conditions, and analysis of any adverse conditions existing at the site. Due to in-situ variations in pavement layers and subgrade materials, it is imperative that field samples are representative of the materials across the site so that the material properties and their reaction to additives can be quantified and accounted for during the mix design process. Laboratory procedures should closely mimic the procedures used in the field during application of foamed asphalt techniques. This will help reduce uncertainty inherent in dealing with in-situ variations in pavement, base, and subgrade layers.

Structural layer coefficients for foamed asphalt can range from 0.13 to 0.35 per inch (M, of 100 to 360 ksi) for an asphalt content ranging from 4.5 to 2.5 percent (See Figure 4). Furthermore, studies performed by Maine DOT using a Portable Seismic Property Analyzer (PSPA) on some of their foamed asphalt projects found a range of 131 to 595 ksi. Texas DOT determined modulus values from DCP, Falling Weight Deflectometer (FWD), and PSPA on portions of foamed asphalt base layers that were exhibiting alligator cracking and rutting in the pavement surface. These tests gave modulus ranges of 20 to 80 ksi (DCP), and 100 to 1200 ksi (Young’s Modulus, SPA)\(^1\).

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\(^1\) Note that there is not a 1:1 correlation ratio for DCP, SPA, PSPA, or FWD moduli. Values are cited for reference.
Figure 4. Layer Coefficient ranges for stabilized foamed asphalt materials
APPENDIX A

Fillmore County CIR with foamed asphalt projects

- **CSAH 8, Length = 3.8 miles:** Needs Section 608, Segments 90 & 100, located between CSAH 7 and TH 52 (Fountain). Performed with ‘foamed asphalt’ 52-34 binder. Wearing course is 58-34. The segments were done in 2005, and had an ADT of 220. Koch materials collected core samples.
  - The existing roadway was reconstructed in 1978, and paved in 1981. The bituminous surface had frequent transverse cracking.

- **CSAH 5, Length = 4.5 miles:** Needs Section 605, Segments 120 & part 130, located between Junction CSAH 4 and approximately 4.5 miles north. Performed with ‘foamed asphalt’ 52-34 binder. Wearing course is 58-34. The segments were done in 2005, and had an ADT of 600. Koch materials collected core samples.
  - The existing roadway was reconstructed in 1970, last paved in 1988. This segment had up to 14 inches of bituminous with frequent transverse cracking.

- **CSAH 5, Length = 4.5 miles:** Needs Section 605, Segments 130, 140 & 150, located from end of 2005 project to TH 52 (Chatfield). Performed with ‘foamed asphalt’ 52-34 binder. Wearing course is 58-34. The segments were done in 2006, and had an ADT of 980. Koch materials collected core samples.
  - The existing roadway was reconstructed in 1964 (mostly), last paved in 1988. This segment had 8” – 12” of bituminous with frequent transverse cracking.

- **CSAH 8, Length = 4.3 miles:** Needs Section 608, Segments 110, 120, 121, & 130, located from TH 52 (Fountain) to CSAH 17. Performed with ‘foamed asphalt’ 52-34 binder. Wearing course is 58-34. The segments were done in 2007, and had an ADT of 1100. No cores were taken.
  - The existing roadway was reconstructed in 1959 & 1962, last paved in 1983. The segments had frequent transverse cracks and numerous longitudinal cracks in wheel tracks.

  - All Fillmore County CIR sections using foamed asphalt are performing very well to date. Transverse cracking and rutting appears to be reduced by using foamed asphalt CIR rehab techniques.
APPENDIX A (cont.)

Olmsted County CIR with foamed asphalt projects

- **CSAH 24, Length = 3.0 miles:** Constructed in 2004. Located between C.S.A.H. 2 and C.R. 124. PG 52-34 foamed bitumen used for CIR (approx. 4”), at a target add rate of 2% by weight. Two 1.5” lifts of 58-34 for wearing course.

- **CSAH 1, Length = 3.3 miles:** Constructed in 2005. Located between T.H. 30 and 87th St. SW. PG 52-34 foamed bitumen used for CIR (approx. 4”), at a target add rate of 2% by weight. Two 1.5” lifts of 58-34 for wearing course.

- **CSAH 10, Length = 1.3 miles:** Constructed in 2005. Located between I-90 and Dover city limits. PG 52-34 foamed bitumen used for CIR (approx. 4”), at a target add rate of 2% by weight. Two 1.5” lifts of 58-34 for wearing course.

  - Although the projects are only 2-3 years old, they appear to be wearing well.
NEED MORE INFORMATION ON RECYCLED MATERIALS OR LOW VOLUME ROAD REHABILITATION OR THE MINNESOTA ROAD RESEARCH PROJECT (MN/ROAD)?

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