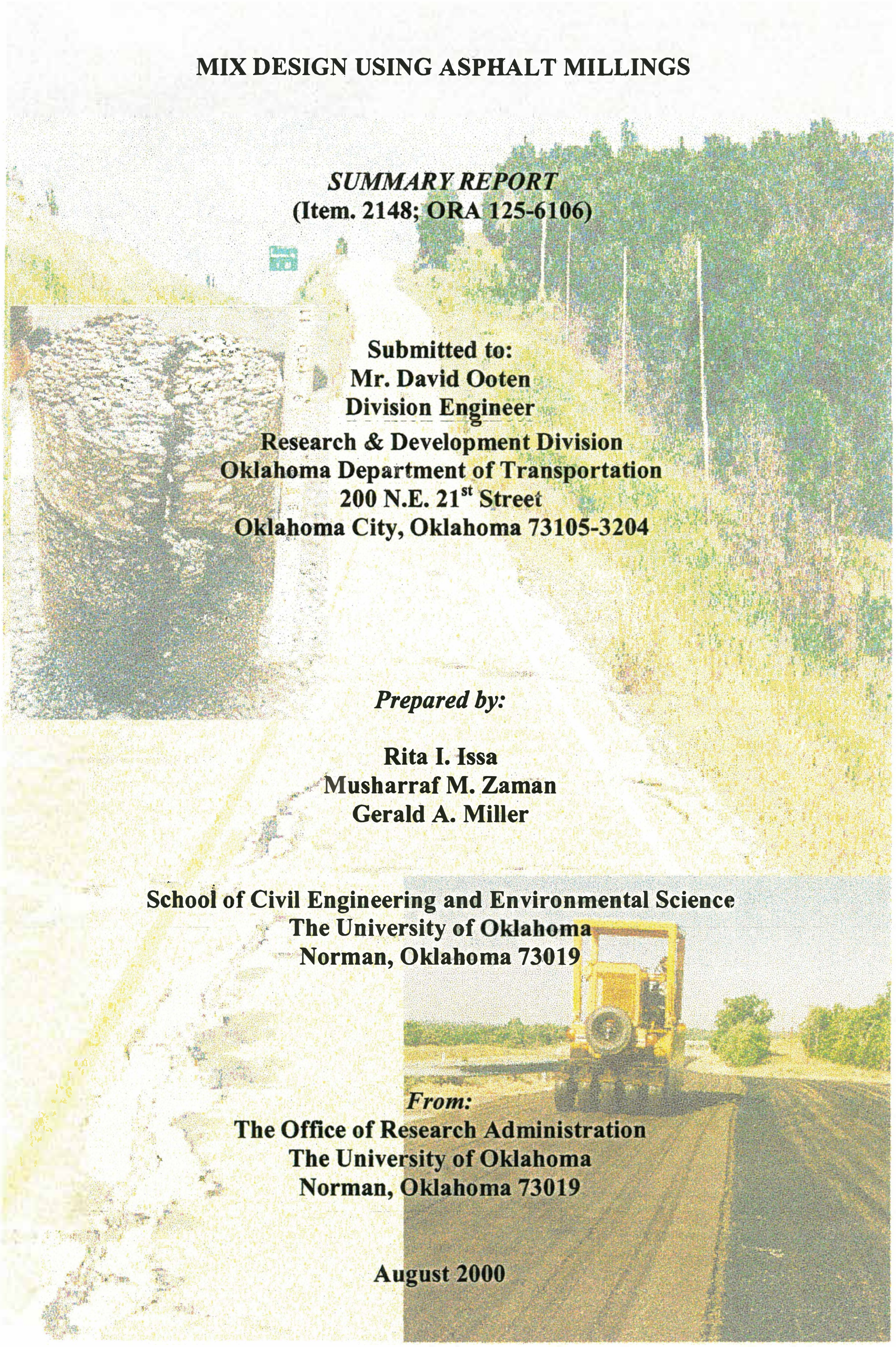

MIX DESIGN USING ASPHALT MILLINGS

SUMMARY REPORT
(Item. 2148; ORA 125-6106)

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August 2000

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. FHWA/OK 00(04)	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO. TE270 .I87 2000
4. TITLE AND SUBTITLE "Mix Design Using Asphalt Millings"		5. REPORT DATE September 1999
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Rita I. Issa, Musharraf M. Zaman, Gerald A. Miller		8. PERFORMING ORGANIZATION REPORT ORA 125-6106
9. PERFORMING ORGANIZATION AND ADDRESS The University of Oklahoma, Norman, Oklahoma 73019-1024		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. Item No. 2148
12. SPONSORING AGENCY NAME AND ADDRESS Federal Highway Administration, 300 North Meridian, Room 105S, Oklahoma City, OK 73105-6560		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

A field demonstration project was undertaken by the Research & Development Division, Oklahoma Department of Transportation (ODOT), to investigate the performance of an asphalt overlay constructed using recycled asphalt millings and the cold-mixed, cold-laid system. The project was pursued in cooperation with KOCH Materials in Wichita, Kansas, and the University of Oklahoma.

A 1.9-km (1.2-mile) section of the US-64 North frontage road in Pawnee County was rehabilitated with a 5-cm (2-in) thick overlay using 100% recycled asphalt millings. The 1.9-km (1.2-mile) section was divided into four approximately equal test sections. A different type of emulsion was used to rejuvenate the asphalt millings for each test section. The purpose was to determine the relative performance of each emulsion type and construction method used in this recycled asphalt pavement (RAP) project. A laboratory investigation was carried out to accomplish two major tasks: the first task was to determine the optimum emulsion and moisture contents of RAP mixes prepared with four different types of emulsions; the second task was to investigate the effect of adding Portland cement to RAP mixes, producing a cement-emulsion composite. One of the objectives of this study was to document the behavior of RAP mixes as affected by the addition of Portland cement, and to find the optimum emulsion and cement contents.

Achieving an adequate compaction is crucial to the successful performance of a cold-mixed, cold-laid overlay. The degree of compaction can greatly vary depending upon rolling pattern, speed, equipment, compaction dynamics, and characteristics of RAP mixes. From post-construction site visits, it was evident that the polymer modified anionic (PMA) emulsion section performed better than the other sections. This was consistent with the results of the laboratory investigation. A PMA mix containing 2% free moisture and 2% emulsion was found to be the optimum RAP mix. For samples prepared from cement-emulsion composite, both dry and soaked stability values increased as cement content increased. The addition of Portland cement, however, affected the stability value of samples cured under soaked conditions much more than those cured under dry conditions. The introduction of as little as 1% of Portland cement to RAP mixes doubled the retained stability of specimens, as compared with a RAP mix rejuvenated with HFE-300 emulsion.

The cold-mixed, cold-laid process of pavement rehabilitation holds significant promises for the future. The current technology, however, needs improvement and refinement through further laboratory and field studies.

17. KEY WORDS Asphalt millings, cold-mix design, field study, recycled asphalt pavement, overlay, pavement rehabilitation	18. DISTRIBUTION STATEMENT No restrictions. This publication is available from Research & Development Division, Oklahoma DOT.

19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 36	22. PRICE

Disclaimer

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views of the Oklahoma Department of Transportation. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

The authors would like to thank the staff of the Research & Development Division, Oklahoma Department of Transportation (ODOT) for their interest and active help in this project. Special appreciation is extended to Wilson Brewer for his help and assistance throughout this project. The goals of this project could not be accomplished without the active help of the drilling crew of the Research & Development Division and the support personnel of the ODOT Tulsa West maintenance yard and the ODOT residency in Sand Springs.

The authors are grateful to John Rains, Todd Thomas and Frank Champion of Koch Materials Inc., Wichita, Kansas for their valuable role in the project. The financial support of the Koch Materials Inc. is gratefully acknowledged.

The authors are thankful to their colleague, Dr. Joakim G. Laguros, David Ross Boyd Professor Emeritus, for his advice and guidance during the course of this study.

Finally, this study would not have been possible without funding from the Oklahoma Department of Transportation and the active support of Mr. Lawrence J. Senkowski, Assistant Division Engineer, Research & Development Division.

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1 INTRODUCTION

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A 1.9-km (1.2-mile) section of the US-64 North frontage road in Pawnee County was rehabilitated with a 5-cm (2-in) thick overlay using 100% recycled asphalt millings. The 1.9-km (1.2-mile) section was divided into four approximately equal length test sections. A different type of emulsion was used to rejuvenate the asphalt millings for each test section. The purpose was to determine the relative performance of each emulsion type and construction method used in this recycled asphalt pavement (RAP) project. A laboratory investigation was carried out to accomplish two major tasks: the first task was to determine the optimum emulsion and moisture contents of RAP mixes prepared with four different types of emulsions; the second task was to investigate the effect of adding Portland cement to RAP mixes, producing a cement-emulsion composite. One of the objectives of this study was to document the behavior of RAP mixes as affected by the addition of Portland cement, and to find the optimum emulsion and cement contents.

2 TERMINOLOGY

The following terms are used throughout this report:

1. *Raw millings*: material resulting from milling the top layer of an old pavement.
2. *Processed millings*: crushed and sieved raw millings but not rejuvenated with asphalt emulsion.
3. *Recycled asphalt pavement (RAP) mixes or rejuvenated millings*: a mixture of processed millings, water, and emulsion.
4. *Cement-emulsion composite*: composite produced by adding Portland cement to a RAP mix.
5. *Free moisture content*: percent of water added to oven dried millings.
6. *Liquid content*: emulsion content + free moisture content.
7. *Dry stability*: stability of samples cured under dry conditions.
8. *Soaked stability*: stability of samples cured under soaked conditions.
9. *Retained stability*: ratio of soaked to dry stability expressed as a percentage.

3 PAVEMENT DESCRIPTION

Before the construction of the overlay, the old frontage road was examined in regard to crack identification, pavement composition, laboratory testing requirements and uniformity in terrain. As evident from Figures 1 and 2, the major form of distress found on the pavement was thermal cracking. Crack spacing varied from 3 m to 21 m (10 ft to 70 ft) and their openings varied in width from 10 mm to 30 mm (0.4 in to 1.2 in). The pavement was composed of a 50-mm (2-in) type C mix on top of a 175-mm (7-in) layer of 'Hot Sand' base, with an average total thickness of approximately 225 mm (9 in).

3.1 Properties of Subgrade Soil

The subgrade soil from the boreholes was classified as clayey sand (SC) in accordance with the Unified Classification System (USCS) (ASTM 1998[b]), and A-2-4, silty or clayey gravel and sand in accordance with the AASHTO classification system (AASHTO 1986), with low potential for swelling. The unconfined compressive strength (UCS) values for two tested asphalt cores were 850 kPa and 1020 kPa (119 psi and 143 psi). Moisture content values varied from 14.4% to 19.2%. Liquid Limits (LL) for boreholes 9 and 16 were 22.7 and 24.1, respectively; and their Plastic Limits (PL) were 14.6 and 15.9, respectively. Thus, the Plasticity Index (PI) of the subgrade soil varied between 7 and 9.5, and the Activity (A) values between 0.28 and 0.41.

3.2 Process of Construction

The old pavement was not milled or treated prior to the construction of the overlay. The processed millings used in the construction of the overlay were obtained from SH 51 in Sand Springs. The millings were sieved to meet the ODOT gradation requirement for type C aggregates. No virgin aggregate was added. One hour before laying the overlay, an SS-1 tack coat was sprayed on the old surface at an application rate of 0.68 l/m^2 (0.15 gal/yd^2).

3.2.1 Construction of the Overlay

The total test section to be rehabilitated was divided into four sections. Four different types of emulsion, namely cationic, polymer modified cationic (PMC), anionic, and polymer modified anionic (PMA), one for each section, were used to rejuvenate the processed millings. Figures 1 and 2 show the emulsion type used for each section. Twelve dump trucks transported the rejuvenated millings or RAP mixes used in constructing the overlay for each section to the site. The amount of emulsion used in rejuvenating was 1.5% (by weight of raw millings). The actual amount varied slightly depending upon the free moisture content of raw millings in the stockpile and other factors. Test section I used approximately 6.00×10^5 Kg (660 tons) of cationic emulsion RAP mix over a 470-m (1,540-ft) length. Test section I used approximately 6.00×10^5 Kg (660 tons) of cationic emulsion RAP mix over a 470-m (1,540-ft) length. Test section II used approximately 6.36×10^5 Kg (700 tons) of PMC emulsion RAP mix over a length of 480 m (1,570 ft). Test section III used about 6.27×10^5 Kg (690 tons) of anionic emulsion RAP mix in 480 m (1,570 ft). The fourth and final test section used approximately 6.27×10^5 Kg (690 tons) of PMA emulsion RAP mix in a 470-m (1,540-ft) stretch of the roadway. The construction process spanned over a ten-day period (September 8,1998 through September 18,1998).

3.2.2 Compaction of the Overlay

Rolling patterns for compaction and the type of equipment varied greatly between the cationic and anionic sections. On Sections I and II, one pneumatic roller was used for the breakdown, intermediate and finish rolling. Four roller passes (down and back sequence) were used on each section. On Sections III and IV, however, three rollers were used. Breakdown rolling was performed by two pneumatic rollers simultaneously, and each roller made five passes. A single drum steel wheel roller was used for intermediate rolling with one pass in section III and two passes in section IV. The rolling speeds were much slower in the anionic sections than in the cationic sections.

In sections I and II, at the completion of the compaction effort, loose material was present on top of the pavement. The roller would stick to and pick-up the RAP, leaving a loose layer (12.5 mm or ½ in) of mix on the surface. Traffic was allowed on the tender surface at the end of the construction day. After two days of trafficking, a power broom was used to remove the loose mix from the surface.

3.3 Properties of the Overlay

Processed millings had an effective size or D_{10} of 0.8 mm, D_{30} of 3.3 mm, and D_{60} of 7.6 mm. For the raw millings D_{10}, D_{30}, and D_{60} values were 1.5 mm, 4.3 mm, and 7.7 mm, respectively. Processed millings contained 0.4% of fines, while, raw millings contained 0.2% of fines. The average uniformity coefficient, C_u, for processed millings was 9.9. The corresponding value for raw millings was 5.2. The coefficient of gradation, C_c, was 1.9 for processed millings and 1.6 for raw millings. Processed millings had a uniformity coefficient of 9.9, which was about twice that of raw millings. It could be concluded that processed millings had a more distributed gradation than raw millings.

Water content of stockpiles of processed millings varied among the four different sections. For the cationic section the water content ranged between 2.1% and 3.2%; the corresponding range was 1.9% to 4.0% for PMC; 3.1% to 5.9% for anionic; and finally 3.3% to 4.0% for the PMA section. Such variations in water contents of stockpiles are acceptable. From the literature review, it was noted that for one cold RAP project moisture contents of stockpile varied from 4.0% to 5.8% (Corti 1983).

Terracon consultants, Tulsa, Oklahoma, measured the densities of various segments of the overlay in the field using a nuclear density gauge in accordance with ASTM Standard D2590 (ASTM 1998[a]). Table 1 summarizes minimum, maximum, and average density values for each of the four sections. Sections I and II had lower average density values than sections III and IV. This is probably due to the use of two rollers for compacting the first two sections as opposed to three rollers for compacting the last two sections. Moreover, the rolling speed was slower in sections III and IV. Thus, these sections were expected to achieve higher densities than sections I and II. McKeen (1996) indicated that densities below 1.92 gm/cm^3 (120 pcf) were considered low. Overall, density values for all sections could be considered relatively low; indicating that compaction may have been inadequate at the site.

Two site visits were made to rate the performance of the four mixes based on visual observations of each test section. The first visit to the site was on October 20, 1998, approximately one month after the construction of the overlay. In section I (cationic emulsion mix) aggregates appeared to be properly coated, and the density of the pavement increased since construction in most cases. This section did not develop frequent cracks except at the lowest spot. Section II (PMC mix) showed frequent cracking, every 9 m to 12 m (30 ft to 40 ft), especially going uphill. It is reasoned that proper compaction was not achieved, since aggregates were not coated and bound well. Also, the construction joint led to some rutting between the wheel paths. Section III (Anionic mix) presented a better appearance than the previous sections. The mix appeared to have more cohesion than in section I. Cracks were rare, though in the central part of the road some flow of mix and a resulting depression were observed. *Finally, section IV (PMA mix) appeared to have the best mix among all the four sections.* The polymer in this section could have led to the absence of rutting, although transverse cracks were visible at several locations.

The site was visited again on June 30, 1999, approximately 9.5 months after the construction of the overlay. In section I the asphalt appeared to have formed conglomerates without aggregates. As a result, there was no stability in the mix. Lack of stability in the mix was clearly evident on the edges of the pavement that looked crumbly and unstable. Such behavior was not as clearly evident in sections III and IV. Several reflective transverse cracks appeared approximately every 6 m (20 ft). Moreover, some raveling was found at the construction joint. Section II exhibited a bit more stability on the sides than Section I. This could be due to the presence of polymer in the mix. However, this section had more cracks than the previous, through which a lot of potholes developed around the center of the pavement. Section III showed better performance than the previous two sections, with smaller and fewer cracks. Potholes were rare in this section. Finally, no potholes were observed in section IV. Although, some cracks appeared, they were relatively small and smooth compared to those in previous sections.

Three different observers rated the performance of the overlay. Overall, the three evaluations were similar. They all agreed that section IV performed the best and section II the worse among the four sections at the time of the visits. This result was based on the observations of potholes and quality of compacted mix on the sides of the pavement in each section.

4 SPECIMEN PREPARATION AND TESTING

The laboratory investigation reported in this section was carried out to accomplish two major objectives: (i) to determine the optimum amount of emulsion and moisture needed to optimally rejuvenate processed millings, and (ii) to evaluate the effect of Portland cement on stability and tensile strength of rejuvenated millings.

To accomplish the first objective, RAP mixes were prepared containing four different types of emulsion (cationic, polymer modified cationic, anionic, and polymer modified anionic), as in the field situation. Two different sets of samples were prepared:

(1) *field-mix*: the RAP mixes from the processing plant in the field were collected periodically and samples were prepared using a Texas Gyratory compactor available at the ODOT Residency in Sand Springs; (2) *laboratory-mix*: processed millings were collected from the processing plant, and compacted using a Texas Gyratory compactor in the laboratory. Hveem stability tests were performed on both of these sets of samples in accordance with ASTM Standard D 1560 and the results were compared (ASTM 1998[a]).

To investigate the effect of Portland cement on the behavior of rejuvenated millings, a procedure was developed to prepare samples with both emulsion and Portland cement as the rejuvenating agents. Based on Hveem stability test and tensile strength test results, the optimum amounts of emulsion and cement were determined. Samples were prepared at field density, laboratory density, and intermediate density. All samples were tested for Hveem stability as well as for tensile strength. The tensile strength was obtained from the split tensile test conducted according to ASTM Standard D4867 (ASTM 1998[a]). One of the goals of this series of tests was to find the optimum cement and emulsion contents that would give a high Hveem stability without causing brittle failure of the RAP mix.

General test results are reported in this section, while average values, graphical results, analysis of results, and comments are reported in section 5.

4.1 Preparation and Testing Methods

Samples were prepared and cured in accordance with the procedure suggested by KOCH Materials, Wichita, Kansas, with some adjustments (KOCH 1998).

4.1.1 Preparation and Compaction

The following procedure was followed:

1. Place 1200 gm (2.6 lbs) of oven dried millings at 40°C (104°F) in a pan.
2. Add water and mix thoroughly with a spoon so as to get free moisture content close to that expected in the field.
3. Add a desired amount (by weight of oven dried millings) of emulsion, stored at a temperature between 50°C and 60°C (122°F and 140°F), to the mix and mix thoroughly by hand using a spoon.
4. Pour the mix into a Hobart mixer and mix for about one minute.
5. Place 1200 gm of the mix, immediately after mixing, in a 10-cm (4-in) diameter Hveem stability mold. The mix should be placed in layers with a spoon and tamped lightly using a bent spoon.
6. Compact the mix in the mold using a Texas Gyratory compactor (Rainhart 1998).

The above procedure was also used for specimens prepared with Portland cement. However, the cement was added, in powder form, after the addition of water in step 2.

4.1.2 Curing of Samples

Since standard procedures for curing of cold processed RAP specimens are not available in either ASTM or AASHTO, the following procedure was selected in coordination with the KOCH Materials Co., ODOT, and the Oklahoma Asphalt Pavement Association (OAPA):

1. Cure the specimens at 60°C (140°F) in a Blue M oven for 24 hours.
2. Set the specimens at room temperature, 25°C (77°F), for another 24 hours (or longer

for extended curing times).

3. Divide the specimens into two groups for dry and soaked curing.
    a) *Dry Curing*: Set specimens at room temperature, 25°C (77°F), for 23 hours and then place in the oven at 40°C (104°F) for one hour before testing.
    b) *Soaked Curing*: Submerge specimens in a water bath at room temperature, 25°C (77°F) for 23 hours and in a second water bath at 40°C (104°F) for one hour prior to testing.

Specimens prepared with Portland cement were also cured according to the above procedure, except step 2 was skipped. Moreover, the specimens were oven cured for 2 hours, instead of one hour, prior to testing.

4.2 Field-Mix Samples

Raw millings were passed through an impact crusher, sieved, and mixed with water and emulsion in a pugmill at the ODOT Tulsa West maintenance yard. Each day several bags of processed millings (collected at different times) were transported from the plant to the ODOT residency in Sand Springs. The sample's tonnage (or batch) was recorded on the laboratory molded specimens. At least three specimens were prepared from each batch. About 6000 gm (13.2 lb) of processed millings from each bag was separated into four equal parts using a sample splitter. From each part, a 1200-gm (2.6-lb) sample was prepared (see steps 5 and 6 of Sub-Section 4.1.1).

Cured samples were tested to determine the Hveem stability values. According to the Asphalt Institute (1989), the minimum stability value for cold RAP mixes should be 30. RAP mixes with higher moisture contents produced lower stability values, with some exceptionso For the cationic RAP mix, dry stability values ranged from 45 to 52, while soaked stability values varied between 35 and 41. For the PMC RAP mix, dry and soaked stability values varied from 32 to 41 and 29 to 36, respectively. Dry stability values for specimens from the anionic mix ranged between 22 and 31, and soaked stability values between 18 and 29. Finally, the PMA specimens had dry stability values varying from 26 to 41, and soaked stability values from 21 to 34.

Overall, the cationic mix had the highest dry and soaked stability values, 52 and 41, respectively, at a moisture content of 3.2%; while, the anionic mix had the lowest dry and soaked stability values, 22 and 18, respectively, at a moisture content of 5.86%. For further discussion refer to Sub-Section 5.1.1.

4.3 Laboratory-Mix Samples

Preparation of the specimen was carried out as discussed in Section 4.1. To determine the optimum moisture content, the emulsion content was kept constant at 1.5%. In order to determine the optimum emulsion content, the moisture content and curing time were kept constant at 2% and 3 days, respectively, and the emulsion content was varied from 1% to 3%. Moreover, to study the effect of curing time on Hveem stability, samples were cured for 3, 7, 14, and 28 days prior to testing.

The PMA RAP mix resulted in the highest dry stability value, 57, while, the PMC RAP mix had the highest soaked stability value, 37. Overall, both dry and soaked stability values decreased with the increase in *liquid content.* In general, dry stability values were higher than soaked stability values. However, as the moisture content increased from 2% to 6%, the difference between the two stability values decreased. For example, the difference between dry and soaked stability values for the PMC RAP mix at 2% free moisture content was 7; the corresponding difference at 6% free moisture content was reduced to 3.

Finally, an increase in curing time increased the stability values, as expected. This is because as more water evaporates from a sample with time and the emulsion sets, the stability and strength of the sample experience an increase.

4.4 Field Cores

Several 100-mm (4-in) diameter and 50-mm (2-in) thick cores were obtained from the field and brought to the laboratory for testing. Two attempts were made by the ODOT crew to obtain cores from the field, the first on September 4 and 5, 1998, and the second on March 10, 1999. In the first attempt, the cores had a diameter slightly greater than 100mm (4 in), so they did not fit in the stabilometer. This problem was resolved in second coring. In both attempts, only samples from Section I (cationic) could be cored. Only pancake type cores (1.25 cm to 2.5 cm (0.5 in to1 in) thick) could be recovered from other sections, although the field (nuclear) density was slightly higher in Sections III and IV. Disintegration of cores may have taken place during the retrieval process. Additional research is needed to explain the phenomenon.

Overall, the cores were of poor quality. The surfaces were uneven, particularly the bottom surface (in contact with old pavement), and they had to be capped with a gypsum paste for stability testing. Four cores were selected for testing, of which two were tested for dry Hveem stability, and two for tensile strength. The results of these tests are presented in the following sections.

4.4.1 Hveem Stability

Stability values of the two cores were 23 and 27, with an average of 25. In spite of extended curing time, the stability of field cores was substantially lower than those of the field-mix and laboratory-mix samples. It is important to note that the samples tested for stability were cored approximately six months after construction. The compaction and curing conditions in the field were also quite different from that in the lab. Thus, a direct comparison of stability between field cores and laboratory samples was not feasible.

Differences between field and laboratory behavior are not uncommon. Specimens are prepared and tested in the laboratory under controlled conditions, whereas, in the field these conditions may vary significantly. Scholz et al. (1991) recorded substantial differences between Marshal stability results of field and laboratory samples, although both were from the same RAP mix. It was noted that the significant differences between the two resulted from the method of compaction, age, temperature, and moisture during curing and traffic conditions (Scholz et al. 1991).

4.4.2 Tensile Strength

The two field cores tested for tensile strength were relatively short in size, 50.8 mm and 53.3 mm (2.0 in and 2.1 in). Core 1 and Core 2 had tensile strength values of 189 kPa (27.4 psi) and 214 kPa (31.1 psi), respectively. Comparatively, the tensile strength of laboratory samples for a similar mix varied between 262 kPa and 297 kPa (38.0 psi and 43.1 psi).

4.5 Specimens Prepared With Portland Cement

Processed millings were rejuvenated with high float emulsion (HFE-300) and Type I Portland cement to prepare the *cement-emulsion composite samples*. Since no standard procedure is available in the literature to introduce Portland cement to rejuvenated millings, several procedures were tried to come up with a workable approach. All attempts to introduce cement in a slurry form failed. As a result, the Portland cement was introduced in powder form. If cement is introduced after the addition of emulsion, then aggregate surface becomes coated with emulsion. This was found to hinder cementation of aggregate particles. Also, cement particles formed clusters and did not disperse adequately, producing a highly non-homogeneous RAP mix. In the preparation technique adopted, Portland cement was added in powder form directly after mixing the processed millings with water (refer to section 4.1.1). The logic was to wet the surface of aggregates before adding cement. Thus, hydration of cement would be fast and effective. Moreover, cement would create a bond between the aggregates, and emulsion would coat the mix and hold it together.

4.5.1 Samples Prepared With Varying Emulsion Contents

Three sets of samples, each with different emulsion contents (1.5%, 2%, 2.5%), and 2% free moisture content were prepared and tested for stability. About 42 samples were prepared for each set and the effect of varying the cement content on the dry and soaked stability was determined. The cement content varied from 0% to 3%. A minimum of two dry and two soaked samples were prepared for each cement content. If the resulting stability values varied significantly, additional samples were prepared and tested for increased reliability.

For tensile strength tests, 32 samples were prepared with varying cement contents, 2% free moisture, and 2% emulsion. A minimum of three dry and three soaked samples were prepared for each cement content. If the resulting tensile strength values varied significantly, additional samples were prepared and tested to identify any discrepancy.

Samples prepared with cement contents higher than two percent looked and felt very dry. By touching the mix one can notice the lack of cohesion between the particles. Moreover, the mix was not workable, and it was extremely difficult to accommodate the desired amount of mix in the compacting mold, and compacting the mix was problematic.

4.5.2 Samples Prepared With Various Densities

In addition to the laboratory density of 2.2 gm/cm^3 (137.3 pcf), an attempt was made to prepare and test samples at the field density, 1.8 gm/cm^3 (112.3 pcf), and at an intermediate density of 2 gm/cm^3 (124.9 pcf). Two percent of water and two percent of emulsion were added to the oven-dried processed millings, and four different percentages of cement (0%, 1%, 2%, 3%) were considered. Two dry and two soaked samples were prepared at each percentage resulting in a total of 16 samples. All the samples, with cement contents as high as 3%, did not meet (too weak) the requirements of the Hveem stability test. Thus, stability values for these samples could not be recorded.

The samples prepared in the laboratory may not be representative of the field cores, although the density was similar to that of the field. Field cores were tested six months after construction of the overlay. The extended curing time resulted in increased stability although the stability was low. Comparatively, laboratory samples were tested only after two days of curing. Since the density was low, these samples were too weak for Hveem stability testing. One of the most important observations from this portion of the study is that *density, compaction dynamics, and curing* play a key role in the cold-mixed, cold-laid method. Additional research is needed to address the issues pertaining to the effect of compaction and density on the strength and stability of rejuvenated millings.

4.5.3 Testing

The following subsections include the results of the Hveem stability and indirect tensile tests performed in this study.

4.5.3.1 Stability

Dry and soaked stability values of samples prepared with different cement contents and 1.5% emulsion varied between 41 and 64, and 34 and 62, respectively. For 2% emulsion, dry stability values varied between 33 and 56, and soaked between 21 and 60. Comparatively, for 2.5% emulsion content dry stability values were between 20 and 40, and soaked between 17 and 33. For all cases, the highest stability values were observed for samples prepared with 3% cement and the lowest for samples prepared with 0% cement.

It was concluded that the stability value increased with the increase in cement content. The soaked stability, however, was found to increase at a higher rate than the dry stability. It was evident that the addition of Portland cement possibly affects the stability of samples cured under soaked conditions much more than those cured under dry conditions (refer to section 5.2.4 for discussion of results).

4.5.3.2 Tensile Strength

An increase in cement content increased the tensile strength. For example, the tensile strength values for samples prepared with 0% cement varied between 247 kPa and 297 kPa (35.8 psi and 43.1 psi), while, the corresponding values for samples prepared with 3% cement ranged from 222 kPa to 461 kPa (32.2 psi to 66.9 psi). However, addition of too much cement caused an early hardening of the specimens that would lead to cracking. As the cement content increased, the samples became stiffer and less ductile. This could be detected by comparing the loading and unloading slopes, and the ultimate strain values (i.e., strain at failure). With the increase in cement content, the loading and unloading slopes increased, and the ultimate strain decreased. As a result, an optimum amount of cement should be perceived as the amount that yields increased strength and stability without causing ductility and workability problems.

5 ANALYSIS OF RESULTS

This section summarizes the results of the laboratory investigation. It is divided into two parts; in the first part Hveem stability for samples prepared with the four types of emulsion are discussed. Analysis of Hveem stability and tensile strength results from the tests performed on the cement-emulsion composite samples is presented in the second part. The analysis was performed on the basis of average stability and tensile strength values. Tables 2 and 3 show qualitatively the influence of several components and factors (emulsion, free moisture, cement, etc.) on the Hveem stability and tensile strength of different RAP mixes.

5.1 Samples Prepared With Various Emulsion Types

Four types of emulsion were used to prepare two sets of samples: the first included field-mix samples, and the second laboratory-mix samples.

5.1.1 Field-Mix Samples

Figure 3 compares the average stability values for field-mix samples. The cationic RAP mix had the highest dry and soaked stability values and the anionic RAP mix had the lowest values. However, moisture contents of the batches differed. The cationic mix had the lowest moisture content, 2.95%, and the anionic mix had the highest, 3.96%. Thus, a direct comparison of stability for mixes with different water contents was not feasible. Figure 4 shows the relationship between moisture content and stability for the field-mix. It is evident that stability decreases as moisture content increases; thus, it can be stated that the amount of free moisture is an important factor in cold processing of RAP mixes.

5.1.2 Laboratory-Mix Samples

Hveem stability versus emulsion content for laboratory-mix samples is plotted in Figure 5. It is noted that as the emulsion content increased, generally the stability values decreased. As noted by Jantzen (1993), although emulsion acts as a rejuvenator that binds aggregates together, too much emulsion in the mix would act as an elastic dispersion medium for the aggregates causing the mix to loose its stability.

The decrease in dry stability values was higher than that of the soaked stability values. For samples rejuvenated with PMA emulsion, a substantial decrease in the dry stability value, from 52 to 21, was noticed as the emulsion content increased from 2% to 2.5%. The PMA RAP mix had higher dry stability values than the PMC RAP mix. For samples prepared with 2% emulsion the average dry stability values for PMA RAP mixes was 52, while that for PMC RAP mixes was 29.

Figure 6 shows stability values versus water content for laboratory-mix samples. In general, stability values decreased as free moisture content increased. At low free moisture contents, dry stability values for PMC and PMA RAP mixes were much higher than soaked stability values. However, as water content increased from 2% to 6%, the two values almost became the same. It seems that the increase in free moisture content beyond 4% did not have a large effect on the stability. The reason could be the lost moisture during compaction. At high free moisture content some water seeped out of the sample during compaction in the Texas Gyratory compactor. However, the amount of lost water was not recorded. In future studies, the actual free moisture content of samples after compaction should be measured and recorded.

5.1.3 Effect of Curing Time

The PMC samples prepared in the laboratory with varying curing time were tested for Hveem stability. Figure 7 shows Hveem stability versus curing time. Some fluctuations in stability values between 7 days and 14 days are noticed, however, the general trend of the graph suggests that Hveem stability increased with curing time. As curing duration increased from 3 days to 7 days, a 37% gain in stability was achieved. The corresponding increase in stability between 7 days and 28 days is about 18%.

Similar results have been reported previously by several researchers. Mang and Leonarde (1990) stated that "the binders of the recycled mixes generally increase in stability with increasing curing time." Scholz et al. (1991) also concluded that stability of cold RAP mixes increased over time. These authors attributed the increase in stability to improved cohesive properties of the asphalt due to additional curing of RAP mix (Scholz et al. 1991).

5.1.4 Discussion

During two field trips, the four roadway sections were rated from best to worst as follows: PMA, anionic, cationic, PMC. This rating was based on the frequency and size of the potholes in the pavement in each section. Also, the quality of compacted mix on the sides of the pavement was considered. These observations cannot be compared with results obtained in the laboratory due to the different factors under which the two types of mix were prepared. Moreover, compaction techniques differed remarkably between the field and the laboratory.

The anionic section showed better response to traffic and other conditions than the PMC section. This could be due to inadequate compaction in Sections I and II, as compared to Sections III and IV. Overall, polymer-modified emulsion RAP mixes have higher stability values than emulsions without polymer. The polymer acts as a binding agent that holds the segregated emulsion particles together, thus giving the mix more stability. McKeen (1996) noted that polymer modifiers increase the stability and strength of pavements without stiffening them.

Anionic and cationic emulsions have negative and positive radicals, respectively. Radicals help emulsions stick to opposite charged surfaces. Water was mixed with the oven-dried millings before the addition of emulsion. Since water is a dipole, it has the ability to adhere to either positively or negatively charged surfaces. It is possible that the water molecules are attracted from their negatively charged end, leaving the surface of the mix positively charged. Figure 8 schematically illustrates this argument. Thus, anionic and PMA emulsions, having negative radicals, could result in more stable RAP mixes than their cationic and PMC counterparts.

Based on laboratory tests, PMA mix with 2% emulsion and 2% free moisture content had higher dry stability values but lower soaked stability values than the PMC mix. Thus, the PMC mix had higher retained stability value than the PMA mix.

As mentioned earlier, a direct comparison between results from different testing sets is not feasible; however, stability results from field-mix samples and laboratory-mix samples are presented herein, but no comparison is attempted.

The PMA field-mix contained an average moisture content of 3.65% and emulsion content of 1.5%. The resulting dry and soaked stability values were 32 and 26, respectively. The PMA laboratory-mix prepared with 2% emulsion content and 2% free moisture content resulted in dry and soaked stability values of 52 and 25, respectively.

The PMC field-mix contained average moisture content of 3.40% and emulsion content of 1.5%. The resulting dry and soaked stability values were 38 and 33, respectively. The PMC laboratory-mix prepared with 2% emulsion content and 2% free moisture content resulted in dry and soaked stability values of 39 and 32, respectively.

5.2 Samples Prepared With Cement-Emulsion Composite

Several researchers have noted that the addition of cement to RAP mixes, in any form, results in a build up of early strength (e.g., Al-Qadi et al. 1994, Favretti et al. 1998, Li et al. 1998, Wisneski et al. 1996). The following includes an analysis of the laboratory results for Portland cement added to RAP mixes.

5.2.1 Hveem Stability Tests

Figure 9 shows a plot of the stability versus cement content for three different emulsion contents (1.5%, 2%, and 2.5%). It can be observed that both dry and soaked stability values increased as cement content increased. Moreover, for both curing conditions and all cement contents, stability increased as emulsion content decreased.

Figures 10 and 11 show plots of increase in dry and soaked stability, respectively, due to the addition of cement. For samples prepared with 2% emulsion and 3% cement, dry stability values increased 61%, while soaked stability values increased 155%. In general, it could be concluded that an increase in cement content would affect soaked stability much more than dry stability. This could be due to the role of water in the hydration of cement. Hydration is a continuous process. When cured under soaked conditions, cement had access to water required for complete hydration, thus acquiring more strength.

The addition of cement increased the dry stability of samples with higher percentages of emulsion more than those prepared with lower percentages of emulsion. However, at a certain cement content, samples with lower emulsion content exhibited higher stability values than those with further increase in cement content. For example, the addition of 2% cement caused a 65% increase in dry stability for samples containing 2.5% emulsion; the corresponding increase in dry stability was 42% for samples prepared with 2% emulsion. However, the average dry stability for samples containing 2.5% emulsion was 33, as opposed to 47 for samples containing 2% emulsion. A sample with more emulsion contains more liquids. Water is an ingredient of emulsion, thus a sample with higher emulsion content has higher water content, which appears to accelerate the hydration of cement. Samples prepared with 2% emulsion had the highest gain in soaked stability due to the addition of cement.

5.2.2 Tensile Strength Tests

Tensile strength tests were conducted on samples prepared with 2% water, 2% emulsion, and varying cement content. Figure 12 shows tensile stress versus strain curves of samples for different cement contents. Figures 13 through 17 show plots of cement content versus average tensile strength, average strain at failure, average residual strain, average slope of the loading curve, and average slope of the unloading curve, respectively. It is clear that tensile strength increased for both dry and soaked samples, with the increase in cement content. The strain level at failure decreased slightly with the addition of cement. The average residual strain decreased (Figure15) but the loading and unloading slopes increased (Figures 16 and 17) as cement content increased. It is evident that even though the samples gained strength they became stiffer and more brittle with the increase in cement content. For example, as cement content increased from 0% to 3%, the loading and unloading slopes increased by 102% and 192%, respectively, for dry samples, and 19% and 239%, respectively, for soaked samples. This is a remarkable amount of hardening, causing the sample to loose some of its ductility. As a result, an optimum cement content should be added to the RAP mixes so as to increase stability and tensile strength, thus improving the properties and performance of the pavement, without introducing any significant brittleness to the mix.

5.2.3 Optimum Cement Content

Moisture-induced failure is very common in pavements (Shatnawi and Kirk 1993). A RAP mix containing cement would have more affinity to water than a regular RAP mix. This is due to the hydration properties of cement. However, a RAP mix containing a high percentage of cement would be brittle and stiff. In this section an optimum cement content is recommended.

It was discussed earlier how stability values increased with the increase in cement content. Also, the soaked stability was more impacted positively by an increase in cement than the dry stability. Samples prepared with 2% emulsion and 2% water had the highest gain in soaked stability due to the addition of cement. However, the optimum cement content of a mix is influenced by other factors also, such as tensile strength, ductility, and workability.

When only 1% of cement was added to the millings, the loading and unloading slopes increased by 16% and 59%, respectively. On the other hand, when 2% of cement was added to the RAP mix, the loading and unloading slopes increased by 43% and 200%, respectively. This is about 161% increase in loading and 240% increase in unloading slopes compared with the values for 1% cement. From these results it becomes evident that the benefit of cement was realized most with respect to the stiffness (dry and soaked) of mix when the cement content was 2%. However, while preparing samples, it became evident that a mix had good workability with 1% cement but its workability was reduced with increasing cement content. At 2% cement content, the mix was less workable and with 3% cement the mix became very dry and unworkable. Thus, based on workability considerations the cement content should not exceed 2%; the optimum mix is possibly attained with cement content between 1% and 2%. Further study is needed to address this issue.

The PMA laboratory-mix prepared with 2% emulsion content and 2% free moisture content resulted in dry and soaked stability values of 52 and 25, respectively. Thus, the retained stability was only 48%. The PMC laboratory-mix prepared with 2% emulsion content and 2% free moisture content resulted in dry and soaked stability values of 39 and 32, respectively, with a retained stability of 82%. On the other hand, a sample prepared with 1% cement, 2% high float emulsion (HFE-300), and 2% free moisture content resulted in dry and soaked stability values of 41 and 29, respectively, giving a retained stability of 71%. Dry and soaked stability values of a comparable mix containing 2% cement were 47 and 45, respectively, giving a retained stability of 96%. According to the Asphalt Institute (1989), the minimum stability value for cold RAP mixes should be 30. Summing all the above arguments, it could be concluded that a RAP mix containing 2% water, between 1% and 2% cement, and 2% HFE-300 emulsion would perform superior to conventional cold RAP mixes (Rejuvenated with HFE-300 emulsion).

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From the data obtained and the analysis of results presented in the preceding sections, the following observations and conclusions are made:

1. Two site visits were made to evaluate the performance of the overlay in four test sections constructed with four different types of emulsion RAP mixes. In both visits, it was evident that the PMA section performed better than other sections. This observation was based on the quality of compacted mix at the edges of the pavement, and the frequency of potholes in each section.
2. PMC laboratory-mix gave higher retained stability values than the PMA laboratory-mix. The performance of the laboratory mix was much better than the field overlay because of inadequate compaction during construction and variance in liquid content during field processing. Curing time also plays an important role in field stability of cold-mixed, cold-laid RAP mixes. Premature opening of a rehabilitated pavement to traffic can contribute to poor performance as well.

3. Achieving an adequate compaction is crucial to the successful performance of a cold-mixed, cold-laid overlay. The degree of compaction can greatly vary depending upon rolling pattern, speed, equipment, compaction dynamics, and characteristics of RAP mixes. Breakdown rolling by two pneumatic rollers and single drum steel wheel roller for intermediate rolling used in Sections III and IV were found to be much better than one pneumatic roller for the breakdown, intermediate, and finish rolling. Weight of steel wheel roller (drum type) is also a key factor in compaction.
4. For samples prepared from cement-emulsion composite, both dry and soaked stability values increased as cement content increased. The addition of Portland cement, however, affected the stability value of samples cured under soaked conditions much more than those cured under dry conditions. This is due to the hydration property of cement. Samples prepared with 2% emulsion had the highest increase of soaked stability over dry stability. The addition of Portland cement increased the dry stability of samples with higher percentages of emulsion more than those prepared with lower percentages of emulsion. However, an increase in the emulsion content caused a decrease in the stability value. The decrease in the dry stability values was higher than that in the soaked stability values.
5. The addition of more than 2% cement resulted in a dry unworkable mix that was hard to compact. Also, as cement content increased from 2% to 3%, the loading and unloading slopes increased by 161% and 240%, respectively. This is an indication of hardening and reduced ductility, which could lead to pavement cracking. As a result, the optimum cement content is recommended between 1% and 2%.
6. The introduction of as little as 1% of Portland cement to RAP mixes doubled the

retained stability of specimens, as compared with a RAP mix rejuvenated with HFE-300 emulsion. A RAP mix containing 2% water, 1% to 2% cement, and 2% HFE-300 emulsion is expected to show much superior performance than a cold RAP mix with HFE-300 emulsion.

6.2 Recommendations

In view of the findings of the present study, the following recommendations are made for further studies:

1. The cold-mixed, cold-laid process of pavement rehabilitation holds significant promises for the future. The current technology, however, needs improvement and refinement through further laboratory and field studies.
2. Raw millings from a specific source were used in this study. Since the quality of millings can vary significantly from one site to another and within the same site, a laboratory study should be undertaken to investigate the effectiveness of cement-emulsion composite in rejuvenating millings from different sources. Millings from some selective sources that are of interest to ODOT could be used in such a study.
3. Since the hydration of cement is affected primarily by water, the effect of varying water content on the strength and stability of cement-emulsion composite RAP mixes should be studied.
4. Cement should be introduced in fraction percentages between 1% and 2%, and an optimum percentage of cement should be determined. Also, other properties of cement-emulsion composite RAP mixes, such as resilient modulus, rutting, surface charge of millings etc..., should be investigated.
5. A field project should be pursued with cement-emulsion RAP mixes as overlay

material. A laboratory study should be pursued in conjunction with this field study to come up with an appropriate mix design for the specific raw millings and rejuvenating agents (Portland cement and high float emulsion) to be used, and to aid in the field performance assessment through testing of cores.

Table 1 Density Values for the Four Sections of the Overlay

Section	Density in gm/cm³ (pcf)		
	Minimum	Maximum	Average
I-Cationic emulsion	1.79 (111.7)	1.95 (121.5)	1.87 (116.8)
II-PMC emulsion	1.78 (110.8)	1.94 (121.0)	1.88 (117.4)
III- Anionic emulsion	1.86 (115.9)	1.98 (123.7)	1.90 (118.7)
IV- PMA emulsion	1.88 (117.4)	1.96 (122.1)	1.93 (120.4)

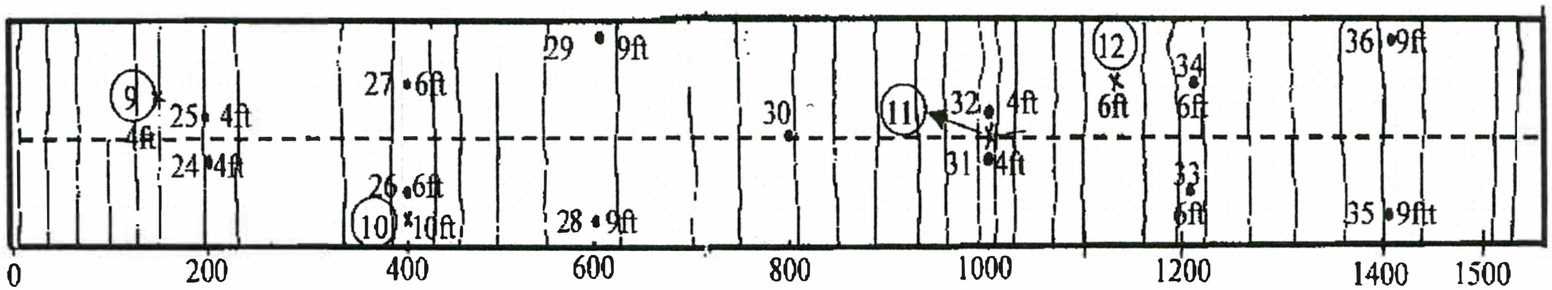
Table 3 Effect of Varying Different Components on the Properties of the Mixes

		Increase In			
		Free Moisture Content	Emulsion Content	Density	Curing Time
Stability	Field-Mix	⇓	⇓	⇑	⇑
	Laboratory-Mix	⇓	⇓	⇑	⇑

Table 4 Effect of Increasing Cement Content on the Cement-Emulsion Composite Mix

	Cement Emulsion Composite				
	Stability	Tensile Strength	Strain at Failure	Residual Strain	Slope
Increase in Cement	⇑	⇑	⇓	⇓	⇑

Section III (Anionic)



Section IV (Polymer Modified Anionic)

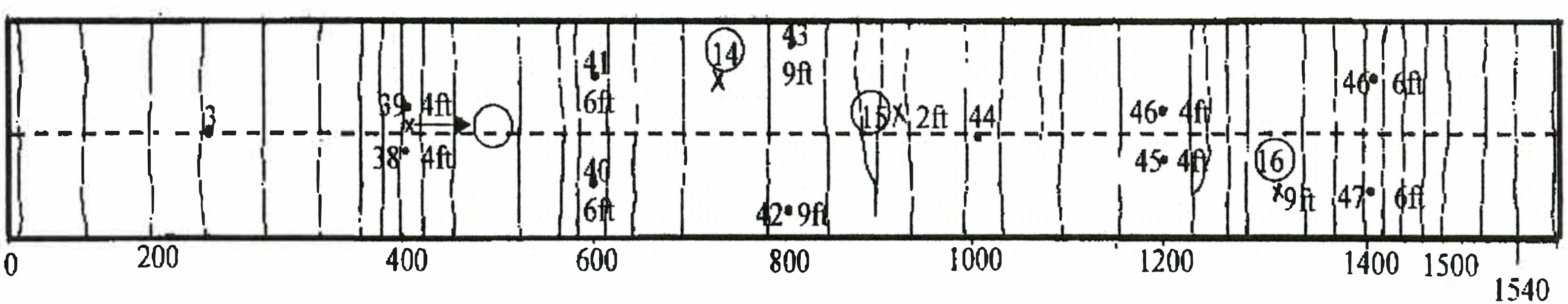


Figure 2 Mapping of Cracks (Sections III and IV)

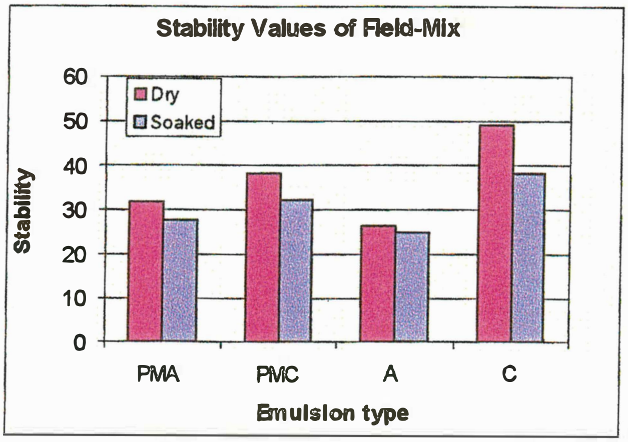


Figure 3 Hveem Stability for Field-Mix Samples

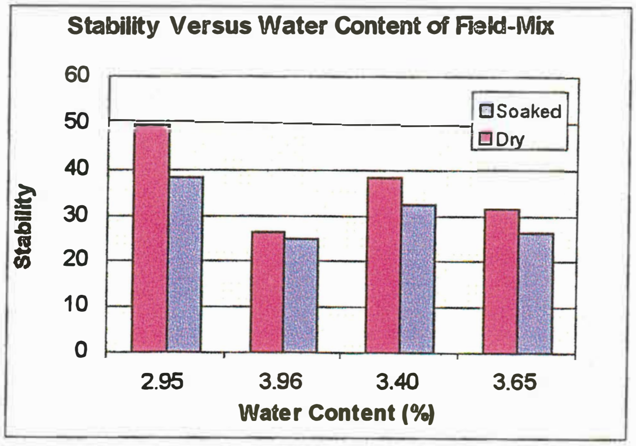


Figure 4 Effect of Moisture Content on Stability for Field-Mix Samples

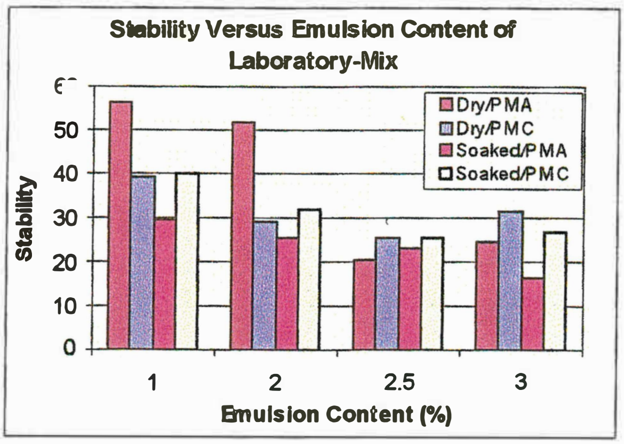


Figure 5 Effect of Emulsion Content on Stability for Laboratory-Mix Samples

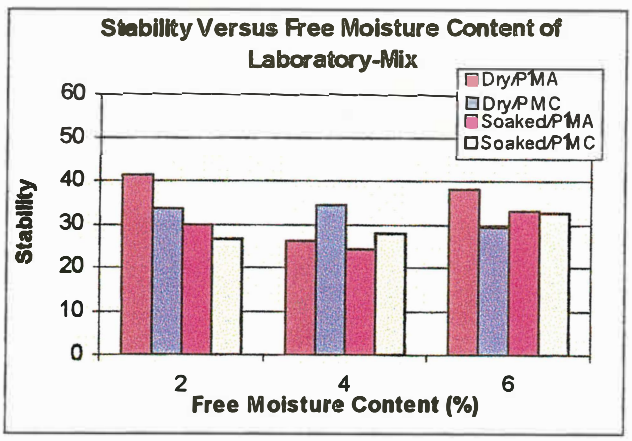


Figure 6 Effect of Free Moisture Content on Stability for Laboratory-Mix Samples

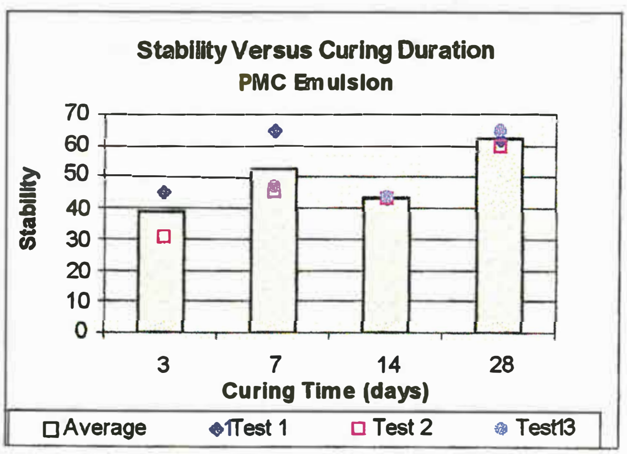


Figure 7 Relationship Between Hveem Stability and Curing Time

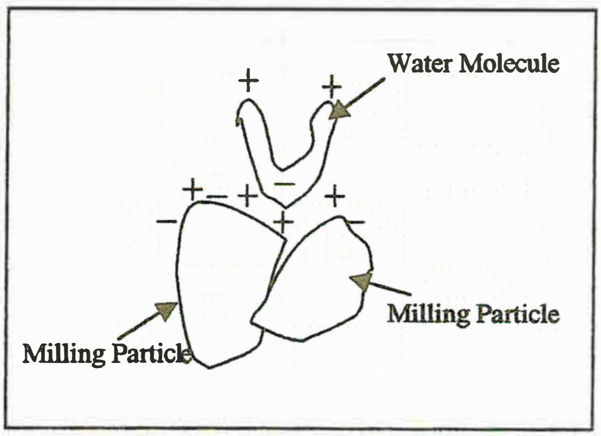


Figure 8 Proposed Sketching of a Water Molecule Adhering to the Surface of Millings

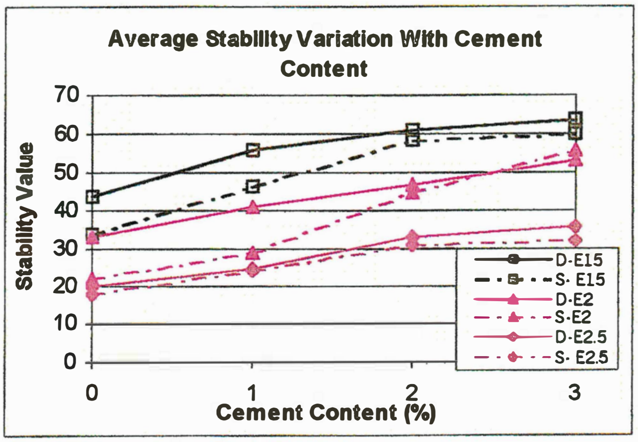


Figure 9 Relationship Between Stability and Cement Content
D: Dry, S: Soaked

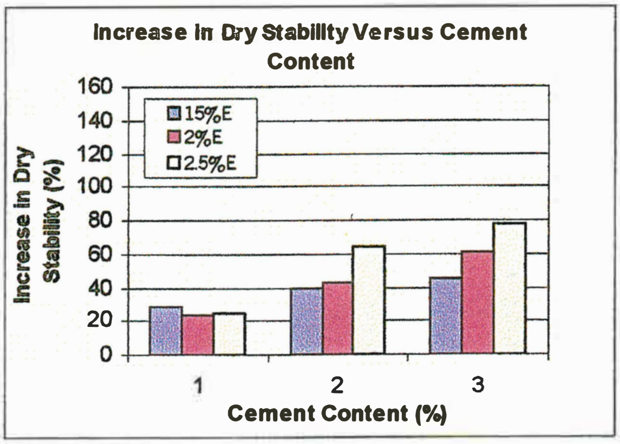


Figure 10 Increase in Dry Stability Due to the Addition of Cement

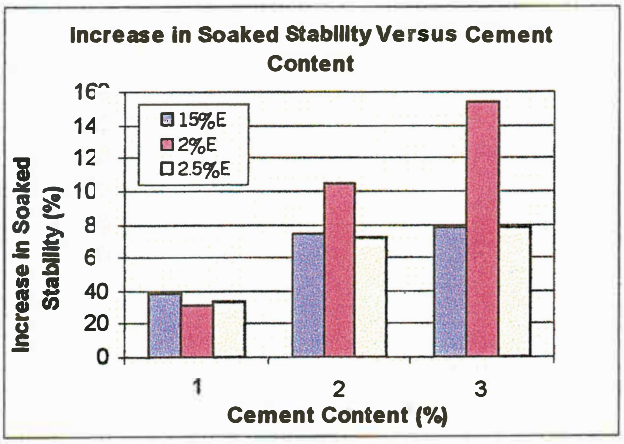


Figure 11 Increase in Soaked Stability Due to the Addition of Cement

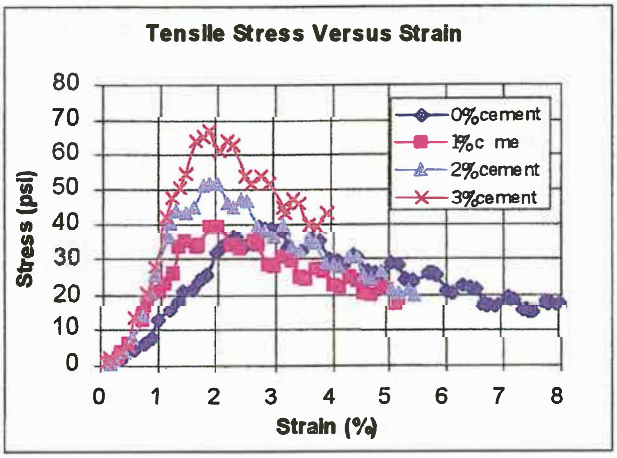


Figure 12 Sample Tensile Stress-Strain Curves

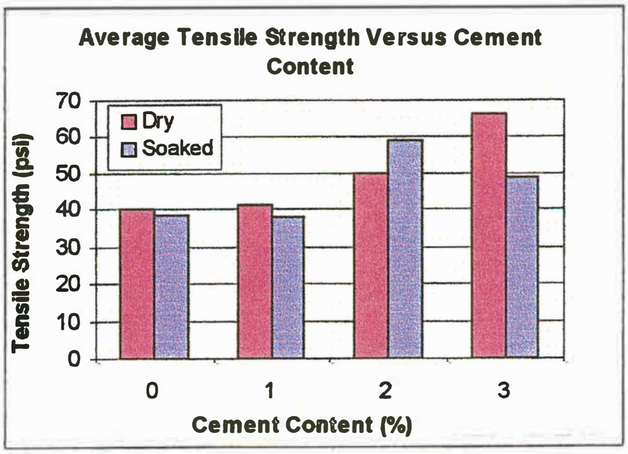


Figure 13 Relationship Between Cement Content and Tensile Strength

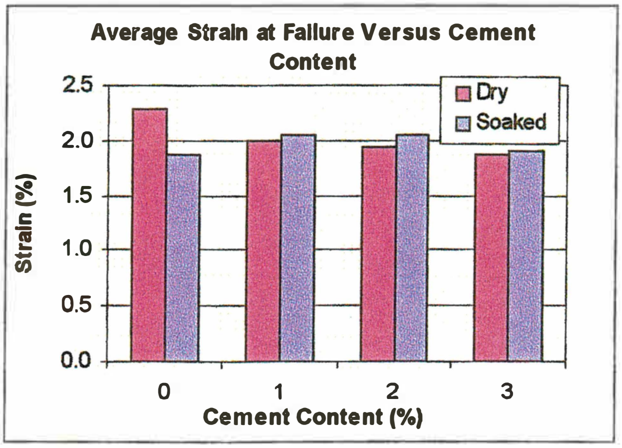


Figure 14 Relationship Between Cement Content and Strain at Failure

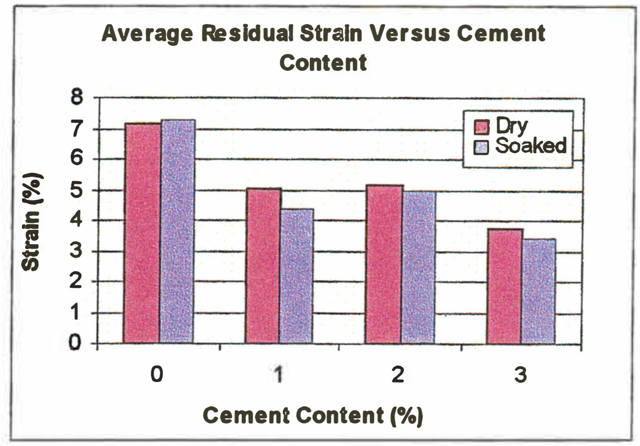
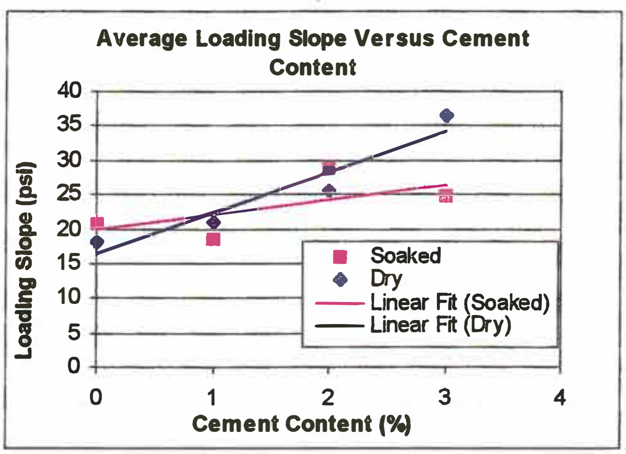


Figure 15 Relationship Between Cement Content and Residu l Str in



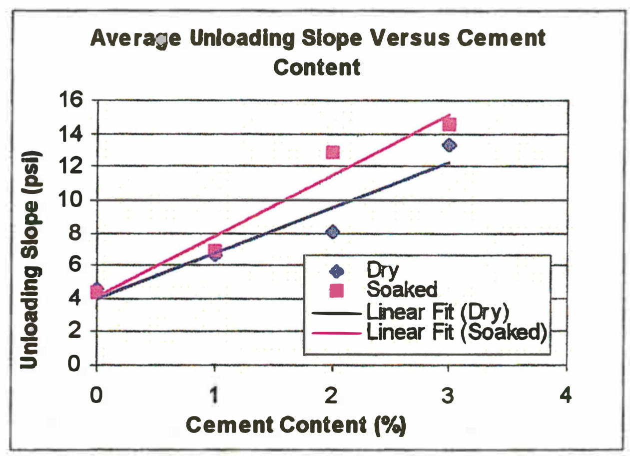


Figure 16 Relationship Between Cement Content and Loading Slope

Figure 17 Relationship Between Cement Content and Unloading Slope

REFERENCES

1. Al-Qadi, I. L., Gouru, H., and Weyers, R.E., "Asphalt Portland Cement Concrete Composite: Laboratory Evaluation," *Journal of Transportation Engineering*, Vol. 120, No. 1, Jan./Feb., 1994.
2. American Association of State Highway and Transportation Officials (AASHTO), "Standard Specifications for Transportation Materials and Methods of Sampling and Testing Part I," 3rd edition, Washington D.C., 1986.
3. American Society for Testing and Materials (ASTM), "Concrete and Aggregates," Vol. 04.02, Easton, MD, 1997.
4. American Society for Testing and Materials (ASTM), "Road and Paving Materials; Paving Management Technologies," Vol. 04.03, Easton, MD, 1998[a].
5. American Society for Testing and Materials (ASTM), "Soil and Rock (I): D420 – D 4914," Vol. 04.08, Easton, MD, 1998[b].
6. Asphalt Emulsion Manufacturers Association (AEMA), "A Basic Asphalt Emulsion Manual," 3rd edition, Series No. 19, USA, 1979.
7. Asphalt Institute, "Asphalt Cold Mix Manual," Series No. MS-14, USA, 1989.
8. Asphalt Institute, "Principles of Construction of Hot-Mix Asphalt Pavement," Manual Series No. 22, Lexington, Kentucky, Aug. 1982.
9. Corti, P. E., "Experimental Use of Cold Recycled Asphalt Pavement on Vermont Route 2A," Initial Report 82-5 Federal Highway Administration, Region 15, 1000 Glebe Road, Arlington, Virginia 22201, Mar. 1983.
10. Das, B. M., *Principles of Geotechnical Engineering*, 4th ed., International Thomson Publishing, Boston, 1998.
11. Favretti, P., Croteau, J. M., Davidson, K., "Deep Cold In-Place Recycling With Emulsion/Cement, Ottawa, Ontario," *Proceedings of The Forty-Second Annual Conference of Canadian Technical Asphalt Association*, Polyscience Publications Inc., Quebec, Canada, 1998, pp. 482-492.
12. Jantzen, M., "Recycling Trend Means Saving for Local Governments," Public Works, Vol. 124, No. 10, 1993, pp. 76-77.

13. Khosla, N. P., and Bienvenu, M. E., "Design and Evaluation of Cold In-Place Recycled Pavement," Center for Transportation Engineering Studies, Department of Civil Engineering, NCSU, Raleigh, NC, 1996.
14. KOCH Materials Co., Wichita, Kansas, Personal Communication, 1998.
15. Li, G., Zhao, Y., Pang, S.-S., and Huang, W, "Experimental Study of Cement-Asphalt Emulsion Composite," *Cement and Concrete Research*, Vol. 28, No. 5, 1998, pp. 635-641e
16. Mang, T., and Leonarde, E. W., "Use of Asphalt Emulsion and Foamed Asphalt in Cold-Recycled Asphalt Paving Mixtures," *Transportation Research Record*, No. 898, 1990, pp. 315-322.
17. McKeen, R. G., "Cold Insitu Recycling Evaluation," Research Report, New Mexico State Highway and Transportation Department Research Bureau, Dec. 1996
18. Oklahoma Asphalt Pavement Association, Oklahoma City, Personal Communication, 1998.
19. Oklahoma Department of Transportation (ODOT) *"Standard Specifications for Highway Construction,"* 1996.
20. Rainhart Co., "Gyratory-Shear Molding Press," Testing Equipment, Catalog No. 140, 1998.
21. Ruth, B. E., and Schaub, J. H., "Gyratory Testing Machine Simulation of Field Compaction of Asphaltic Concrete," Association of Asphalt Paving Technologies, Vol. 35, 1966, pp. 451-484.
22. Scholz, T. V., Rogge, D. F., Hicks, R. G., and Allen D., "Evaluation of Mix Properties of Cold In-Place Recycled Mixes," *Transportation Research Record*, No. 1317, 1991, pp. 77-89.
23. Shatnawi, S. R., and Kirk, J. V., "Premature Asphalt Concrete Pavement Distress Caused by Moisture-Induced Damage," *Transportation Research Record*, No. 1417, 1993, pp. 168-177.
24. Wisneski, M. L., Chaffin, J. M., Davison, R. R., Bullin, J. A., and Glover, C.J., "Use of Lime in Recycling Asphalt," *Transportation Research Record*, No. 1535, 1996, pp. 117-123.