Fly Ash in Cold Recycled Bituminous Pavements

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Since 1986, the Kansas Department of Transportation has been cold recycling about 80 to 160 km of bituminous pavements per year. All of the projects were completed in place, 100 mm in depth, using mostly an emulsified asphalt as an additive, and incorporated a thin surface overlay. However, the emulsified asphalt cold recycle projects can leave a pavement that is susceptible to moisture damage and rutting. Since 1990, fly ash was added to these mixes with and without an emulsified asphalt. Laboratory tests indicated that fly ash would reduce the potential for moisture damage and wheel path rutting. Four test pavements were built between 1990 and 1992. Two pavements incorporated a non–self-hardening fly ash and a Type C fly ash. Water with set retarder was the other additive used. On the basis of the results of this study, the conclusions are (a) fly ash decreases the permeability of the cold recycle mixes thereby increasing the resistance of the mix to the detrimental effects of moisture damage, (b) fly ash increases the strength of the mix and decreases its potential for wheel path rutting, (c) Jeffery ash (Type C) has lower permeabilities and higher strengths than Sunflower ash, and (d) fly ash–only cold recycle mixes have a tendency to ravel under construction traffic. A protective cover material (prime coat, seal, overlay) is necessary even on low-budget projects.

Since 1986 the Kansas Department of Transportation (KsDOT) has been cold recycling about 80 to 160 km (50 to 100 mi) of bituminous pavements per year. All the projects were completed in place, recycling the top 100 mm (4 in.) of the pavement, and using mostly an emulsified asphalt as an additive. A thin surface overlay or a seal coat is applied to protect the cold in-place recycled (CIR) mix. For the most part, these projects appear to have minimum rutting and a life expectancy of 3 or more years. However, there is concern that as more emulsified asphalt is added to make the mix more resistant to cracking and moisture effects, the mix will become unstable and result in increased rutting.

BACKGROUND

Kansas has many miles of thermally cracked roads, primarily in the western half of the state. Distress includes small cracks at 4.5 to 6 m (15 to 20 ft) intervals on thin pavements to wider cracks with secondary cracking and depressions on thicker pavements. Conventional hot mix asphalt (HMA) overlays and hot recycling have not given the service life expected before the existing cracks reflect through the pavement. CIR has shown to be a cost-effective alternative for rehabilitating thermally cracked low-volume [less than 140 equivalent 80 kN (18-kip) single-axle loads per day] pavements in western Kansas.

The aggregates typically used in western Kansas are silicious sands and uncrushed gravels with a history of moisture susceptibility problems. As a result of the use of these sands and gravels and the higher in-place air void contents typically encountered in CIR mixes (*1*), CIR projects leave a pavement that is susceptible to moisture damage and rutting.

By adding fly ash instead of an asphalt emulsion to the CIR mix, the potential for moisture damage and wheel path rutting could be reduced. However, this could be at the expense of more cracking because the pavement system would become more of a rigid system. Fly ash could prove to be a viable additive if the moisture susceptibility and rutting problems could be reduced without causing an appreciable increase in pavement cracking.

OBJECTIVE

The objective of this study was to determine the effects of using fly ash as an additive in CIR mixes. It is believed that fly ash will help prevent moisture damage to the CIR pavements. A typical CIR construction project is susceptible to moisture damage before it can cure and be covered with a seal coat or a hot mix asphalt overlay (*2,3*). Another benefit would be the ability to incorporate a waste product (fly ash) into the old pavement. There is now a larger supply of fly ash than demand in Kansas, and some fly ashes are being deposited in landfills.

SCOPE

The Research section of KsDOT Bureau of Materials and Research conducted a laboratory study to evaluate the effects of using fly ash as an additive in CIR. In addition, four test sections were built between 1990 and 1992 to evaluate the performance and constructability of fly ash in CIR.

PLAN OF STUDY

Phase I

Fly ash was studied in the laboratory to determine its effect on cold recycled mixes. Test specimens were mixed and compacted in the laboratory with cold recycle millings and the following additives:

- Class C fly ash,
- Class F fly ash,
- hydrated lime,
- HFMS–1 high-float asphalt emulsion, and
- CMS–1 asphalt emulsion.

Material properties evaluated were resilient modulus, tensile and compressive strength, moisture susceptibility, and absolute perme-

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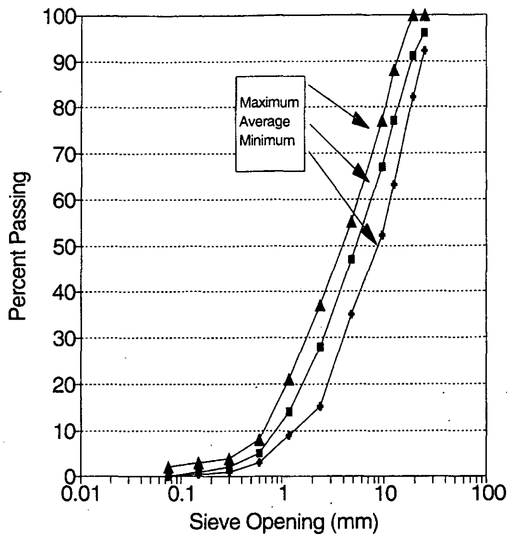


FIGURE 1 Typical RAP gradation.

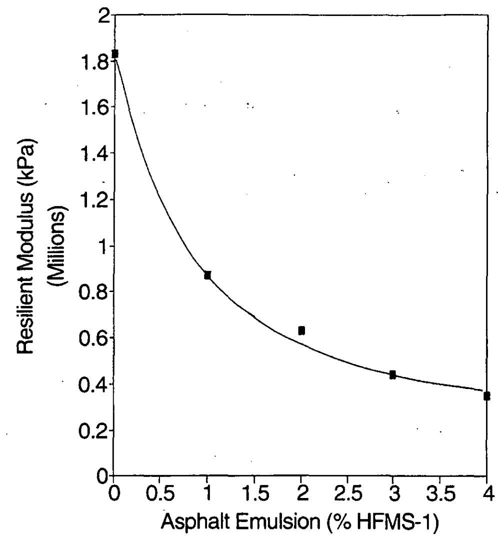


FIGURE 2 Resilient modulus versus percentage of HFMS-1 emulsion.

ability. For the fly ash samples, the effects of time and temperature on the rate of setting were also investigated.

Phase II

The second phase involved incorporating fly ash into four test projects and monitoring the constructability and performance. The projects were located on US-56 in Haskell County, K-27 in Hamilton County, I-70 in Thomas County, and K-27 in Sherman and Wallace counties. The first two test pavements contained test sections using fly ash, asphalt emulsion, and fly ash with asphalt emulsion as additives. I-70 in Thomas County used fly ash, asphalt emulsion, and asphalt emulsion with lime as additives. K-27 in Sherman and Wallace counties used fly ash, asphalt emulsion, and polymer modified asphalt emulsion as additives.

TEST RESULTS AND DATA ANALYSIS

Phase I

Some of the first laboratory tests to be completed were sieve analyses of the cold recycled asphalt pavement (RAP). This was not an extracted gradation but the gradation of the RAP itself. The results of the typical gradation used in this study are shown in Figure 1. The high and low values are presented with the average RAP gradation. As can be seen, a small percentage of material passed the 75 μm (No. 200) sieve in the RAP gradation itself. In fact, a small percentage of material passed the 300 μm (No. 50) sieve.

All test samples were compacted in Marshall molds using 50 blows per side with a Marshall compaction hammer. Typical field unit weight measurements of Kansas CIR mixes are in the 18.8 to 20.4 kN/m^3 (120 to 130 pcf) range, and previous work has shown that a 50-blow Marshall pill compacted at 43°C (110°F) would give laboratory unit weights that would be close to those found under normal field compaction operations.

The initial testing consisted of determining the stiffness and moisture susceptibility of CIR mixes with asphalt emulsions. Table 1 shows the results of this phase of the laboratory testing. Resilient modulus tests (ASTM D4123) (*4*) were conducted on samples of laboratory-molded cold recycled material with increasing amounts of HFMS-1 asphalt emulsion. The results are shown in Figure 2. It is obvious that adding more asphalt decreases the resilient modulus. In addition, moisture sensitivity tests

TABLE 1 Results of Moisture Sensitivity and Modulus Testing

HFMS-1 (%)	UNCONDITIONED	LOTTMAN	ROOT TUNNICLIFF	100% RAP	75% RAP 25% CS-2
	TENSILE STRENGTH (kPa)			RESILIENT MODULUS (kPa * 10^5)	
0.0	296.8	27.6	48.3	18.27	12.34
0.5	287.0	25.5	41.4	N/T	N/T
1.0	229.8	28.3	85.6	8.69	11.51
2.0	178.7	33.1	69.7	6.27	7.52
3.0	118.7	31.1	70.4	4.41	4.90
4.0	N/T	N/T	N/T	3.45	4.14

N/T = Not Tested

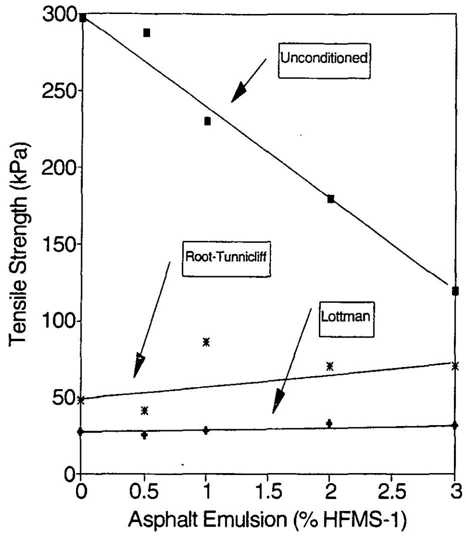


FIGURE 3 Moisture sensitivity of RAP HFMS–1 emulsion mixtures.

[AASHTO T283 (*5*)] were performed. The specimens were molded at 60°C (140°F) and cured for 24 hr at the molding temperature. The results are shown in Figure 3. The unconditioned indirect tensile strength substantially drop with increasing asphalt emulsion content but remain well above the conditioned samples. The results confirm the moisture sensitivity of the CIR and emulsion mixes. Based on the results of the resilient modulus and moisture susceptibility testing, it is questionable whether adding more asphalt emulsion to a CIR mix can really improve the overall quality of the mix.

The next step was to determine whether other additives would improve the moisture susceptibility of the CIR. HFMS–1 asphalt emulsion, 1 percent hydrated lime, and fly ash were evaluated. The fly ashes were from the Jeffery Energy Facility (Type C) near Emmett, Kansas, and the Sunflower Generating Facility located near Garden City, Kansas. A third Type C fly ash, which was used in the I–70 test section, was obtained from the Gerald Gentleman Station near Sutherland, Nebraska. The properties of these three ashes are shown in Table 2. Throughout the remainder of this paper, the fly ash produced at the Garden City plant will be referred to as "Sunflower" fly ash and the Type C ashes as "Jeffery" and "Sutherland" ashes.

The results of the moisture sensitivity tests with the additives are shown in Table 3 and presented graphically in Figure 4. As can be seen in Figure 4, the highest after-conditioned tensile strengths occurred with the Jeffery ash. The highest tensile strength ratios were obtained with hydrated lime or fly ash. Table 3 shows that as the ash content is increased, the tensile strength ratio increases for the Jeffery and Sunflower ashes. This could indicate that the ash is acting as a mineral filler, reducing the permeability and improving the tensile strength ratio. However, the Jeffery ash samples had twice the tensile strength ratio as the Sunflower ash for the same ash content. It appears that the free lime in the Jeffery ash is acting as an anti-strip additive as well.

The third phase of the laboratory portion of the study was to compare the strength [ASTM D4123 (*4*) and AASHTO T167 (*5*)], stiffness [ASTM D 4123 (*4*)], and absolute permeability [ASTM D3637 (*4*)] of mixes made with the Sunflower and Jeffery ashes, CMS–1 asphalt emulsion, and Sunflower ash with 1 percent hydrated lime. Marshall size cold recycled specimens were molded at 43°C (110°F) and tested at room temperature. Different quantities of mixing water were added to each fly ash mix. The test results are presented in Table 4.

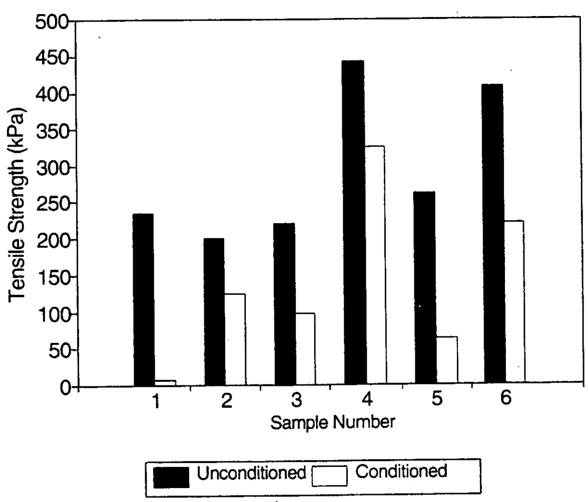
The results of the strength and stiffness tests are shown graphically in Figures 5 through 8. The Jeffery and Sunflower ash with 1 percent lime showed a definite increase in tensile strength (Figure 5) and compressive strength (Figure 6) when compared with the asphalt emulsion and Sunflower ash samples. The resilient modulus

TABLE 2 Typical Fly Ash Composition

COMPONENT	KsDOT TYPE C SPECIFICATION (%)	JEFFERY ASH (%)	SUTHERLAND ASH (%)	SUNFLOWER ASH (%)
Chemical				
Calcium Oxide	25.0 min	31.9	26.4	27.9
Sulfer Trioxide	5.0 max	3.1	2.8	11.7
Sum of Silicon Dioxide, Aluminum Oxide, Iron Oxide	50.0 min	55.2	61.8	48.3
Ignition Loss	6.0 max	0.2	0.2	4.3
Moisture Content	3.0 max	0.00	0.01	0.60
Physical				
Fineness 45 m Sieve	34 max	24.2	20.2	18.9
Pozzolanic Activity Index				
With Portland Cement				
@7 Days (% of control)	75 min	110	101	0
@28 Days (% of control)	75 min	108	108	83
Water Requirement (% of control)	105 max	93	95	102
Soundness-autoclave expansion	0.8 max	0.09	0.04	-0.02
Density (g/cm^3)		2.78	2.59	2.38

TABLE 3 Moisture Sensitivity Results, Lottman Procedure, Using Additives

SAMPLE NUMBER	ADDITIVE	TENSILE STRENGTH (kPa)		TENSILE STRENGTH RATIO (%)
		UNCONDITIONED	CONDITIONED	
1	0.8% HFMS-1 1.5% WATER	234.6	6.9	3
2	0.8% HFMS-1 1% HYD. LIME 3.2% WATER	200.1	124.2	62
3	10% SUNFLOWER 5% WATER	220.8	96.6	44
4	10% JEFFERY 5% WATER	441.6	324.3	73
5	5% SUNFLOWER 2.5% WATER	262.2	62.1	24
6	5% JEFFERY 2.5% WATER	407.1	220.8	54



SAMPLE	ADDITIVE	SAMPLE	ADDITIVE
1	0.8% HFMS-1 1.5% WATER	4	10% JEFFERY ASH 5% WATER
2	0.8% HFMS-1, 1% HYDRATED LIME, 3.2% WATER	5	5% SUNFLOWER ASH, 2.5% WATER
3	10% SUNFLOWER ASH, 5% WATER	6	5% JEFFERY ASH, 2.5% WATER

FIGURE 4 Moisture sensitivity of RAP mixtures with various additives.

test (Figure 7) showed the highest mix stiffness for the Jeffery and Sunflower ash with 1 percent lime. The strength characteristics of the Sunflower fly ash are about equal to the asphalt emulsion specimens and less than those specimens with lime (Jeffery ash and Sunflower ash with 1 percent lime) as additives. From the results presented in Figures 5 through 8, it is apparent that much of the strength enhancements of the Jeffery ash are due to its self-reacting pozzolanic action.

The results of the absolute permeability tests are shown in Figure 8. Absolute permeability test results, reported in units of 10^{-10} cm^2, are classified by KsDOT as (a) over 1,000 is high, (b) 500 to 1,000 is medium, (c) 100 to 500 is low, and (d) 0 to 100 is very low. As shown in Figure 8, the absolute permeability of the asphalt emulsion mix was in the upper range of the medium category. The fly ash samples were all in the very low category, except the Sunflower ash at 10 percent mixing water. As shown by the unit weight of the Sunflower ash mixes in Table 3, 10 percent mixing water appears to be well over the optimum mixing water content. The low absolute permeability for the fly ash treated samples correlates with the higher Lottman conditioned strengths in that water was unable to penetrate and cause damage to the cold recycle specimens treated with fly ash. The Jeffery ash samples had a lower absolute permeability than the Sunflower ash. This reduced permeability could be because of the self-reacting pozzolanic action of the Jeffery ash.

When 1 percent hydrated lime was added to the Sunflower fly ash cold recycled mix, all strength characteristics increased and absolute permeability dropped to the very low category. However, it is recognized that adding two dry additives would create some field construction logistics problems. On the basis of laboratory testing, the best resistance to moisture damage and rutting occurred with the Jeffery (Type C) ash samples.

TABLE 4 Results of Strength, Stiffness, and Permeability Tests

ADDITIVE	MIXING WATER (%)	UNIT WEIGHT (kN/m^3)	RESILIENT MODULUS VERTICAL (10^5 kPa)	RESILIENT MODULUS HORIZONTAL (10^5 kPa)	TENSILE STR. (kPa)	COMPRESSIVE STRENGTH (kPa)	ABSOLUTE PERMEABILITY (10^-10 cm^2)
1% CMS-1	1.5	19.7	7.0	9.7	184.1	1276	963
7.5% Jeffery	2.5	20.5	16.6	51.2	497.8	3172	97
7.5% Jeffery	5.0	20.7	19.2	58.7	496.4	3192	2
7.5% Jeffery	7.5	20.1	15.0	35.2	337.2	2089	3
7.5% Jeffery	10.0	19.9	12.6	37.2	295.1	1862	3
7.5% Sunflower	2.5	20.5	11.1	20.8	217.9	1965	81
7.5% Sunflower	5.0	20.5	10.0	N/T	N/T	1358	18
7.5% Sunflower	7.5	19.8	9.8	15.0	82.1	752	61
7.5% Sunflower	10.0	19.5	8.1	19.0	65.5	786	146
7.5% Sunflower + Lime	5.0	20.6	15.7	58.5	388.9	2730	6

N/T = Not tested.

The final phase of the laboratory portion was to investigate the time-temperature characteristics of the Jeffery (Type C) fly ash. Laboratory specimens were mixed and molded with 5 percent mixing water and 7.5 percent fly ash. Past KsDOT experience has shown that it takes approximately 30 min to mill and compact the old roadway; therefore, the time between mixing and molding was 0, 15, 30, 45, and 60 min. Four different temperatures—4.4°C, 15.6°C, 25°C, and 37.8°C (40°F, 60°F, 77°F, and 100°F)—were used. All samples were cured for 7 days at room temperature. For comparison, samples were made with 1 percent CMS–1 asphalt emulsion with 1.5 percent mixing water. The results are shown in Table 5.

The results in table 5 show a decrease in strength as well as unit weight when the mixing time is increased. The results also indicate that as the temperature decreases, the unit weight and tensile strength decrease for the zero time delay. However, for the 15-, 30-, 45-, and 60-min mix and molding time delays, the unit weight and tensile strengths actually increase with decreasing temperatures. It was believed that the field temperature for cold recycling with Type C fly ash could be substantially reduced, possibly as low as 4.4°C (40°F), and any decrease in unit weight due to reduced temperature could be negated by the additional time allowed for compaction at the lower temperatures.

Phase II

Test sections were constructed on four pavements during the 1990 to 1992 construction seasons. Two of the test sections used the Sunflower ash, and the others used the Type C fly ash from the Jeffery and Southerland plants. Constructability problems were documented during construction and draft Special Provisions to the standard specifications (*6*) were prepared. The results of crack surveys, rut depth measurements, and falling weight deflectometer (FWD) testing are shown in Table 6 and discussed in the following sections.

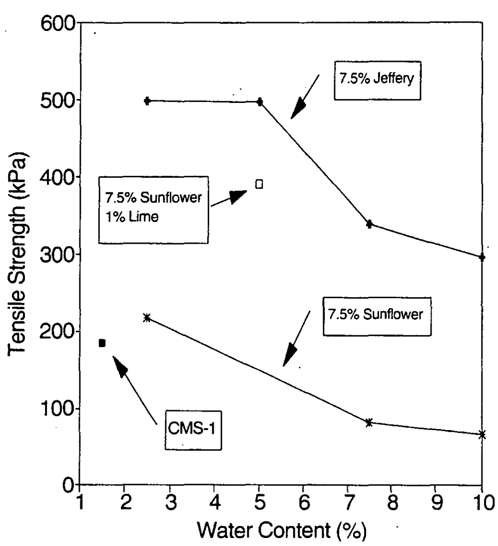


FIGURE 5 Tensile strength of RAP with various additives.

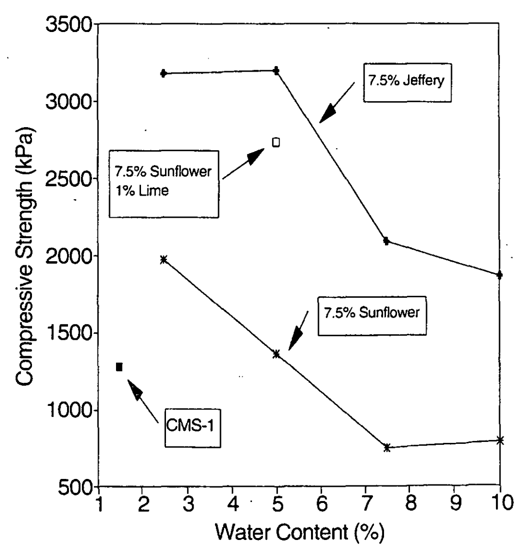


FIGURE 6 Compressive strength of RAP with various additives.

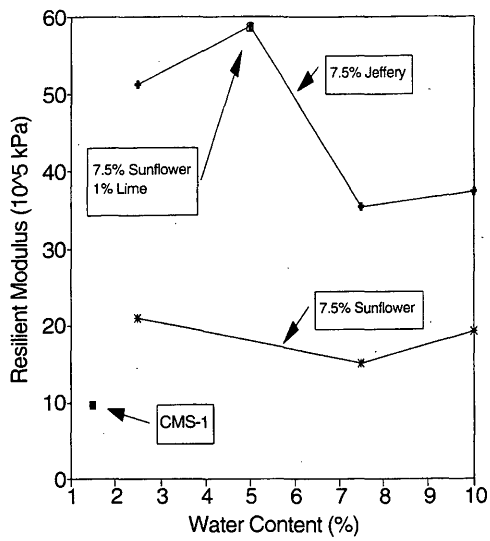


FIGURE 7 Resilient modulus of RAP with various additives.

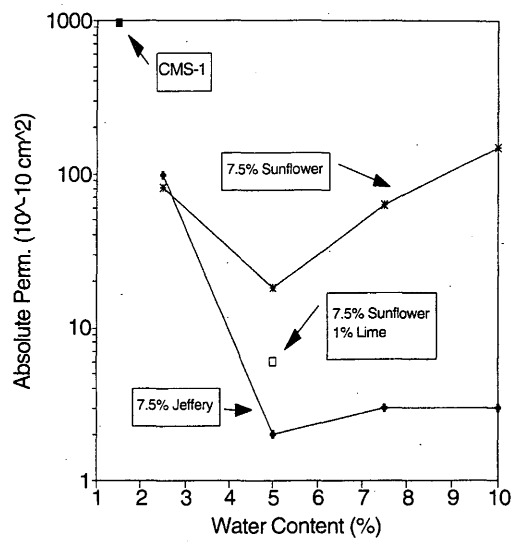


FIGURE 8 Absolute permeability of RAP with various additives.

Sunflower Fly Ash

Two projects were constructed using the Sunflower fly ash. The first project was on US-56 in Haskell County and was constructed in 1990. This was the first CIR project in Kansas to use fly ash as an additive. The project incorporated 0.9 percent HFMS-1 asphalt emulsion, 5 percent Sunflower fly ash, and approximately 8 percent water. A small section was built without the emulsion, but it started to ravel under construction traffic; it was therefore, decided to continue adding asphalt emulsion. The fly ash from the Sunflower plant was slow to set, had very low strengths, and acted more like a mineral filler than a cementitious material. When rain fell on the pavement during construction, water penetration was reduced so that the stripping and stability problems typically associated with RAP and emulsion mixes were reduced. Permeability of the fly ash/RAP/emulsion mix appeared to be substantially reduced when compared with the RAP and emulsion mix. On the basis of the initial findings of this first project, it was decided to incorporate fly ash into additional projects.

The second project was located on K-27 north of Syracuse in Hamilton County and was constructed in 1991. Three test sections were used: one containing 5 percent Sunflower fly ash, one containing 1 percent CMS-1 asphalt emulsion, and 5 percent fly ash with 1 percent CMS-1 asphalt emulsion as additives. A 38-mm (1.5-in.) HMA was placed over the test sections. Less water (3 percent), was added to the RAP/fly ash/emulsion mix. No major raveling or construction problems were encountered on this project. Crack survey results (shown in Figure 9) indicate more cracking in the fly ash sections. However, the cracks appear to be staying closed, without depressing. No unusual amounts of rutting were reported on any of the test sections.

Type C Fly Ash

Also in 1990, an 8-mi segment of I-70 in Thomas County was being reconstructed. A portion of the project used the Type C fly ash from Sutherland. The test sections contained 250 mm (10 in.)

TABLE 5 Time Temperature Strength Characteristics, 7.5 Percent Jeffery Fly Ash, 5 Percent Water

	MIXING TEMPERATURE (°C)							
	4.4	4.4	15.6	15.6	25	25	37.8	37.8
MIXING TIME (min)	TENSILE STR. (kPa)	UNIT WEIGHT (kN/m^2)	TENSILE STR. (kPa)	UNIT WEIGHT (kN/m^2)	TENSILE STR. (kPa)	UNIT WEIGHT (kN/m^2)	TENSILE STR. (kPa)	UNIT WEIGHT (kN/m^2)
0	427.5	19.22	434.4	19.22	496.5	19.31	531.0	19.84
15	427.5	19.27	462.0	19.31	482.7	19.52	351.7	18.51
30	448.2	19.45	372.4	19.24	262.0	18.17	289.6	18.37
45	441.3	19.36	296.5	18.77	268.9	17.95	275.8	18.25
60	386.2	19.24	248.2	18.31	213.8	17.78	268.9	18.19
	1% CMS-1 WITH 1.5% MIXING WATER							
0	69.0	17.45	69.0	17.29	96.5	17.75	179.3	18.51

TABLE 6 Results of Field Testing

PROJECT/ ADDITIVE	TOTAL CRACKING (m/30.48 m) AFTER 12 MONTHS	AFTER 24 MONTHS	RUTTING (mm)	FWD PAVEMENT MODULUS (MPa) AFTER CONSTRUCTION	AFTER 12 MONTHS	AFTER 24 MONTHS
K-27 Hamilton Co.						
5% Sunflower	5.2	8.9	< 4	N/T	N/T	N/T
CMS-1	1.0	5.7	< 4	N/T	N/T	N/T
5% Sunflower + CMS	13.4	37.6	< 4	N/T	N/T	N/T
K-27 Sherman-Wallace Co's.						
13% Jeffery	0	N/A	3	1.98	1.17	N/A
CMS-1	0	N/A	4	0.92	1.2	N/A
CMS-150P	0	N/A	4	0.85	0.96	N/A
I-70 Thomas Co.						
7% Sutherland	0	1.7	0	N/T	1.3	0.73
CMS-1	0	0	0	N/T	1.04	0.77
CMS-1 + Lime	0	0	0	N/T	1.81	1.22

N/A = Data not available, less than 24 months old.
N/T = Not tested.

of RAP with (a) CMS–1 asphalt emulsion, (b) CMS–150P polymer modified asphalt emulsion, and (c) 7 percent fly ash with 8 percent mixing water. Each section was overlaid with 76 mm of a hot recycled mix and a 19-mm HMA friction course. The project was completed in 1991, and the available field test results are shown in Table 6.

The results in Table 6 show that, to date, the test sections have experienced minor rutting and cracking in each test section. Figure 10 shows the results of the FWD testing performed after construction and within 4 days of 1 year. The results are for the stiffness of the entire bound layer and indicate that the stiffness of each section is decreasing. The subgrade modulus also decreased. There were insufficient data to draw definite conclusions at the time of this writing, but it appears that the pavement may be experiencing moisture damage.

The fourth test pavement is K–27 in Sherman and Wallace counties. The test sections contain 13 percent fly ash, CMS–1, and CMS–150P, each with a 38-mm (1.5-in.) HMA overlay. The results of the field testing are shown in Table 6. The results indicate little or no cracking or rutting at this time. The FWD data are shown in Figure 11 and represent the stiffness of the entire bound layer. The results show that the fly ash section is experiencing a loss of stiffness with time where the emulsion sections are remaining constant or increasing. The magnitude of the stiffness of the sections are approximately equal at this time. The pavement modulus is being monitored to determine long-term trends.

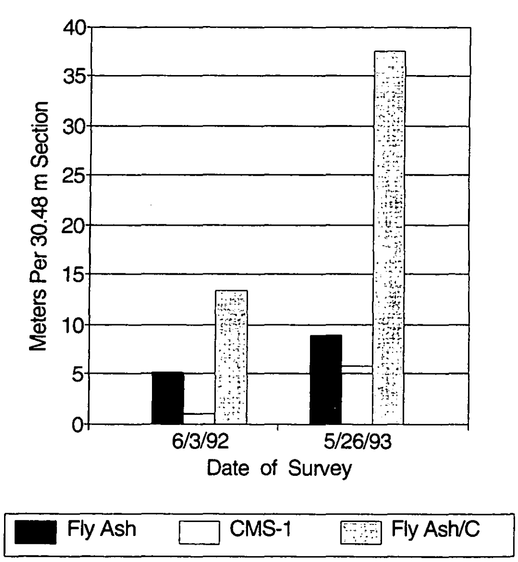


FIGURE 9 Crack survey for K–27, Hamilton County.

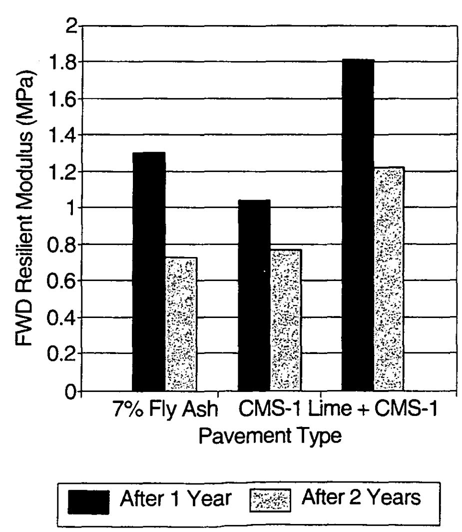


FIGURE 10 FWD pavement modulus for I–70, Thomas County.

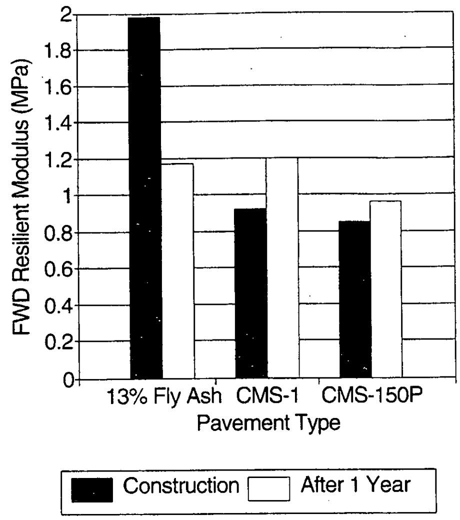


FIGURE 11 FWD pavement modulus for K-27, Sherman and Wallace counties.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the initial success of the above test sections and laboratory testing, four additional CIR fly ash projects were constructed during the 1992 construction season. The four projects used approximately 10,320 tons of Class C fly ash and a set retarder (HP-5/Ammonium Lignosulfonate) at a rate of approximately 0.5 percent (based on the weight of fly ash) as additives. Three of the projects incorporated Type C fly ash at a rate of 7 percent, based on the weight of the RAP, and one smaller project used 13 percent fly ash. Each received a 38.1-mm (1.5-in.) HMA overlay. Water contents varied slightly but typically ranged from 5 to 7 percent (based on the weight of RAP + fly ash). No major construction-related problems were encountered on these projects, although there was a tendency for the mixture to ravel under traffic during construction.

On the basis of the results of this study, the following conclusions are drawn:

- Fly ash decreases the absolute permeability of the cold recycled mixes, thereby increasing the resistance of the mix to the detrimental effects of moisture damage.
- Fly ash increases the strength of the mix and decreases its potential for wheel path rutting.
- Type C fly ash had lower permeability and higher strength than the Sunflower ash.
- Fly ash–only cold recycled mixes have a tendency to ravel under construction traffic. A protective cover material (prime coat, seal, overlay) is necessary, even on low-budget projects.

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